Hydrogen and Fuel Cells —
How, What for, and Why?

Hans U. Fuchs, 2019

Dear Reader,

this is a fairly non-technical text for all of us who are not engineers or scientists. It outlines some background of hydrogen and fuel cell technology. Some more technical themes have been included, though, which have been moved into boxes marked by the label

- **T**

So, maybe, on a first reading, you might like to just follow the main lines of the description and explanation, leave out these boxes, and come back to them later, if at all…

Hydrogen as a fuel, and fuel cells for empowering electricity through hydrogen, might one day replace our current fuels and ways of making energy available. At least three questions are raised by this prospect: How does such a system work, what would we use hydrogen and fuel cells for precisely, and why would we want to embark on a new technology if the old one has served us well, and might continue to serve us for a long time to come?

Arguments in favor of FCH-Technology

1. Hydrogen can be a renewable fuel.
2. Burning hydrogen, or using it in fuel cells, only produces water.
3. Hydrogen working in fuel cells is potentially highly efficient.

There are at least three arguments in favor of Fuel Cell and Hydrogen Technology (FCH-T):

1. The fuels currently used are mostly non-renewable. Coal, oil, and natural gas have been laid down in the Earth's crust a very long time ago, and once used up, they won't come back.
2. Burning the usual fuels creates substances that harm the environment in several ways. For example, they pollute the air we breathe and the water we drink. Most importantly, carbon dioxide produced by burning coal, oil, and natural gas is making our planet warmer at a rate that will not be acceptable to future generations—and should not be acceptable to us.
3. From a physical and technical viewpoint, burning fuels is wasteful—producing heat is not what we should be doing. There are better ways, at least theoretically, from a basic scientific and engineering perspective, to use fuels.

Hydrogen

Physically, hydrogen is a simple *substance*, like water or air, just not so abundant on Earth; It happens to be the main "stuff" our Sun is made out of. On Earth, under typical environmental conditions, it appears as a gas, just like some other simple gases such as nitrogen, oxygen, and carbon dioxide, which are parts of the air.

Chemically, hydrogen is an *element*, just like oxygen, or helium, or iron. Actually, as a gas on Earth, hydrogen is a compound: its molecules are made of two hydrogen atoms. In chemistry, we use the symbol H for the element we call hydrogen; therefore, the symbol for hydrogen is H_2 (two H-atoms combined).

It can serve as a fuel, meaning it can react in a chemical reaction with oxygen and so drive other processes such as heat, or electricity, or motion. In other words, it makes energy available to drive those processes. Put still differently, hydrogen can be a source of energy, it is an *energy storage medium*.

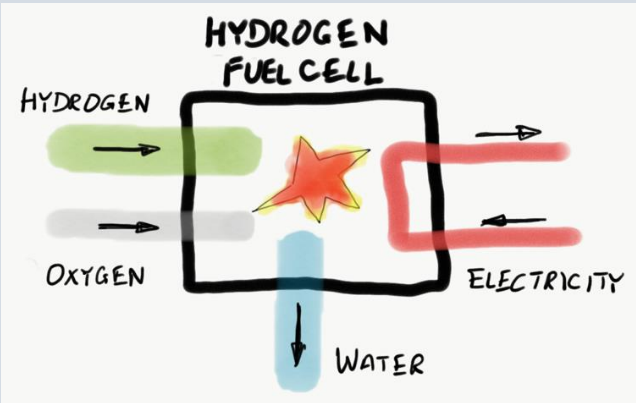
We can also call hydrogen an *energy carrier*: when we receive hydrogen, it brings its energy with it.

FCH-Technology, on the other hand, has the potential to answer to all these concerns. Hydrogen can be produced continuously with the help of the Sun. Burning hydrogen or, better still, using it in fuel cells, produces water as the "waste product;” there is no carbon involved that would lead to the production of carbon dioxide.

Moreover, using a fuel in a fuel cell means that it is not burned: there is no fire; it is not used to produce heat—the energy made available by a fuel can be used to power the electric process of a fuel cell (a fuel cell basically works like a battery).

Fuel cells

A fuel cell is a kind of machine. As such, it is not unlike an electric water pump, a dynamo, or the combustion engine of a car. Just like all these engines, it is made to *couple two processes*: the first drives a second desired process. In an electric water pump, for instance, we make use of the power of electricity to drive the flow of water from a lower to a higher place. In a fuel cell, a chemical process drives an electrical one.



A fuel cell uses a fuel such as hydrogen or methane, lets it react in a chemical reaction, and so powers an electric process. In the most basic type, a fuel cell uses hydrogen that reacts with oxygen, which produces water and leads to an electric tension that allows electricity to be “pumped” through wires and appliances. This is very similar to what a battery does, with the difference that, in a fuel cell, the reacting substances are supplied, and the products of the reaction are removed continuously.

To be sure, FCH-Technology, in its entirety, would still lead to the production of some harmful substances, and producing hydrogen and using it in fuel cells will never be 100% efficient despite apparent theoretical promises. However, the product of inefficiency of FCH-T is essentially some additional heat. This does not pose additional risks to our planet.

In the following, we want to discuss the questions posed in the title and describe aspects associated with them in some more detail. The second of these (FCH-T: What for) is answered quite easily: It is used mostly for the technologies where we use fuels today to make energy available. The third question (FCH-T: Why) will take more time to answer. By considering it, we will be rewarded with some knowledge of physical and chemical processes and, most importantly, with a better understanding of the potential of FCH-T for a sustainable energy future. But before we begin answering these questions, we start with the first.

FCH-Technology: How?

A system that gives us hydrogen and uses hydrogen for some purpose, might look as follows (see Fig. 1). First, hydrogen needs to be generated. A direct way of doing this is from water. Through a chemical reaction, water is transformed into two gases, hydrogen and oxygen; this can be achieved with the help of electricity.

Using the Sun's light for…

1. driving electricity directly in solar cells;
2. generating the winds that power wind turbines for electricity;
3. driving the hydrological cycle giving us hydroelectric power.

If we want the Sun to power electric processes, we can build a photovoltaic solar plant. We can also use winds or water flowing at the surface of our planet to drive wind or water turbines which then drive electric generators. Since, on Earth, wind and water flows are caused by sunlight, the energy of wind and water lastly comes from the Sun as well.

When we let electricity flow through lightly salted water, the water undergoes a chemical reaction that produces hydrogen and oxygen. The process is called *electrolysis*. Oxygen can be let into the atmosphere; hydrogen is collected and stored for any length of time desired.

When hydrogen is needed, it can be fed into a fuel cell where the chemical reaction that produced it in the first place is reversed—water is produced from hydrogen and oxygen which might be taken from the air. As a result, the fuel cell can power some device, very much like we can operate an electric motor with a battery.

The device might be a heat pump in a home. Operating the heat pump leads to heat being pumped from a place that is relatively cold—such as the ground outside the home—to a warmer place—such as water in a hot water tank, or the air inside the home.

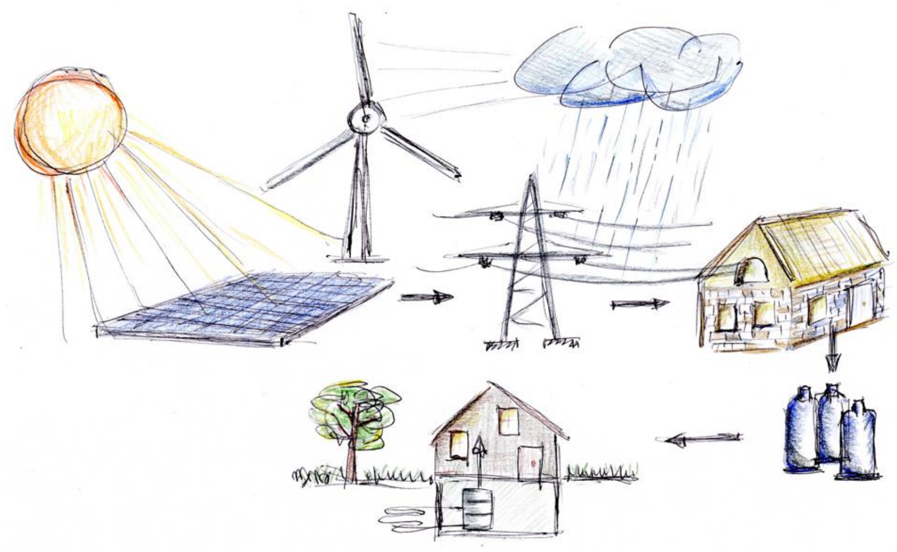


Figure 1: A fuel-cell-hydrogen system powered by the Sun and used for heating a home. Note the hydrogen tanks in the middle of the chain of processes.

Fig.1 shows just one concrete case of an energy system at the beginning of which stands the Sun, and at the end of which we have some phenomena for which we use energy. The electricity provided to us by hydrogen used in fuel cells can drive engines in trucks, cars, trains, and even ships, light cities, or run refrigerators.

We can continuously produce hydrogen as long as the Sun shines, store the fuel and move it to where it will be needed, and feed it into fuel cells that give us the equivalent of an electric generator. In other words, indirectly, the Sun and hydrogen can be used to power most if not all of the devices and machines we use in our daily lives.

FCH-Technology: What for?

Fuel-cell-hydrogen technology (FCH-T) combines two elements that do not necessarily need to be combined: use of hydrogen as a fuel and using fuels in fuel cells for powering an electric process. However, joining the forces of hydrogen and fuel cells has some important advantages.

Hydrogen

Hydrogen is not just a fuel; it plays an important role as a chemical for producing other chemicals and pharmaceuticals as well. But here we are concerned with its role as a fuel. Where today we use our traditional fuels such as coal, oil, or natural gas, we can use *hydrogen* in the future.

Important large-scale uses of fuels

4. Heating of buildings and process heat.
5. Electric power from large-scale power plants.
6. Transportation (land, water, air).

Fuels are used for quite a number of applications. Three of these stand out: burning fuels for *heating* and *process heat* in industry; burning fuels in *electric power* plants; and burning fuels in engines for *transportation* (such as car engines, or diesel engines and gas turbines used in trains and ships). In the first case, we make use of heat, in the second we want electricity, in the third we produce motion.

In all three cases, fuels are burned. So, actually, the first thing that happens is that heat is produced. For heating purposes, this might be considered to be fine, but even in this application, there are better ways of using fuels. In the second and third, we may wonder why we have to go through heat in order to arrive at electricity or motion.

Fuel cells

This is where *fuel cells* come in. Rather than burning a fuel, a fuel cell uses a fuel to directly power an electric process, just like a battery does. Where electricity can be used to power other desired processes—especially motion—fuel cells can replace existing technology. Fuel cells can be used for transportation, and they can basically replace electric power plants—because they are themselves power plants. We even could use them for heating by producing heat electrically. But that does not only *sound* like a waste, like running in circles, it *is* a waste—we can use electricity to drive heat pumps and get much more heat for a unit of energy than if we burned a fuel such as hydrogen or produced heat in an electric heater (by letting electricity flow through thin wires that heat up).

FCH-technology could potentially replace our current use of fuels for heating, electric power, and transportation with renewable, cleaner, and more efficient processes. Why this technology leads to cleaner and more efficient processes, will now be explored.

FCH-Technology: Why?

At the very beginning, we gave three main reasons for why we might want to move aspects of our use of fuels in the direction of FCH-technology: hydrogen can be produced in renewable processes; used as a fuel, it only creates water as a residue; and used in fuel cells, it has the potential of creating a more energy efficient infrastructure.

This leaves the important question of how FCH-technology is supposed to achieve all these goals. Can we understand why hydrogen would be a renewable fuel, why it is potentially clean, and why it can be used in a potentially efficient manner?

In order to answer these questions, we have to delve into some science and engineering. Importantly, learning about these aspects does not have to be intimidating—there are ways of creating narrative descriptions and explanations that appeal to our every-day experience and understanding of the world around us. These narratives use natural language and images that need not be formal or otherwise inaccessible to the majority of us.

The chemistry of burning fuels

Let us start with chemical aspects of the use of fuels. For simplicity, and for concreteness sake, let us just consider two fuels: hydrogen and methane. Hydrogen is normally a gas whose molecules are composed of two hydrogen atoms. Methane is composed of carbon and hydrogen atoms. It is the primary component of natural gas, and it is produced in many biological processes (cows "fart" methane!). Methane is also a powerful greenhouse gas; too much of it in the atmosphere has a strong warming effect for the planet.

When a gas such as hydrogen gas or methane is burned, it combines with oxygen normally taken from the air. Burning hydrogen gas leads to water. Burning methane yields water and carbon dioxide. So, at least potentially, burning hydrogen is "clean" whereas burning methane is not. (Note, however, that if we get methane from biogas production, burning it and producing carbon dioxide is not a problem: the carbon dioxide was originally from the air taken by plants. So, bio-methane is basically carbon-dioxide-neutral.)

> **T Burning hydrogen and methane**
>
> Hydrogen gas is composed of two hydrogen atoms. The symbol H is used for hydrogen (atoms), so hydrogen gas is denoted by H_2 in chemistry. Oxygen gas in air is composed of two Oxygen atoms (O), so it carries the symbol O_2.
>
> Burning hydrogen gas means getting it into a chemical reaction with oxygen gas which produces water. Since water is composed of two parts of hydrogen and one part of oxygen (H_2O), we need to let two units of hydrogen gas react with one unit of oxygen gas to produce two units of water:
>
> $$2\ H_2 + 1\ O_2 \longrightarrow 2\ H_2O$$
>
> On the other hand, burning methane (CH_4, where the symbol C stands for carbon) creates water and carbon dioxide (CO_2):
>
> $$1\ CH_4 + 2\ O_2 \longrightarrow 2\ H_2O + 1\ CO_2$$
>
> Here we see the origin of our problem of producing the greenhouse gas carbon dioxide: it is an unavoidable by-product of burning hydrocarbon fuels such as oil and natural gas. It is produced by burning coal as well.

Things are not that simple, though. When we burn hydrogen in air, we get other by-products because air contains not just oxygen (which, together with hydrogen, makes water). Specifically, at high temperatures, nitrogen gas in the air combines with oxygen to produce nitrogen oxides (such as NO_2 and N_2O) which pollute the air we breathe. Reacting with the light of the Sun, NO_2 (nitrogen dioxide) produces ozone (O_3) which is an irritant for our lungs and for animals and plants. Nitrous oxide (N_2O) and ozone are also greenhouse gases.

These are some of the reasons why we should not simply burn hydrogen; let us call these the chemical reasons. Later we shall learn that there is another very important physical reason for not burning hydrogen: burning fuels creates heat, and creating heat is never a good solution to challenges in energy engineering. Rather, we should use fuels in fuel cells, especially if we desire electricity for further applications.

Energy carriers and their tensions

On our journey to learning about FCH-technology, an important prerequisite for understanding aspects of energy engineering is the following: we need to learn and accept that what we call *light*, *heat*, *electricity*, or *motion* are ***not*** *energy*; rather, they are *energy carriers*.

Actually, it makes sense to use words such as *light*, *heat*, *electricity*, or *motion* for *phenomena* that encompass a number of aspects—energy is only one of them. Together with fluids (such as water and air) and the myriad chemical substances we make use of, light, heat, electricity, or motion can be best understood as *forces of nature*—phenomena endowed with power (see the document *Forces of Nature and Energy*).

Apart from being associated with energy—through their aspect of being powerful—forces of nature are mainly characterized by two more aspects: phenomena can be *more or less intense*, and they can be *bigger or smaller*—there can be more or less of them (see Fig.2). There are *intensities* of light, heat, electricity, and motion; intensities are visualized as levels, they are *high* or *low*. Note that differences of intensity produce what we experience as *tensions*. And then there are *quantities* of light, heat, electricity, and motion.

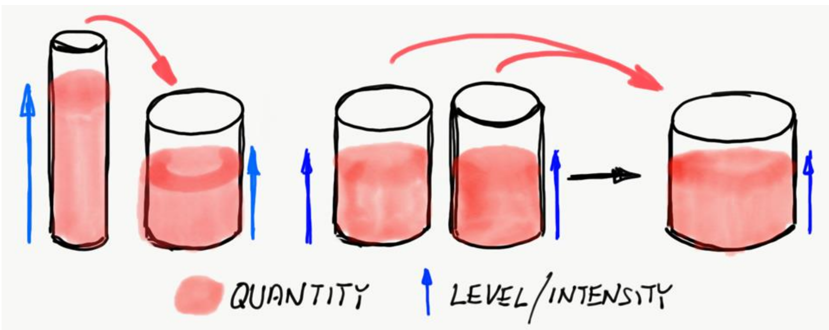


Figure 2: Fluidlike quantities—*quantities of* fluid, electricity, heat, light, motion, etc.—are visualized as the red "stuff" in containers. Their intensities are indicated by the levels of the "stuff" in containers. The same quantity can be associated with different levels (left) or twice the same quantity can be associated with the same level (right).

The fact that we see *quantities* behind physical and chemical phenomena—quantities of fluid, of heat or electricity, of motion or substance—can be captured by the image of *fluidlike quantities* (Fig.2). Quantities of electricity, light, fluids, heat, motion, or substance are *contained* in storage elements (heat in a hot stone, motion in a moving stone, electricity in a capacitor, water in a jar, etc.), and they can *flow* into and out of these elements and from element to element (Fig.3).

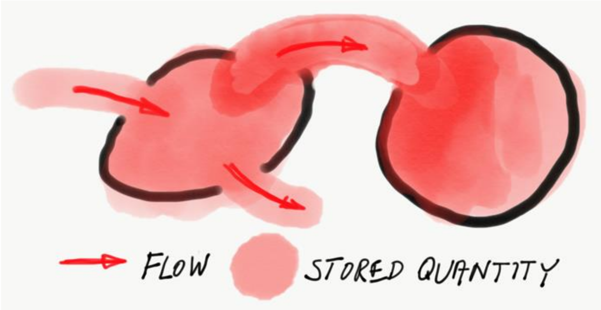


Figure 3: Fluidlike quantities—*quantities of* fluid, electricity, heat, light, motion, etc.—can be stored and they can flow into and out of storage elements or from storage element to element.

When we study water, this is clear. There can be more or less water, water can be at high or low pressure (and pressure differences constitute a tension associated with water flowing or being stored). And water can be more powerful or less powerful: we might say that water is endowed with more energy or less *energy*. Actually, as far as energy is concerned, it makes sense to see water as an *energy carrier*; it certainly is *not* energy.

It is important to see light, heat, electricity, and motion the same way. They are characterized by intensities: *brightness*, *temperature*, *electric potential*, and *speed*, respectively; and they are associated with tensions: differences of brightness, temperature differences, electric tension, and differences of speed, respectively. *Quantity of light*, *quantity of heat* (*caloric*), *quantity of electricity* (*charge*), and *quantity of motion*, on the other hand, should be imagined as energy carriers (see Fig.4).

Naturally, substances are energy carriers too; therefore, hydrogen is an energy carrier as well!

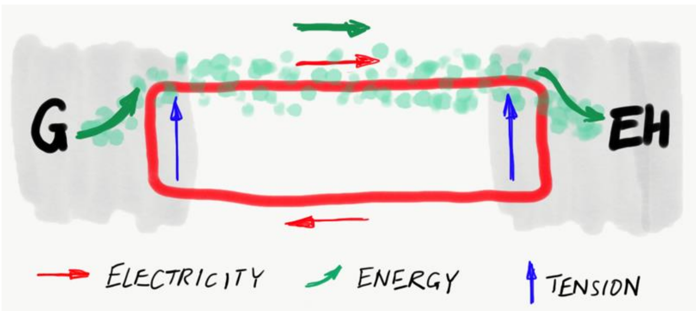


Figure 4: *Electric heating*: Electricity (electric charge) flows in a circle (red closed loop). It carries energy it received in the generator (G) to an electric heater (EH) which is simply a long, thin wire. There it “unloads” the energy it received. Energy is symbolized as a green “stuff.” When electricity receives energy in the generator, a tension is set up.

Energy: Making it available and using it

When water flows down a mountain, it can be used to power other processes (see Fig.5). Typically, we use it to drive a water turbine which powers an electric generator, which drives some electrical device, maybe an electric motor, and so on.

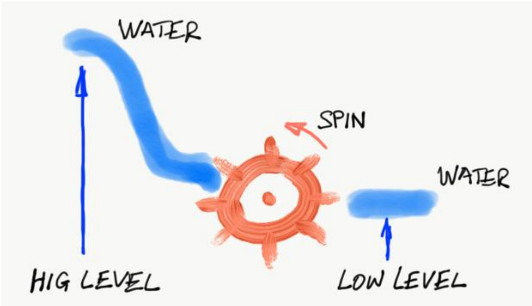


Figure 5: Water falling down in a waterfall can drive a water wheel. We say that, in doing so, water powers rotational motion (*spin* is the technical name for quantity of rotational motion). Water is going from a high to a low level. What we do not see that spin is actually going from low intensity to high intensity (fast spinning).

Note what is happening here: there are chains of processes with forces of nature *interacting*. The falling water interacts with the rotational motion of the turbine (see Fig.6), and the force of rotational motion interacts with the force of electricity, which interacts with rotational motion of the electric motor. The first interaction takes place in the turbine, the second in the generator, and the third in the electric motor. The physical objects—turbine, generator, and motor—are called *couplers*. They couple forces of nature.

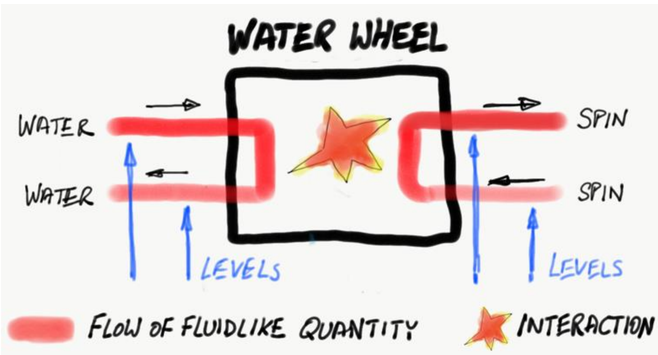


Figure 6: Abstract rendering of the interaction of water (as a force of nature) with rotational motion (as a different force of nature). The quantity of fluid enters the box (symbolizing a coupler) at high level and leaves it at low level. Spin is then "pumped" from low (zero) to high (high spinning speed) level. The image is similar to how we have depicted the operation of a fuel cell on page 3.

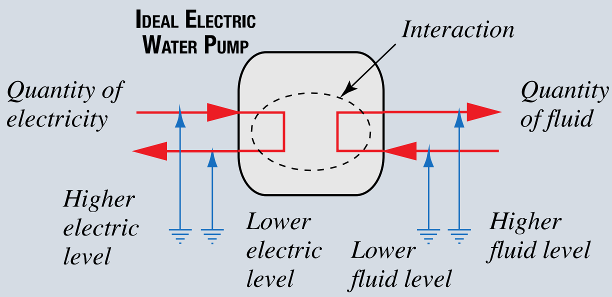
In coupling of two processes, the first force is the *causal agent* whereas the second is *caused* by the first. A good example of this is what happens in an electrically powered water pump. Actually, if we used a handpump where we turn a crank, the abstract image of the coupling would be simply the reverse of what we have in Fig.6: spin goes from high to low spin-level and so drives water uphill (water now goes from a low to a higher level).

When we think about it, the causing phenomenon is characterized by the quantity of the force *falling* from a higher to a lower level (in the turbine, this is amount of water flowing from high to low; in an electric water pump, quantity of electricity, i.e., charge, falls from a high electric level to a lower one). The caused or forced phenomenon, on the other hand, is characterized by the quantity of the force being *pumped* from a lower to a higher level (in the turbine, this is amount of rotational motion going from low to high rotational speed; in the electric water pump, water is pumped).

➢ T Interaction of forces of nature in couplers: Process diagrams

In an ideal electrically powered water pump, two forces of nature interact: water and electricity. Electricity is the *driving agent*, water *is driven* (it is "suffering"). The pump is the coupler.

When electricity drives another agent in a coupling process, it does so because it flows from a high electric level to a lower one. Water, on the other hand, is driven, i.e., pumped, from a lower level (pressure) to a higher one. We can depict this little story of interaction in the following *process diagram*:



Process diagrams are an abstract rendering of our imagery of how forces of nature work. We have boxes for couplers, (red) arrows going in and out for flows of fluidlike quantities, and (blue) vertical arrows denoting levels or intensities.

If we want to quantify the interaction (coupling) of two forces of nature, we need to think of a new quantity. This is energy. We say that the driving or causing process *makes energy available*; the caused or driven process *uses energy*. The strength of coupling is described by how much energy is exchanged from causal agent to caused force every second. This quantity is called the *power of the process*.

So far, in Figs.2 and 6, we have used a silly symbol, kind of like what we see in comics when the artist wants to indicate that "something violent" is happening: a colorful star as a metaphor for an "explosion." In Fig.7, we now use a somewhat more "scientific" symbol, green arrows pointing down or up for making energy available (at a certain rate) or for using it, respectively.

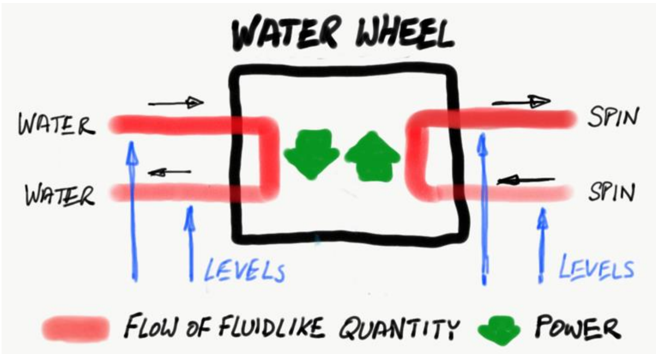


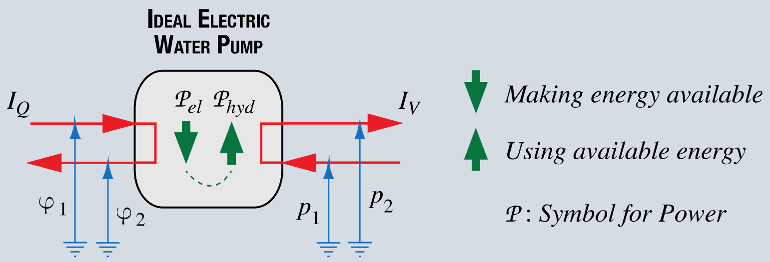
Figure 7: Abstract rendering of the interaction of water (as a force of nature) with rotational motion (as a different force of nature), as in Fig.5. Here, we have replaced the colorful star in the center by green arrows denoting rates at which energy is made available and used. In this form, the figure is what we call a process diagram of interactions of forces of nature. Such diagrams can be joined to represent chains of processes. Since energy is exchanged in a coupler, we can call couplers *energy exchangers*.

There are a few noteworthy aspects of depicting the interaction of forces of nature in this manner. First, the example we have used here—the interaction of water and rotational motion—is assumed to have occurred ideally. This means that all the energy made available by falling water has been used by spin going from a low to a high spin-level. We know that this is not how things work in nature. We shall come back to this important point—to the imperfection of coupling—later on.

Second, we could represent a system consisting of falling water, spinning turbine, and rotating electric generator and "package" it in a single box or coupler as in Fig.6. In this case, we would not see the turbine represented any longer. There would be falling water directly powering electricity. We are perfectly permitted to do this—science is often the art of choosing how to look at reality. If it suits the purpose of making an explanation shorter, this "packaging" is what we will do.

➢ T Making energy available and using it: Power of a process

The actions of making energy available or using available energy can be depicted easily in process diagrams.



Vertical fat arrows are used to denote the rate at which energy is made available or used. I_Q *and* I_V are the symbols for flows of quantity of electricity or fluid, respectively; *j* and *p* symbolize electric level and pressure, respectively.

Energy carriers and chains of processes

We are not in a position to create descriptions of entire chains of processes—as they occur in nature and in engineered system—and so learn the role of energy and energy carriers from still another viewpoint. Let us revisit the discussion of "packaging" a system consisting of a chain of falling water, spinning turbine, and rotating electric generator. When "packaged" into a single coupler/exchanger, it looks as if water were driving electricity directly. Let us now "unpack" this system to show what is going on inside.

We now have two couplers/exchangers: the water turbine and the generator. The turbine couples the flow of water to the transport of spin, and the generator couples the flow of spin to the flow of electric charge.

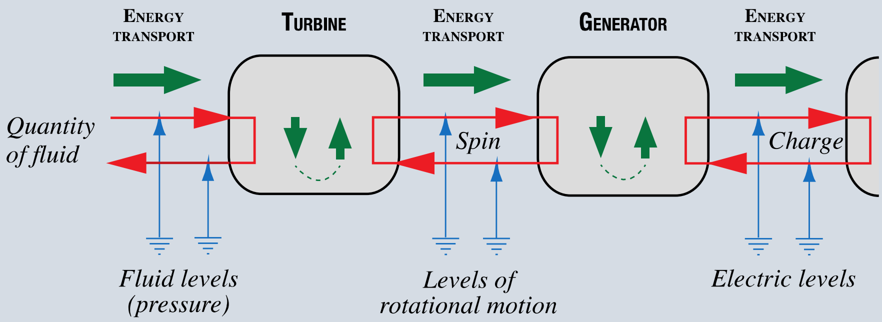
The description of the turbine takes the form visualized in Fig.6. Water goes from high to low level and makes its energy available to drive spin (quantity of rotational motion) from low rotational speed (actually from zero, from the ground where the turbine is attached) to high rotational speed (of the shaft of the turbine). Obviously, the energy made available must have been brought to the turbine by the water: this is the role of water as an energy carrier.

Spin has "picked up" energy in the coupler. It makes sense to assume that it carries the energy from the water turbine to the electric generator attached to it via the shaft. This means that we see spin as the energy carrier of rotational motion. Spin and energy will enter the generator where the energy is "offloaded," i.e., made available for the coupling of rotation to electricity.

In the generator, electric charge goes from low to high electric level. It uses the energy made available by the rotational process, and it carries it along on its way to a place where it will drive a device, maybe a motor, lights, or an electric heater. In other words, just like water or spin, electric charge is an energy carrier. We can depict this idea as in Fig.4.

➢ T Energy carriers and energy flows in process diagrams

When we let a number of devices—natural or technical—work in a chain of processes, energy is carried from device to device. Here's an example of a chain going from turbine to electric generator to some electric machine.



Energy does not flow by itself—it must be carried. Carriers can be *quantity of fluid (water)*, *amount of rotational motion* (*spin*), *quantity of electricity* (*electric charge*), etc. Most carriers are invisible (*quantity of electricity*, *quantity of heat* (*caloric*), *spin*, *quantity of motion*…).

The energy carriers flow from higher to lower levels or are pumped from lower to higher levels inside the devices, then flow at constant levels into or out of the devices. All of this is visible in *process diagrams* like the one above.

From everything we have said about energy carriers and energy, it probably makes sense to assume that a carrier carries the more energy the higher its level or intensity. If water flows at a higher level toward a water mill, it will carry more energy. If electric charge flows toward an electric device at higher electric level (electric tension), it will bring with it more energy.

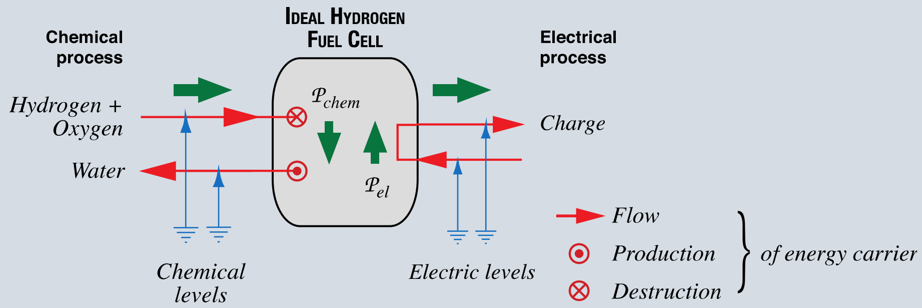
Hydrogen as energy carrier and agent in chemical reactions

As we have said before, hydrogen is an energy carrier too. And it is a chemical agent. It can carry energy to and from places, it can make energy available when it reacts with oxygen, and it can use or pick up energy when it is produced with the help of electricity in the process called electrolysis (see page 26).

Together with oxygen, hydrogen is in tension with water—that's how hydrogen is powerful, and that's why water is produced when hydrogen and oxygen react. In the reaction, energy is made available. The energy made available can be used for producing caloric (quantity of heat) when it is burned, or for pumping the electric energy carrier (electric charge)—this happens in fuel cells.

➢ T Using hydrogen in a fuel cell

The reaction of hydrogen with oxygen that produces water makes energy available. In a fuel cell, the energy made available is used for pumping electric charge from a lower to a higher electric level, setting up an electric tension.



When hydrogen gas reacts with oxygen gas, the two gases disappear. In their place, water appears. As a result of the reaction, charge is pumped.

Note that something is different between processes involving water, electricity, or spin and those involving reacting chemicals. In the former case, the energy carriers flow into and out of the couplers. The same quantities go in and out. If we look at a fuel cell, we see what happens in the latter case: there are different substances flowing in and out. Hydrogen and oxygen flow in (Fig.2) and water flows out. In other words, in this particular reaction, hydrogen and oxygen disappear and water appears. Hydrogen and oxygen are destroyed, and water is produced.

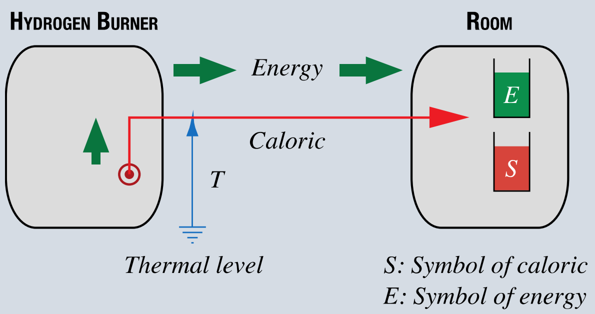
The tension between the combination of hydrogen and oxygen on the one hand, and water on the other hand, is so high that the reverse does not happen spontaneously—water does not spontaneously decay into hydrogen and oxygen. In order to get this done, we can let the force of electricity help by supplying energy.

Caloric (quantity of heat) as energy carrier and thermal agent

Heat—or rather, quantity of heat, which used to be called *caloric* when the science of heat was first being developed more than 200 years ago—is an energy carrier. When caloric flows from one object to another, it takes energy with it.

➢ T Caloric as energy carrier

When caloric (quantity of heat, the energy carrier in thermal phenomena) produced by burning a fuel is used to heat a room, it flows from the burner to the room and is stored in the room.



Caloric carries the energy that was used to produce it with it into the room; there, the energy is stored as well.

We need to distinguish quantity of heat from its intensity. The intensity or *level* of the carrier is *temperature*; temperature difference is the *thermal tension*. In Fig.2, caloric would be this "red stuff" inside the containers, and temperature, as the intensity of heat, would be the level of caloric inside a body where it is stored.

Another important aspect of thermal processes is the meaning of temperature difference. Indeed, we are well equipped to associate bodily experiences with temperature differences: they are what we would call *thermal tensions*. Thermal tensions have a role analogous to hydraulic tensions (pressure differences), electric tensions (differences of electric potentials), differences of brightness of light, or differences of speed in moving objects.

Temperature

Temperature simply measures *how warm something is*. Metaphorically speaking, temperature is the thermal level—it is high or low—and temperature differences are level differences or *tensions*. Thermal tensions *drive* thermal processes or *are established* by thermal processes.

Like all energy carriers, caloric can flow and it can be stored. When it is inside materials, it makes them warm or lets them expand (such as air) or melts or evaporates them (when ice turns to water and water to steam).

Like all energy carriers, caloric can make energy available (for other things to happen) when it flows from high to low, from a warm place to a cold place. Like all energy carriers, it can be pumped from low to high (cold to warm) when energy is available—this happens in heat pumps.

The former phenomenon explains how heat engines work. Sadi Carnot likened the operation of a steam engine to that of a waterfall driving a water wheel (1824; see Fig.8). This analogy is apt and useful. As Carnot put it:

> *According to established principles at the present time, we can compare with sufficient accuracy the motive power of heat to that of a fall of water … . The motive power of a fall of water depends on its height and on the quantity of the liquid; the motive power of heat depends also on the quantity of caloric used, and on what may be termed, on what in fact we will call, the height of its fall, that is to say, the difference of temperature of the bodies between which the exchange of caloric is made. In the fall of water the motive power is exactly proportional to the difference of level between the higher and lower reservoirs. In the fall of caloric the motive power undoubtedly increases with the difference of temperature between the warm and the cold bodies; but we do not know whether it is proportional to this difference.*

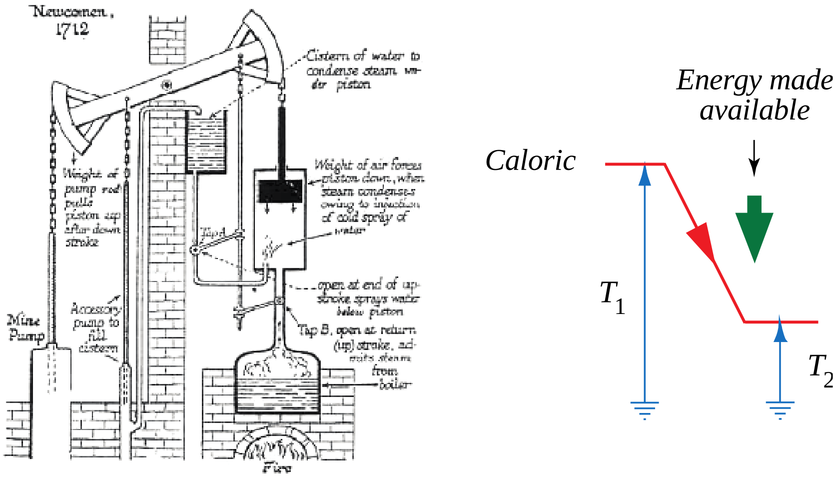
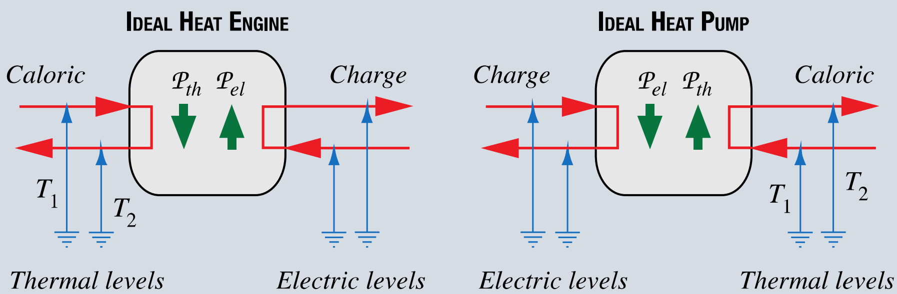


Figure 8: Sadi Carnot's waterfall image of the operation of a heat engine. Caloric is produced in a furnace, appearing at high temperature. With the help of steam, it is then transported to a cold place—the cooler—where the caloric is emitted into the environment. In the fall of caloric through a thermal tension, energy is made available.

➢ T Caloric drives engines and can be pumped

When caloric falls from a hot to a cold place, it makes energy available that is used to drive or power another process. This is the basic principle of heat engines. We get an ideal heat engine if all the energy made available is used for driving the desired process (typically mechanical or electric).



Alternatively, if energy has been made available, caloric can be pumped. This happens in heat pumps and refrigerators: caloric is moved from a cold place to a warm place. Heat pumps are used to heat materials, refrigerators are built to create a cold space in a warm environment.

➢ **T** **Temperature and absolute temperatures**

If we want to understand what is said about heat engines (steam engines, gas turbines, combustion engines in cars) or heat pumps, we need to know about how to specify temperatures. Temperatures should always be considered in the *absolute Kelvin scale*. There is a point below which temperatures cannot go: it lies at – 273°C and is given a value of 0 K (zero Kelvin).

The freezing point of water is 273 K, room temperature is roughly 300 K, water boils at roughly 370 K, copper melts at 1360 K, steel at 1780 K, and our Sun's surface temperature is about 6000 K. A typical nuclear power plant runs between temperatures of 600 K in the reactor and 300 K in the environment.

How heat is related to energy depends upon the absolute temperature at which a phenomenon takes place. That is why we need to know the Kelvin scale when considering thermal processes for energy engineering.

Why we cannot use all energy when we burn a fuel

Unlike most energy carriers, but like chemicals, *caloric can be produced*. When we rub hands, when electricity flows through a wire, when water or oil flow through pipes, when tires rub on asphalt, when fuels burn, and when sunlight is absorbed by materials, caloric is produced.

Very importantly, producing caloric always takes energy: a prior process must have made energy available. This is the answer to the question why we cannot use all the energy for driving engines when we burn a fuel. So, let us take a closer look at what it means when we produce caloric.

We have already spoken of a case where caloric is produced—burning of hydrogen. To understand better what this means, consider an electric heater. This is a simple device where electric charge is let flow through wires that get hot and emit heat to a room or to water to be heated.

When electric charge flows through a conduit, it flows from a high electric level to a lower level. Before it can do so, it must have been pumped to a higher level by a generator, solar cells, a battery, or a fuel cell, all of which establish electric tensions. As a consequence of "pumping," electric charge picks up energy. This energy will be made available again when charge flows through a wire, driven by the electric tension along the conduit (see Fig.4).

Processes that produce caloric

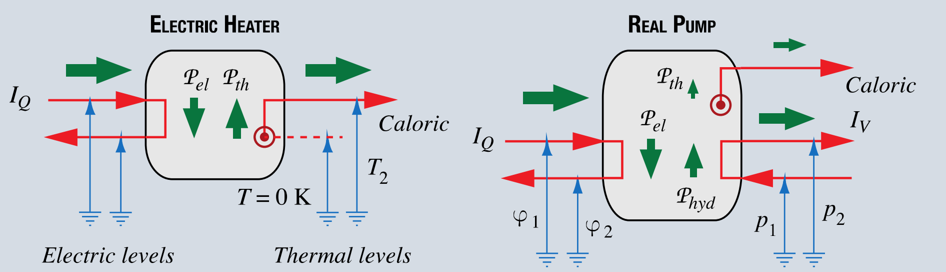
1. Burning fuels.
2. Letting electric charge flow through wires.
3. Rubbing; all mechanical processes where friction occurs.
4. Absorbing sunlight.
5. Fluids flowing through pipes.
6. Mixing materials; mixing fluids at different temperatures.
7. Conducting caloric through materials in heat transfer.

The energy made available can often be used for some very useful purpose such as powering motion. When charge flows through a wire, though, all that happens is that the available energy powers a process of producing caloric.

The caloric produced in the wire makes the wire hot which leads to the caloric to be emitted to the environment. On its way, it takes the energy used for producing it along to the environment. This means that if we produce caloric, the caloric must always end up in the environment, at least in the end, and then it takes a certain amount of energy with it. This amount of energy is said to be *lost*.

T Producing caloric

Caloric can be produced if energy has been made available. Often, this happens as an unwanted by-product of desired processes (as in a real pump).



So, what happens when we burn a fuel? Basically, from the viewpoint of caloric, it is all the same as when electricity flows through a wire. The energy made available by the reaction is used almost exclusively for producing caloric (some will be used to expand the air in the flame). If so desired, and designed, the caloric can drive motion in a heat engine.

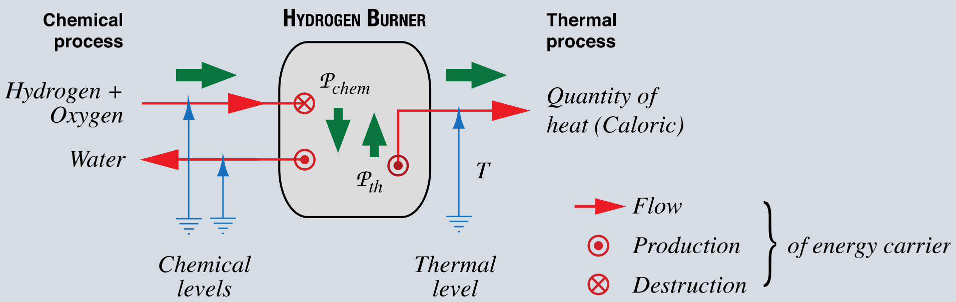
Again, even if we make use of the caloric that was produced for heating of a room, in the end the caloric must flow into the environment, taking with it its energy that will be lost to further use. Remember, we had to pay for the production of caloric with energy that might have been used more wisely.

The meaning of loss becomes even clearer if we consider the case where we burn a fuel in order to drive a heat engine. We produce caloric at a more or less high temperature. The caloric is then used to power motion or electricity. This means that the caloric coming from the burner at this more or less high temperature falls through the engine to a lower temperature which we can assume to be the temperature of the environment. The caloric is then emitted to the environment at this lower temperature.

The caloric coming from the burner brings some energy with it. When it falls to the lower temperature, some of the energy is made available for driving the engine. The energy made available is then used by the desired process powered by the engine.

➢ T Burning hydrogen to produce water and caloric (quantity of heat)

The reaction of hydrogen with oxygen that produces water can happen through burning. If this is the case, heat is produced with the help of the energy made available by the reaction.



When hydrogen gas reacts with oxygen gas, the two gases disappear. In their place, water appears. Moreover, *quantity of heat* (called *caloric*) appears—it is produced just like water is produced. It then leaves the burner together with energy.

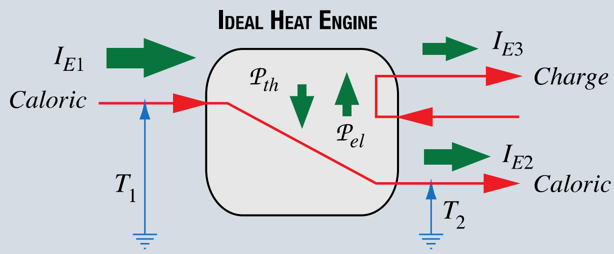
What we are interested in is why this is only “some” of the energy that came from the burner in the first place. Remember that the caloric needs to leave the engine and flow into the environment through the cooler. Since the temperature of the environment is not absolute zero—actually, it is about 300 standard units (300 Kelvin) of temperature above absolute zero—caloric flowing into the environment takes energy with which is then lost for further use. Caloric flowing at a certain level—at a certain temperature—always takes energy with it; the higher the temperature, the more energy is carried.

So, an answer to why we cannot use all the energy coming from burning fuel has to do with the fact that there is an absolute lowest level for temperature—called absolute zero temperature—and our environment is well above this level. This means that whenever we, or our engines, produce a certain amount of caloric, it will take a certain amount of energy with it into the environment after everything is done.

This loss has nothing to do with the engine not being ideal. Indeed, we have assumed in the description that the engine itself works ideally: the energy made available by the fall of caloric in the engine is all used by the process that is powered by the engine.

➢ T Power and energy flows for an ideal heat engine

Caloric from a burner enters a heat engine at high temperature T_1, falls to T_2, and then leaves the engine. In the fall, it makes energy available at a rate $\mathcal{P}_{th}$.



The energy made available is all used, so we have $\mathcal{P}_{el} = \mathcal{P}_{th}$. However, since the caloric leaving the engine takes energy with it, the energy carried away by the carrier driven by caloric is only the difference of energy carried into and out of the engine by caloric: $I_{E3} = I_{E1} - I_{E2}$.

The situation is not unlike what we have with a hydroelectric powerplant in the mountains (Fig.9). Imagine water coming to the turbines from the mountains at 1500 m above sea level. The power station is at 750 m above sea level. Therefore, the energy made available by the water falling from 1500 m to 750 m is proportional to the difference of heights, i.e., to 750 m.

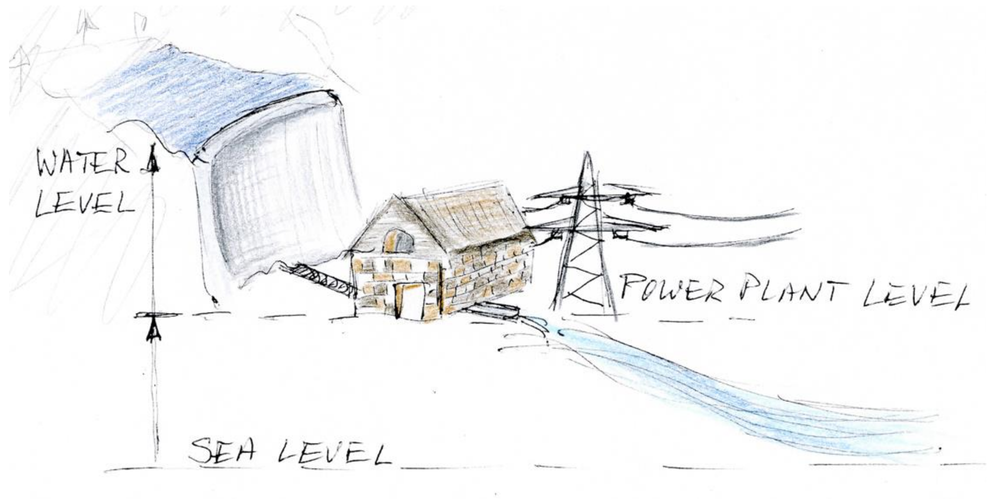


Figure 9: If we count heights in mountains and valleys with respect to sea level, only a part of the energy that can be made available by water flowing down the mountains all the way to the sea is made available at a power station in a valley halfway to the sea.

The water leaving the powerplant will eventually end up in the sea. Theoretically, at least, we could make use of the fall of water from 750 m to sea level which would make again as much energy available as before. If we cannot make use of these circumstances, fifty percent of the energy of the water is lost. Again, this loss has nothing to do with whether or not the powerplant is ideal. After all, the plant makes use of one hundred percent of the energy made available in the fall of water from the mountains to the valley.

Finally, we can describe the difference between using hydrogen in an ideal fuel cell and burning it and then using it in an ideal heat engine. To make it simple, assume that the ideal heat engine drives an ideal electric generator, so the output is electricity just like in the case of the ideal fuel cell.

Take an amount of hydrogen that makes one unit of energy available when reacting with water—it does not matter if this happens in a fuel cell or by direct burning. One unit of energy is made available in both cases.

Now, if the hydrogen is used in an ideal fuel cell, one hundred percent of the energy made available will be used for pumping electricity—so, the quantity of electricity flowing carries with it one hundred percent of the energy of the fuel.

However, if we first burn the quantity of hydrogen that gives us one unit of energy, and if the burning takes place at twice the absolute temperature of the environment (about 600 Kelvin), only half of the energy will be made available; the other half will end up in the environment along with the caloric produced. In other words, the electricity powered by the ideal heat engine plus ideal generator receives only fifty percent of the energy made available by hydrogen.

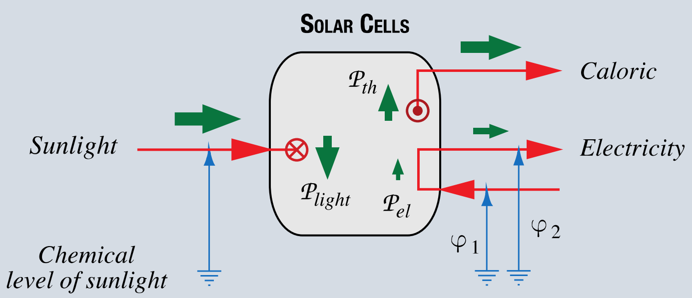
A Fuel-Cell-Hydrogen system

Let us now discuss a possible FCH system, such as the one sketched in Fig.1, in some detail. We know about energy carriers, levels (intensities) and tensions, and energy made available, used, and transported by the carriers. For our discussion, the important carriers are light, water, electricity, heat, hydrogen, and motion.

A solar-electric powerplant. A regenerative energy system for FCH-Technology typically starts with our Sun. If we desire electricity for producing hydrogen, a direct avenue is photovoltaics—solar cells exposed to sunlight, establishing an electric tension that powers the following processes.

➢ **T** **Solar cells**

Sunlight carries energy that is made available for powering an electric process and the production of caloric in solar cells (PV cells).



The mechanism of solar cells involving light, electricity, and heat as carriers and agents works as follows. Sunlight carries a lot of energy that is made available when the light falls upon, and is absorbed by, solar cells (photovoltaic cells or PV cells). The light actually disappears like a chemical in reaction, but it leaves its energy behind. The energy made available is used to separate positive and negative electricity in the cells and so set up an electric tension. If allowed, charge will flow through a circuit such as one that connects an electrolytic cell—where hydrogen is produced from water—to our PV powerplant.

This story has left out an important aspect: solar cells are not ideal devices. They only use a part of the energy made available by the light that was absorbed by them. The fraction used for powering electricity is around twenty percent. The rest of the available energy powers a process we would rather not have but cannot keep from happening: production of caloric. Usually, the caloric is let directly into the environment where it also dumps the energy it takes away with it.

Hydrogen from water. Now that we have a solar-electric powerplant, we can consider the next step on the way of powering some useful process in our homes, in industry, or in transportation. We need hydrogen which can be produced from water.

In order to get hydrogen from water, we need to run the spontaneous reaction that creates water from hydrogen and oxygen in the opposite direction—for this we need energy made available by electricity. The process that does this is called *electrolysis*.

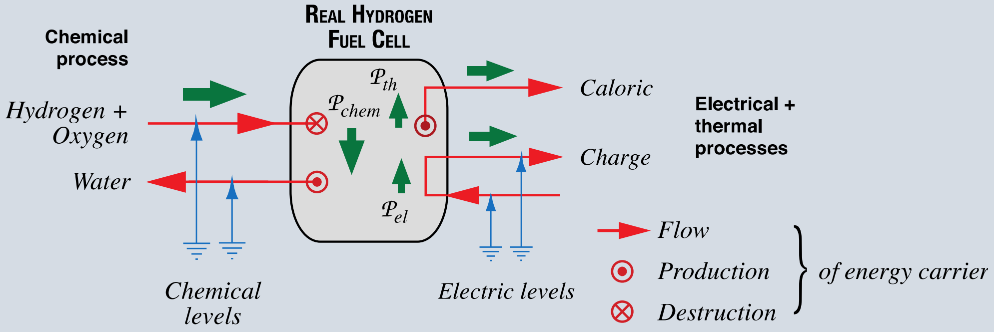
Electrolysis can be demonstrated quite easily in the kitchen. We need a battery, wires, two pencil lead electrodes (simply two leads from pencils), wires, a glass of water, salt, and some means of fastening wires and lead electrodes. If we place the electrodes in lightly salted water and connect them to the two terminals of the battery, we will soon see bubbles rising from both electrodes (Fig.10). It turns out that one of the gases appearing is hydrogen, the other one is oxygen. We can collect the hydrogen and store it for later use. Naturally, for real-life applications we need a large-scale electrolysis plant where this is done professionally and there are means of transporting hydrogen to customers.

Figure 10: Hydrogen can be produced in the kitchen with the help of a battery, two leads from pencils for electrodes, and some salt water.

Hydrogen in fuel cells—electricity from water. At the place where energy is needed, be it for heating, transportation, or other means, we can make use of the power of hydrogen. We now know that burning the fuel is not the way to go, not even if we want heat for heating.

➢ T Real hydrogen fuel cells

A real (hydrogen) fuel cell is fed with hydrogen and oxygen. Their reaction drives an electric and a thermal process in parallel.



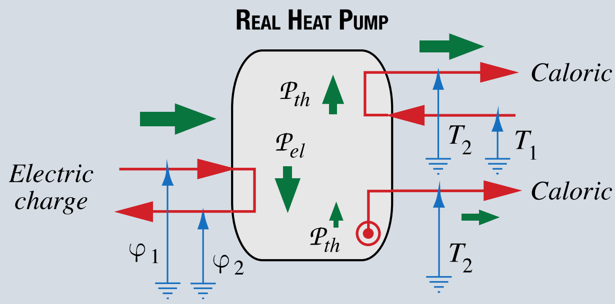
In a real fuel cell, like in all real processes, caloric is produced even if we do not necessarily want this to happen. If we introduce hydrogen and oxygen to the cell, the substances react and make energy available. In a real fuel cell, the available energy is split and powers two processes in parallel: electric charge is pumped and caloric is produced. In a home, we could make use of both electricity and heat to power typical devices such as lighting and heating.

Electrically powering a heat pump for heating a home. Assume that, in a home, all we want at a certain time is heating. From everything we have discussed so far, it has become clear that we should not burn hydrogen—we should use it in a fuel cell and let the electricity drive a heat pump.

A real heat pump works like a real water pump. Electricity makes energy available. Part of it will be used to take caloric from a colder place outside the home to be heated, typically from the air outside or from the ground, and pumps it to the desired temperature which might be the temperature of the water used for heating the rooms.

Depending upon the quality of the heat pump and the outside temperature, we might pump three to five times as much caloric than we would get by generating it electrically. If we add to this the caloric produced by the fuel cell, we might get two to three times as much caloric than if we had just burned the hydrogen in a furnace.

> **T Heat pumps**
>
> A real heat pump uses an electric process to pump caloric from a cold to a warm place. At the same time, caloric is produced. In this manner we get several times as much caloric than if we had produced it electrically or by burning a fuel.



Why FCH? Why not use the Sun directly?

The FCH system described here in some detail is quite interesting and, fundamentally, it works. But is it the best way to go? The first part of the chain of processes depicted in Fig.1—solar photovoltaics to hydrogen—is not very efficient. If PV were about 15 percent efficient, and electrolysis of water a little more than 60 percent, the overall efficiency of this part would be about 10 percent. If we add the second step and use the hydrogen for electrical purposes, we might get an efficiency of only 5 percent, sun to electric outlet in a home.

If we were to use PV directly for electrical purposes at home, we should achieve an efficiency of 10 to 20 percent—much better than the FCH-electrical system. And for heating, it looks even worse. If we want hot water for the household, the efficiency of a thermal hot water solar system will easily top 40 percent!

The point is that efficiency is not all. We need to be able to provide energy for doing what we need to do at the right rate, which might mean high power, and at the right time such as at night or in Winter in countries that are too far from the equator. Fuels are still unsurpassed for delivering energy at high rate and at times when the Sun does not shine strongly enough.

So, in Summer in a country that can be pretty cold in Winter, we do not need solar-PV-hydrogen-fuel-cell technology in order to get hot water for a household, and we do not need it for getting electricity. However, if we think of other applications such as transportation, and of other times where heating requirements are high and the Sun is shy, FCH-technology might just be one of the better solutions available to us in the future.