SOLAR POWER TO THE PEOPLE

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"Singing power to the people
Power to the people
Power to the people
Power to the people, right on ..."

John Lennon, 1971

John Lennon wrote his 'Power to the People' protest song just before the Club of Rome published its *Limits to Growth* in 1972, before the first energy crisis of 1973, and long before the Brundtland Commission issued its report, *Our Common Future*, in 1987. The Club of Rome focused attention on the limits of the use of our finite raw materials. The energy crises made it clear that fossil fuel resources were concentrated in a small number of countries. And *Our Common Future* introduced the concept of 'sustainability' for the first time.

Naturally, John Lennon used the word 'power' to refer to political power, not to energy. But he did call for change, change that would bring power to the people. Today, we also want change: from a fossil to a sustainable energy supply. We have to bring the energy of the sun to the people. Power to the People takes on a new meaning: *Solar Power to the People*, energy from the sun to the people!

SUMMARY

We are carrying out a unique energy system in Nieuwegein-Utrecht. Nine hundred homes, equipped with solar cells and rainwater harvesting systems, and a solar farm of 8.6 megawatt peak (MWp) and rain harvesting, will together produce 10 million kilowatt hours (kWh) of electricity and 60,000 cubic meters of rainwater every year. This will allow us to meet all of the energy needs of these homes – for heating and electricity as well as transport. We will also meet the needs for demiwater, which is ultra-pure water, for the production of hydrogen. The demiwater will moreover be used in dishwashers and washing machines in the homes, with the added benefit of decreasing detergent use.

Thanks to subsurface storage, the system can satisfy the demand for heat and demiwater at any time of the year. This is how we will bring Solar Power to the People!

Solar Power to the People, bringing the energy of the sun to the people: that is what a sustainable energy and water system is all about. In one hour the sun gives us more energy than the world consumes in one year. There is enough sustainable energy, the issue is how to make use of this energy in the right form, at the right place and at the right moment.
But the sun's energy not only provides us with heat and light, it also gives us wind, rain and biomass. Thanks to solar cells and wind turbines, we can easily produce all the energy we need in the form of electricity. While the rainfall amply satisfies our water needs. And a very little bit of biomass can provide us with the carbon we need to make chemical products.

Worldwide, in 2020 we will be able to produce electricity at a cost of 2 to 3 US cents per kWh through solar cells placed in the deserts; by about 2040, we expect this cost to drop to less than 1 US cent per kWh. By this same year, it should also be possible to have floating wind turbines in the ocean produce electricity at a cost of 1 US cent per kWh. We will transport this electricity to people in the form of hydrogen. By means of electrolysis, the electricity and water are converted into hydrogen and oxygen. We can then transport this hydrogen – compressed, liquified or converted into ammonia – anywhere in the world, and store and use it whenever we want. From hydrogen (electricity), carbon (biomass), oxygen (electricity) and nitrogen (air), we can make all of our chemical products in bulk. Moreover, with hydrogen and electricity we can also make all of our metals.

In cities, villages or in the countryside, where we live and work, we will produce mainly electricity with solar cells. But in countries like the Netherlands we will produce too much in the summer and too little in the winter. We can convert the surplus summer electricity into hydrogen or heat.

We will harvest rainwater from the solar panels and buffer it underground. We can then subject this water to reverse osmosis to make the demiwater required to produce hydrogen, and then remineralise it to provide us with drinking water. The hydrogen can be transported and stored in a hydrogen network, the adapted natural gas network. We can use a heat pump to produce heat in the summer, store it underground and then use it in the winter for heating. On summer nights, electric car batteries can supply electricity, while in the winter the electricity we need will come from hydrogen fuel cells.

In the Nieuwegein-Utrecht project we will provide, for the first time, solar energy and rain for the production of electricity, heat, hydrogen and demiwater to people in a new housing development. We will bring *Solar Power to the People*: wherever, whenever and in whatever form they like!

1 SOLAR POWER TO THE PEOPLE

1.1 The sun as an endless source of energy

The earth's energy budget

If you go for a walk outside on a nice summer's day and feel the sun's burning heat, you get an immediate sense of the amount of energy that the sun radiates to the earth. Even at a distance of 150 million kilometres, our star radiates enough energy to make all of life here on earth possible. The incoming solar radiation that reaches the earth is 340 watts per square meter (W/m^2) [1], [2], which amounts to a total of 173,800 terawatts (TW) (= $173{,}800*10^{15}$ watts). This means that the sun, after shining for one hour, has already sent 625 exajoules (EJ, $625*10^{18}$J) of energy to the earth. This is more than the total global energy requirements of 556 EJ in 2016 [3].

In one hour the earth receives more solar energy than we use in one year worldwide.

The sun thus delivers an enormous amount of energy to the earth. But what happens with all this energy? Part of the incoming sunlight is reflected (100 W/m^2), part of it is absorbed by the atmosphere (77 W/m^2), but another larger part actually reaches the earth's surface (163 W/m^2) [1], [2]. This energy drives other processes on earth, such as the blowing of wind and the evaporation of water. Wind energy and hydroelectricity are thus indirectly also forms of solar energy. Sunlight is also the driving force behind photosynthesis. It is therefore responsible for the production of biomass, which is the source of the all-so-vital oxygen.

Are all forms of energy then actually solar energy? No, not all of them: there are two other sources of energy that are renewable. The first is tidal power, which is produced by the attractive (gravitational) force of the earth, the moon and also a little bit of the sun. Total tidal power is estimated to be 115 EJ per year [4]. That is certainly a lot, but it is still equivalent to less than 15 minutes of solar radiation.

Geothermal energy is the second energy source that is not influenced by the sun. Geothermal energy is heat released in the earth's subsurface which orginates in the slow decay of radioactive elements in the earth's core. Total geothermal energy is estimated to be around 1,000 EJ, less than 100 minutes of solar radiation [5].

There are therefore energy sources that aren't directly or indirectly related to the sun, but their potential is considerably lower than that of solar energy. We can conclude in any event that there is no question of a shortage of energy: there is more than enough. The challenge lies primarily in the conversion of this energy into energy carriers that we can use. But in view of today's developments in wind and solar technology, this can hardly be considered a problem. Actually, the real issue is the distribution of this energy in terms of time and place. How do we get the required energy to our homes at the right time?

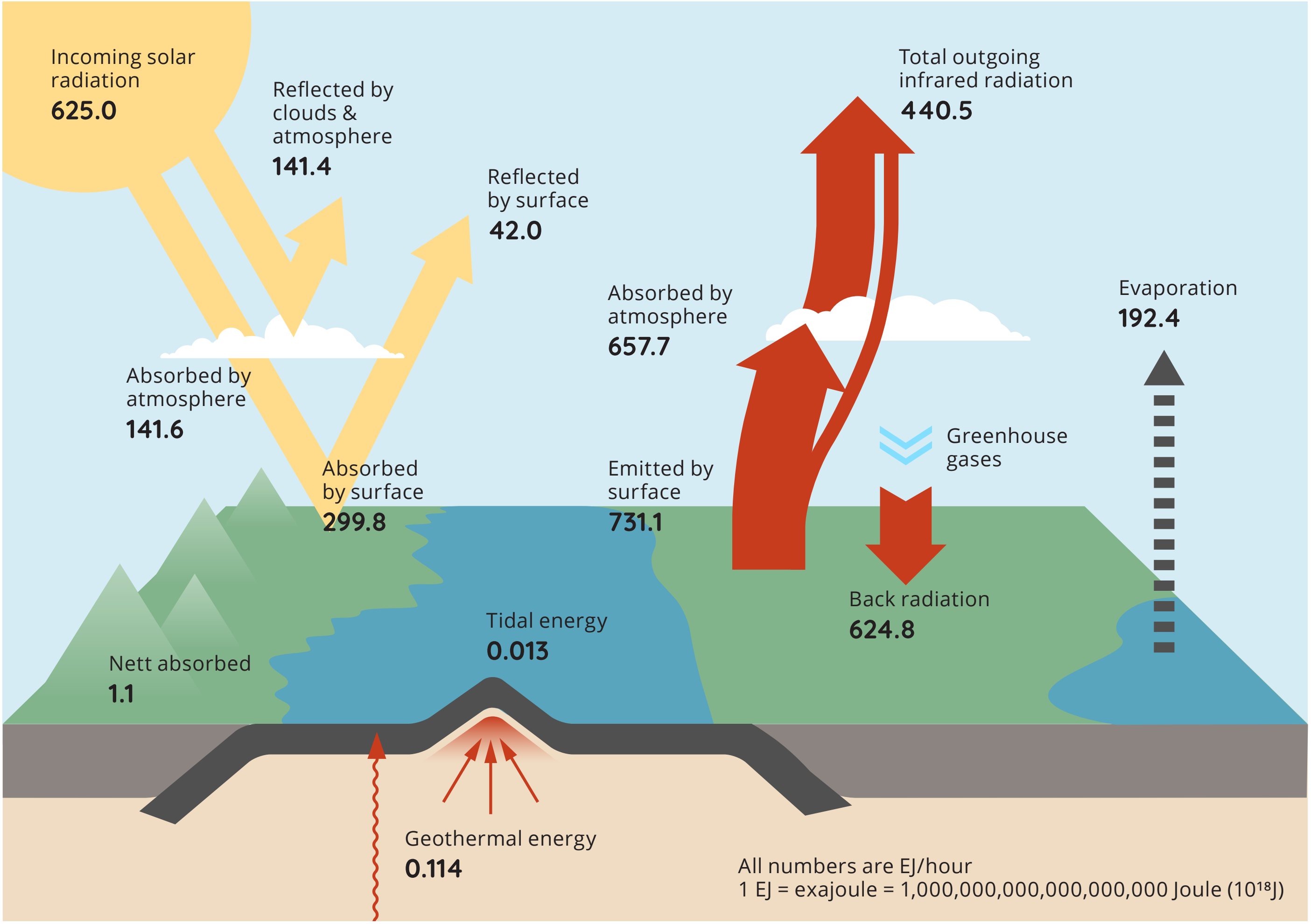
Solar radiation worldwide

We have already established that there is no shortage of energy, and that the sun in particular provides us with more energy than we use on our planet. But what does this mean exactly? Let's look at the extent of the surface we need to cover with solar panels to satisfy global energy needs. Solar panels do not produce the same amount of energy everywhere. In the Netherlands a solar panel can count on about 1,000 kWh per square meter of solar radiation per year [6], while in the Sahara Desert this can exceed 2,500 kWh/m^2/year. Global energy consumption in 2016 was 556 EJ, which converts to about 155*10^{12} kilowatt hours (kWh) or 155,000 terawatt hours (TWh).

The conversion efficiency of solar panels in 2017 is around 20% [7], which means that 20% of the incoming solar radiation is converted into electricity. There must also be some room between the panels, so that no shade falls on any of the neighbouring ones. When it comes to deserts we don't need to take shadow effects into account, since there are not too many trees around. We therefore assume an utilisation of 60% [8]. This means that, with a solar radiation of 2,500 kWh per square meter per year, a conversion efficiency of 20% and an utilisation factor of 60%, 300 kWh of electricity can be generated per square meter per year. In total, in order to meet global energy needs, 520,000 square kilometres (km^2) would be required, a surface equivalent to 720 by 720 kilometres, that is, a bit more than 5% of the Sahara's total surface.

If we cover an area the size of Spain with solar panels, we could generate the equivalent of our annual global energy consumption.

The Great Victoria Desert in Australia, with a surface of 650,000 km^2, is the biggest in the country. This desert is large enough on its own to produce all of the energy the world needs. Australia is today one of the biggest coal producers and exporters. But the country could

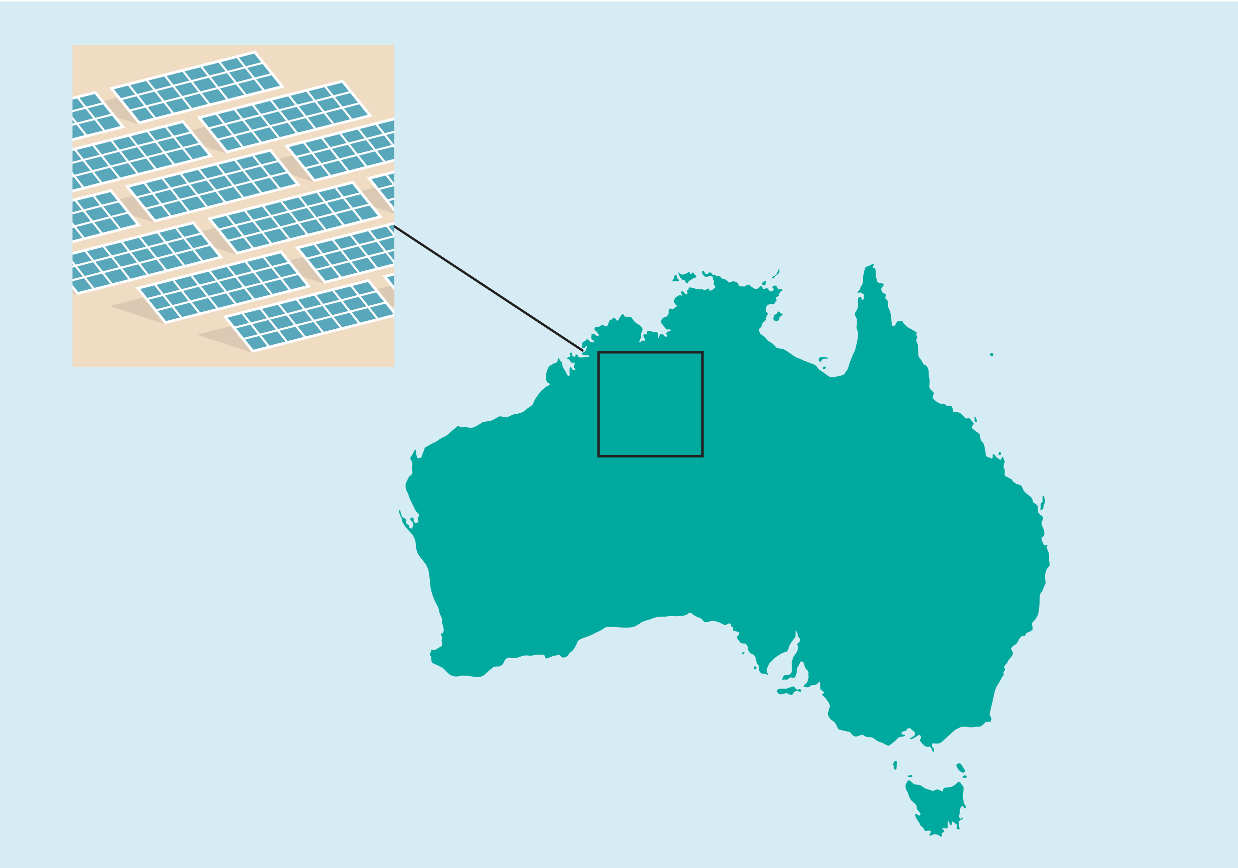


Earth's energy balance [2], [4], [5].

also quite easily export the same amount of energy in the form of solar power.

Another desert area with high solar radiation is the Arabian Desert: 2.3 million km² extended over countries including Saudi Arabia, Oman, Yemen and the United Arab Emirates. Today the area is rich in oil and gas resources, but in the future it should easily be able to export the same amount of energy in the form of solar power as it does today in oil and gas. And the supply of solar energy is inexhaustible.

And such high-radiation desert areas can be found on all continents: in the United States and Mexico, in China and Mongolia, in Syria and Iraq, and elsewhere.



Surface required to meet global energy production needs through the sun.

Wind energy worldwide

We've already mentioned that wind energy comes indirectly from the sun. But the sun does not heat up the earth's atmosphere uniformly. Certain areas receive higher levels of solar radiation than others, leading to relatively higher rates of water evaporation and air warming. The warm air rises because it is less dense than cold air. This creates a pressure difference with colder air in adjacent areas, so that the warm air flows to the colder areas. When this air then becomes colder, it descends again. This creates a high-pressure area and we get wind on the earth's surface. Wind is therefore simply air that flows from a high-pressure area to a low-pressure one.

> *Offshore wind turbines, occupying 1.5% of the surface of the Pacific Ocean, could generate the equivalent of our annual global energy consumption.*

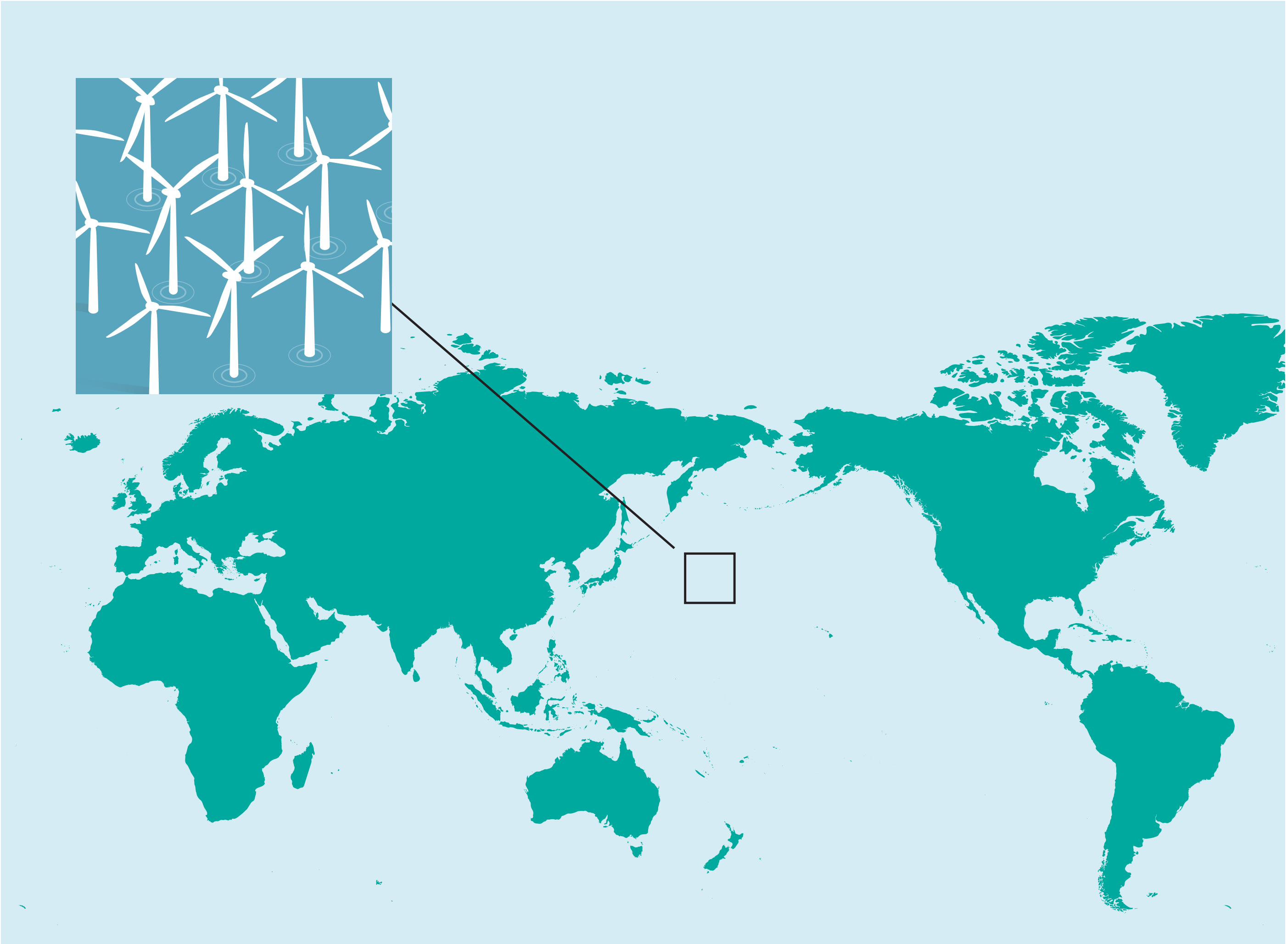
One of the consequences of this mechanism are the so-called trade winds, which occur in the area between the equator and the tropics. These winds blow in a very consistent direction: north-easterly in the northern hemisphere, and south-easterly in the southern hemisphere. For a large part of the year these winds blow very strongly, while for a few months of the year there's hardly any wind at all.

Wind can also have other origins. Ocean breezes can occur where sea and land interface. On hot days the land warms up, as does the air above it. This air warms up considerably faster than the air above the water does; the result is the creation of pressure differences. The warm air over the land rises and flows in the direction of the sea, where it cools down and then descends. This increases the air pressure above the sea and eventually cool ocean breezes blow onto the land from the sea. This ocean breeze phenomenon is significant in California, for instance, where the cold California ocean current means that the seawater is cold, as is the air above it. The resulting strong ocean breezes fortunately coincide with the airconditioning needs to deal with the large amounts of warm air flowing from the neighbouring desert areas in Utah and Arizona.

Constant high wind speeds are common over the oceans, where wind speeds of 15 meters per second are not unusual. This is because the sea surface is not 'rough' and the wind near the water's surface encounters little resistance. Wind speeds on land are lower because the vegetation and buildings present the wind with much greater resistance. Average wind speeds of 10 meters per second at a height of 80 meters occur in the northern hemisphere in the Pacific Ocean at the latitude of Japan, and in the Atlantic Ocean at that of the United Kingdom. But it is particularly in the southern hemisphere below South Africa and Australia, and at the level of Patagonia in Argentina, where one finds vast areas with very high wind speeds.

Let's then calculate how much ocean surface we would need to provide the total global energy consumption requirement of 556 EJ, or 155,000 TWh. We are capable of installing large floating wind turbines on the ocean, which can produce 10 MW each, or even more. The blades of these wind turbines measure about 100 meters. If you install them on an ocean where the average wind speed at axle height is 10 meters per second or more, the wind turbines will almost always be operating at full capacity. Their operational time is between 60 to 70%. In other words, they can achieve about 6,000 full-load hours. A 10 MW wind turbine can therefore produce 60 million kWh per year. The wind turbines have to be positioned at a sufficient distance from each other to avoid the wind 'shadow' effect which reduces their output. Let's assume that we install one 10 MW wind turbine per square kilometre. So, to satisfy our global energy consumption we would need 2.6 million 10 MW wind turbines. They would occupy an area of 2.6 million square kilometres, with only one wind turbine per square kilometre. In net terms, therefore, wind turbines take up a lot less space, aquatic life is undisturbed, and ships can sail between them. To put this in perspective: we need about 1.5% of the surface of the Pacific Ocean to produce all the energy the world needs.

Large-scale sustainable electricity production is cheapest in areas, oceans and deserts that are located very far from where people live and work.



Surface required to meet global energy production needs through the wind.

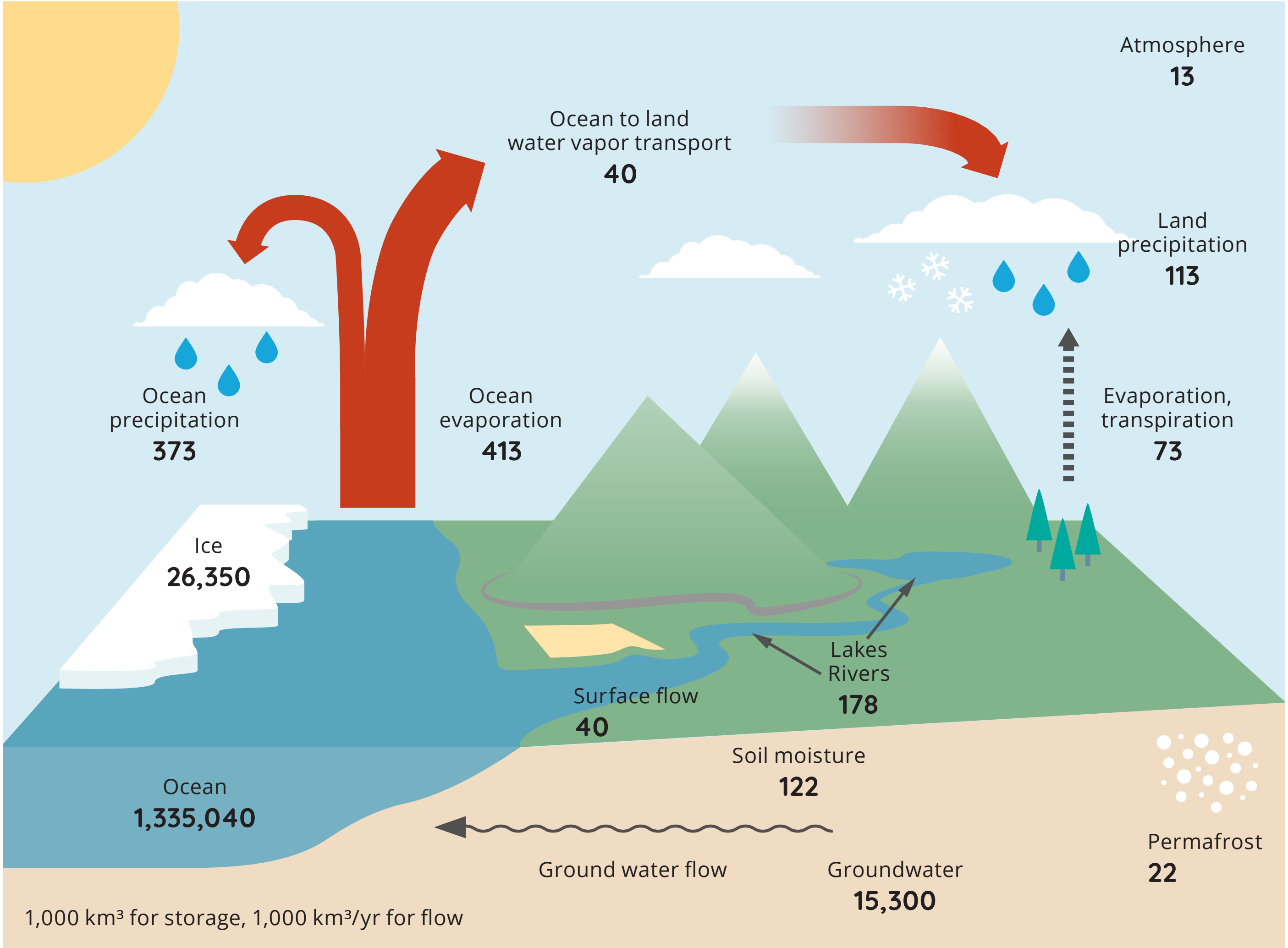
The hydrological cycle

A portion of the sun's energy (86.4 W/m^2) is responsible for evaporation of water. Every year a total of 413,000 cubic kilometres (km^3) of seawater, and 73,000 km^3 of surface water and transpiration from plants, are converted into water vapour [9]. The clouds formed by this vapour don't often remain at the same location. Eventually, 373,000 km^3 of this condensed water falls back into the sea as precipitation [9]. But a portion of the clouds created above the ocean rain onto land; so the volume of the rainfall above land exceeds that of the water that evaporates from the land. Depending on where the water falls, it can also be a source of energy in the form of hydroelectricity.

The volume of rain that falls on land in two weeks exceeds the volume of freshwater we consume globally in one year.

Apart from being a source of energy, the hydrological cycle is also important for our freshwater supply. Total global freshwater production is estimated to be 150,000 km^3 per year, three quarters in the form of precipitation, and the remainder in the form of river water and groundwater [10]. In 2010 the world consumed 4,000 km^3 of this water. The rain that falls on land over a period of two weeks therefore exceeds the world's freshwater needs for a year. At first glance then, it would seem that there is more than enough freshwater. But the precipitation is unevenly distributed. Some areas have high levels of precipitation, such as the tropical rain forests in central Africa and Indonesia. North-west Europe and the eastern United States also generally get sufficient precipitation – between 725 and 5,000 millimetres per year. In contrast, northern Africa, the Middle East and southern Australia get less than 250 millimetres per year. What is true for energy is thus also true for water: the problem concerns not so much the volume, but the distribution in time and place.

There is no energy crisis or shortage of water, it's mostly a matter of the distribution of energy and water in time and place.



The hydrological cycle [9].

1.2 Our energy and water consumption

Humans can't live without energy and water. Over the course of history we have consumed more and more energy and water. But how much exactly, and what do we use all this energy and water for?

What do we use energy for?

Energy is used in a wide variety of ways in our modern life. We use energy to live and work in comfort in our homes and offices. We use it to move about in our cars, boats and planes. We use it in industry, to make products, but also as a feedstock for products like plastics and artificial fertilisers. And we use energy for power and light, in the form of the electricity that powers a wide range of devices we work with as well as our lighting.

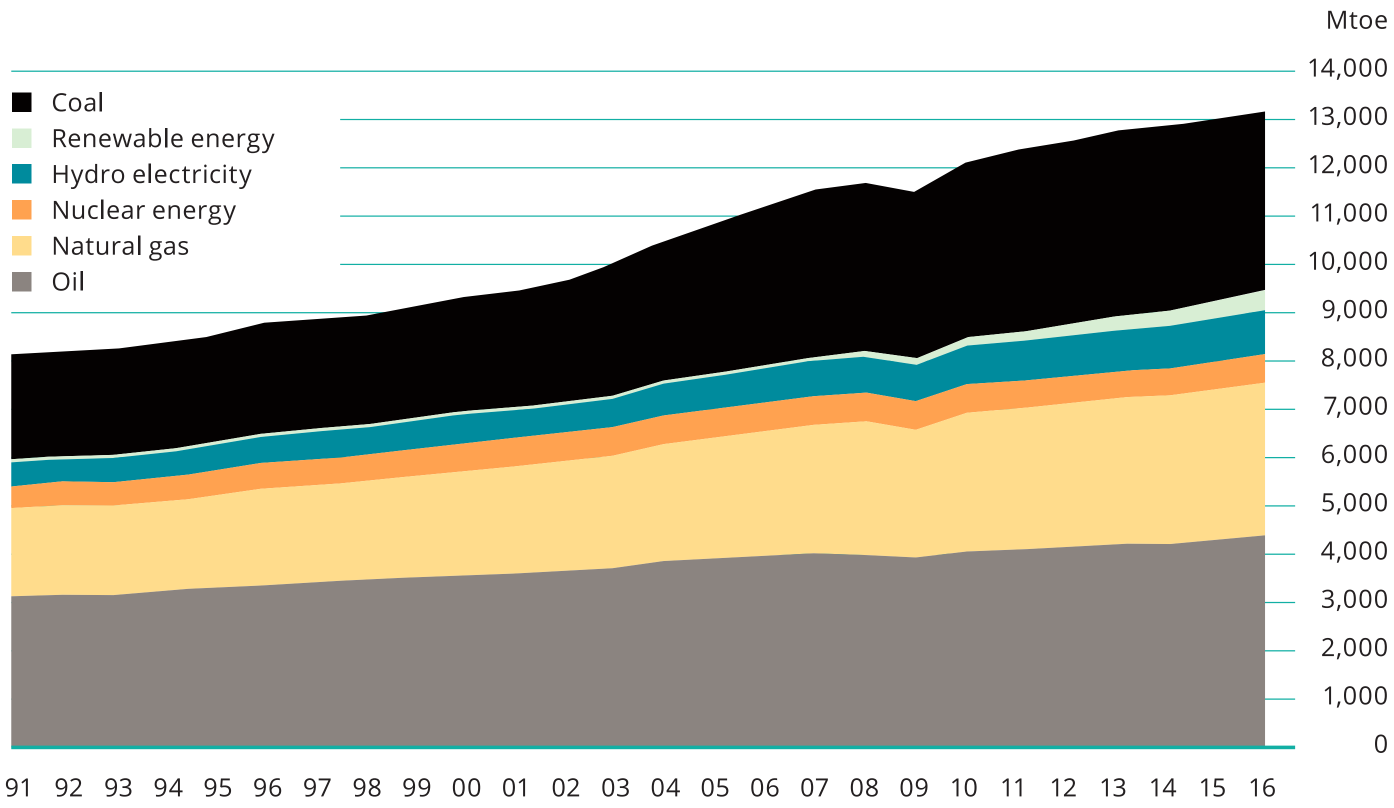
In a fossil energy system, the first step is to extract the energy, in the form of oil, gas and coal, from the ground. We then have to transport it by ship or pipeline, and convert it into a usable energy carrier such as electricity or petrol, before being able to use it for driving or lighting. In other words, we need energy to produce the usable energy carriers themselves. We therefore use two measures when determining energy consumption: the amount of energy we extract from the ground we call the primary energy consumption; while the amount of energy we pump into our car, or that reaches our house in the form of electricity, we call the final energy consumption. The difference between primary and final energy consumption is particularly large in the case of electricity, mainly because of the conversion efficiencies of electric power stations.

Primary energy consumption worldwide

Primary energy consumption worldwide in 2016 totalled 13,276 Mtoe (megatonnes of oil equivalent) according to the *BP Statistical Review* [3]. If we convert this to a common energy measure, namely the joule (1 Mtoe = 41,868*10^{15} J), then global primary energy consumption amounts to 556 EJ = 556*10^{18} joules. In kilowatt hours (1 kWh = 3.6 MJ), this is 155,000 billion kWh, or 155,000 TWh.

In 2016 556 EJ of energy was consumed worldwide, ten percent of which from renewable energy sources.

The BP Statistical Review [3] figures only reflect commercially traded energy. A great deal of biomass, for example wood and fertiliser, which is used for cooking and heating in developing countries, is not included in these statistics.



Primary energy consumption worldwide by source from 1991-2016 [3].

Solar Power to the People	Primary energy consumption worldwide - 2016		Source: [3]
Source	**Primary energy consumption Mtoe**	**Primary energy consumption EJ**	**Primary energy consumption %**
Oil	4,418	185	33.3
Gas	3,204	134	24.1
Coal	3,732	156	28.1
Nuclear	592	25	4.5
Hydroelectricity	910	38	6.8
Renewables	42	18	3.2
Total	13,276	556	100

Electricity consumption worldwide

Electricity consumption worldwide in 2014 was 24,816 TWh [11]. Of this, 23.7% came from sustainable sources, 10.5% was nuclear and the rest (65.8%) was from fossil energy. Coal provided a large part of this fossil energy [11] – in fact, with regard to fossil-based electricity production, coal still accounts for the largest share by far. With regard to sustainable energy, hydroelectricity accounts for the largest share.

In the 2005-2015 period, electricity consumption grew by 2.8% annually, while primary energy consumption in the same period increased by 1.8% annually. In other words, electricity consumption has grown more rapidly than primary energy consumption, which is an indication that electricity is playing an increasingly significant role in our total energy supply.

In 2014 total electricity consumption worldwide was 25,000 TWh, almost a quarter of which produced from sustainable sources.

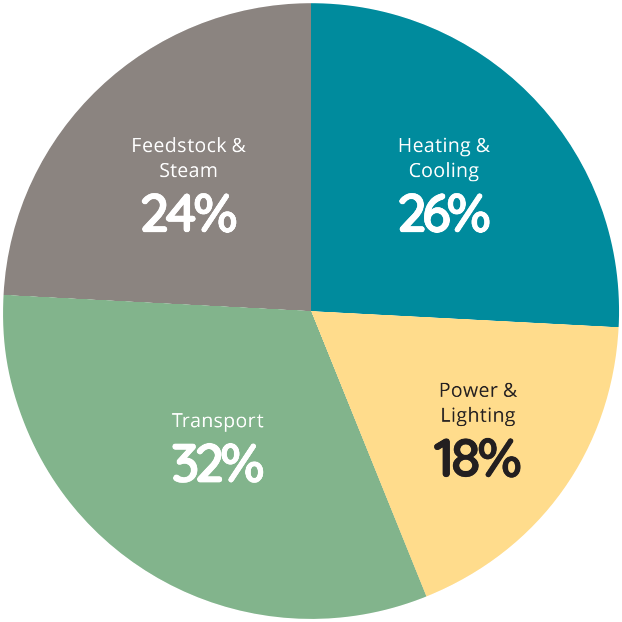
Solar Power to the People **Electricity consumption worldwide - 2014** Source: [11]

Source	TWh	%
Fossil	16,322	65.8
Nuclear	2,617	10.5
Hydroelectricity	4,023	16.2
Wind	960	3.9
Geothermal and biofuel	562	2.3
Sun	332	1.3
Total	24,816	100

Final energy consumption worldwide

Final energy consumption measures what we use the energy for. It is the amount of energy that, via the gas and electricity meter, flows into our house, or the fuel we put into our tank. We divide our final energy consumption according to the four functions of energy: heating and cooling, transport, steam and feedstock in industry and, lastly, the power and light for devices and lighting.

Roughly speaking, we can say that these four energy functions each account for a quarter of the final energy consumption. The available data are from 2010 [12], but the relative proportions of the four functions have not changed much since that time. The energy we use for transport comes primarily from oil. In industry, energy is used as a feedstock and for steam production. Coal, oil and gas each provide about one third of the energy consumed in industry globally. Gas accounts for half of the energy used for the heating and cooling of buildings. The use of coal and oil for heating and cooling has dropped over the last decades,



Final energy consumption can be divided into four parts: heating and cooling, transport, steam and feedstock, power and light.

Final energy consumption worldwide [12].

due to environmental and health considerations. Power and light are entirely produced by electricity.

What do we use water for?

Humans have a growing need for energy but, besides energy, water is even more vital. One can get by without electricity for a day or even a week, but a week with no water causes far more problems. Water is hugely important for our wellbeing, and not only in the form of drinking water. Water also plays a key role in hygiene and in the prevention of disease.

In agriculture, water is indispensable. Without irrigation we would never be able to eat green beans from Kenya or rice from Thailand. As our production of energy – of electricity in particular – has grown, the other functions of water, such as cooling and heating, have become more and more important. Water is also used in industrial processes, especially in the form of demiwater in boilers.

There are great differences in water usage, water quality and water availability worldwide. Climate change and globalisation are affecting water supply by increasing the number of areas affected by drought, while in other areas it is the excess of water that presents a growing problem.

Drinking water

Our bodies consist of 64% water, and to remain healthy we need to drink 2.5 to 3 litres of water every day [13]. In 2015, 71% of the world's population had access to a source of safe drinking water. That was the same year that the *Sustainable Development Goals* were formulated: goal number six refers to giving everybody access to safe drinking water by 2030. At the same time, drinking water consumption accounts for only 0.2% (8 cubic kilometres) of the total amount of water consumed in the world in a year.

> *Every person needs 3 litres of clean drinking water daily.*

Hygiene, sanitation and cooking

Besides the water we drink, we also use a lot of water in our homes to prepare our food, flush our toilets, shower and wash our clothes. WHO recommends a minimum amount of 5 to 12 litres of water a day for these purposes [13]. But under normal circumstances this number is a lot higher in most countries: on average, worldwide, we use 180 litres per person per day. This can vary significantly from one country to another. In a country like the United States, household water consumption, besides drinking water, exceeds 500 litres per person per day. In Brazil the figure is less than half of the United States, but still more than average (230 litres). In China and Germany it is a little lower than average (around 150 litres), while in India the amount is about 118 litres per person per day.

> *Every day worldwide we use an average of 180 litres per person per day for hygiene, sanitation and cooking.*

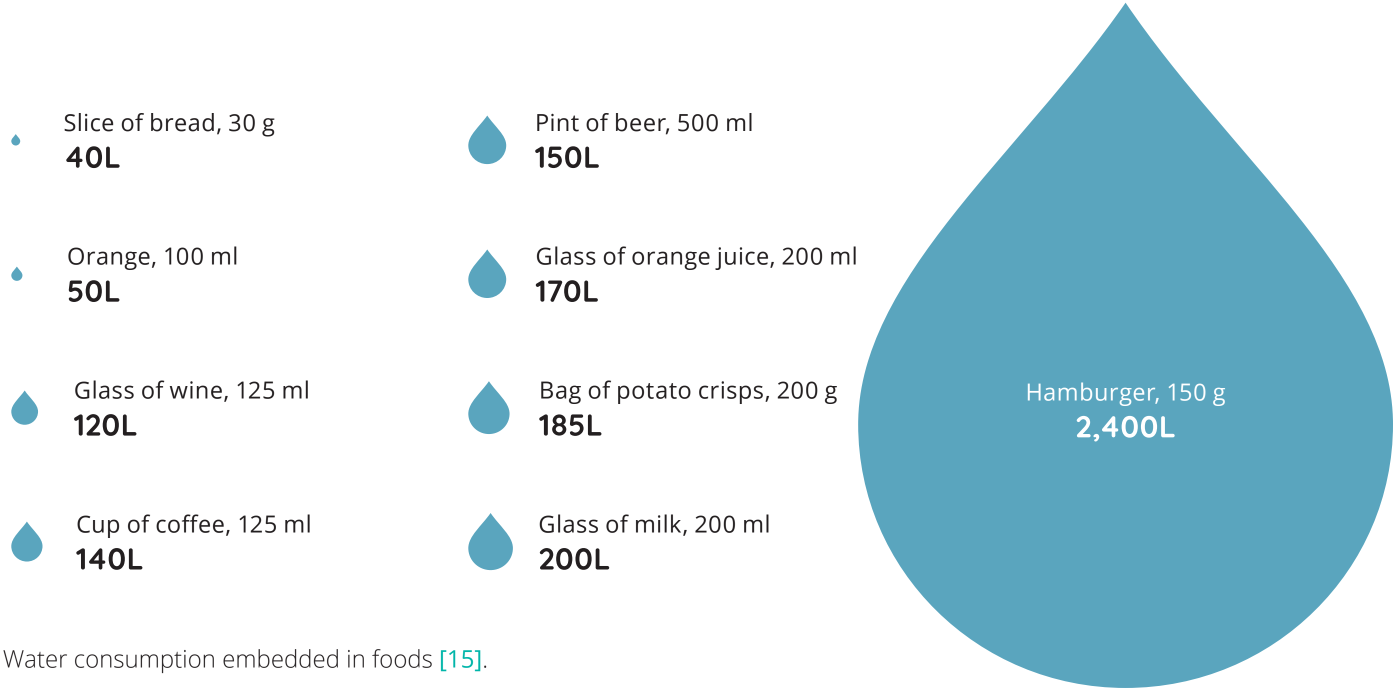
Water consumption for hygiene, sanitation and cooking amounts globally to 456 cubic kilometres, that is, 11.4% of total water consumption [14].

Agriculture and irrigation

Agriculture, and particularly irrigation, accounts for most water consumption in the world, amounting to 2,769 cubic kilometres (km^3) per year, or almost 70% of total water consumption [14]. Besides irrigation, livestock farming and aquaculture (fish, shellfish and mollusc farming) are big water consumers. Water consumption in agriculture is thus a major determinant of world water consumption. In India, 688 km^3 of water is used in agriculture, 90.4% of the country's water consumption. Agriculture is also an important sector in the United States, consuming 175 km^3 per year, which represents 12.7% of the country's total water consumption. This percentage is lower because industry in the United States is also a big water consumer. In China, 64.5% (764 km^3) of water is consumed for agricultural and irrigation purposes. Brazil has a comparable proportion of 60%; the country grows a lot of soya for animal feed, but also sugar cane for the production of bio-ethanol. Germany for its part hardly makes use of irrigation since, thanks to its north-western European climate, rainfall provides most crops with the water required. The Germans only need 0.21 km^3 of irrigation water per year (0.6%). So besides the role played by the agriculture sector in a country, it is also important to keep in mind that the climate and the type of crops are important determinants of water consumption.

Water consumption worldwide for agriculture and irrigation is almost 70% of total water consumption.

We have seen that freshwater usage for the production of our food is huge. This involves not only agricultural usage, but also the water consumed in the cleaning, packaging, transportation, preparation, as well as in the waste of (part of) the food. If all of these are taken into consideration, then making a cup of coffee, for instance, requires 140 litres of water, while a hamburger has 2,400 litres 'embedded' in it [15].



Water consumption embedded in foods [15].

Industrial processes

Industrial processes generally consume a lot of water. This doesn't actually involve consuming water in order to convert it into something else, but instead involves the transport of energy. Machines are cooled down using cooling water, typically in the form of surface water that flows along the machines in a closed system and is then discharged at a higher temperature or converted into steam in cooling towers. Water is also circulated during industrial processes. This usually involves demiwater, which is used in boilers and steam cycles. In this case the water does not carry cold but heat, by producing steam to drive various processes.

In addition, before energy can be produced, water plays an important role in the extraction of the raw materials involved, as in the case of coal mining. The use of water in oil and gas extraction depends on the technology used but, as a rule of thumb, one can say that the less conventional the energy extraction (shale gas, tar sands) the more water is consumed compared to conventional techniques. In 2014, almost 400 km^3 of water was needed for energy production, which is approximately half of industry's total water consumption [16]. At the same time, industrial processes account for 19% (786 km^3) of the world's total water consumption. This means that, overall, about 10% of total worldwide water consumption is involved in energy production. The percentage of water used for industry is much higher in industrialised countries: in Germany it is 85% (32.6 km^3/per year), and in the United States it is 51% (284 km^3/per year). Brazil and China with, respectively, 17% and 23%, are at average levels. In India, as noted above, it is the agricultural sector that accounts for the largest part of water consumption, with industry consuming only 2.2% of the total.

Water consumption for industrial processes is about 800 cubic kilometres per year, half of which for energy production (mining and electricity production).

World water consumption

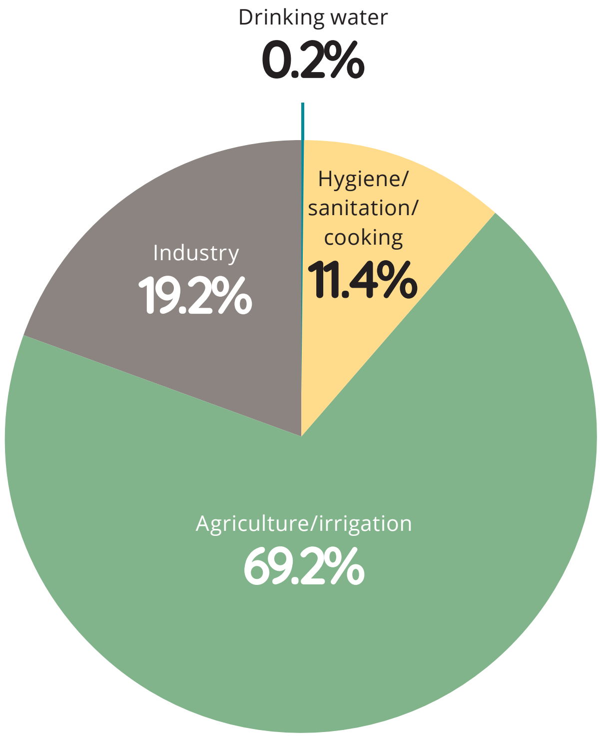
Water is indispensable for life on earth and for humans. We drink water, but we also use it for our hygiene and sanitation, to produce food and to produce energy. It is important to realise that not all of this water needs to be of the same quality. Drinking water of course has to meet high standards, but this water represents only a small fraction of the water consumed in the world. Irrigation and industrial applications for their part can do with water of different quality, though in much larger volumes.

World water consumption in 2010 was 4,000 cubic kilometres, almost 1,600 litres per person, per day.

The world's total water consumption in 2010 was 4,000 km^3. This amounts to a consumption level of almost 1,600 litres per person, of which only 3 litres are for drinking water. Drinking water thus represents a tiny part of total water consumption, that is, 0.2%. By far the greatest share of water, almost 70%, is used in agriculture and irrigation.

Solar Power to the People **Worldwide water consumption** Source: 1[17] 2 [18] 3[19] 4[20] 5[21] 6[14]

km³ per year	US[1]	Brazil[2]	India[3]	China[4]	Germany[5]	World[6]
Drinking water	0.3	0.2	1.4	1.5	0.1	8
Hygiene/sanitation/cooking	61.8	17	54.6	73.5	5.3	456
Agriculture/irrigation	175.1	44.9	688	392.2	0.2	2769
Industry	248.4	12.7	17	140.6	32.6	768
Total	486	75	761	608	38	4001



World water consumption [14].

2 SUSTAINABLE ENERGY SYSTEMS IN THE FUTURE

Before the industrial revolution our energy consumption was limited and also actually entirely sustainable. We had the sun or burned some wood, straw or dried manure for our heat and light. Animals did the heavy work and we used them for our transport. We used water power and wind energy to mill our flour and pump our water.

In the middle of the 18th century the steam engine, fuelled by coal, took over the heavy and transport work from horses. This was much simpler and easier. The first electric power stations were built by the end of the 19th century. Electricity made the supply of light and power even easier. And finally, at the beginning of the 20th century, the internal combustion engine was introduced in transport, and petrol, made from oil, was the ideal mobility fuel.

Our energy system still works on this basis. To heat our buildings, we moved from wood to coal, then to oil and today we frequently also use gas. But we still burn these materials in boilers. The internal combustion engine – fuelled by petrol, diesel or gas – provides our main means of locomotion. Our industry uses large amounts of steam, produced in giant boilers, for process heat. It also uses coal, oil and gas as feedstocks to make metals like iron and steel and products like plastics, nylon or artificial fertilisers. And we have come to use electricity everywhere: for power, heat, steam and light. But electricity is still mostly produced using an old-fashioned steam engine, combined with a generator. Only one new piece of technology has been added: the gas turbine. This is used, together with the steam turbine, for more efficient electricity production, for air transport, and for industrial steam production.

Our energy system has therefore not changed much over the last hundred years. The system is based on fossil energy sources – coal, oil and gas – and energy conversion technologies – steam turbines, gas turbines, internal combustion engines, generators and boilers.

But what will our energy system look like in the future? How are we going to power our energy functions, and what will we actually be using energy for? And how are we going to produce the energy we need for these purposes? Let’s see if we can catch a glimpse of future.

2.1 Energy consumption becomes all-electric

Let's first look at our future energy consumption. We use energy for heating and cooling, for transport, for light and power for our devices, and as a feedstock and steam in all sorts of industrial processes. Let's run through these four components of our energy consumption.

Heating and cooling

In large parts of the world we heat our homes, schools, offices, shops and greenhouses mostly using boilers fuelled by natural gas, oil or still even coal. Unfortunately, our buildings are not really energy-efficient; they generally have poorly-insulated floors, roofs, walls and windows. There are therefore huge gains to be made by efficiently insulating our homes and buildings.

We are capable of building new houses that need no energy at all for heating and cooling. In Germany, for example, they are building new houses – so-called 'passive houses' – that are so well-designed and insulated that the residents and their devices themselves, plus the heat recovered from the ventilation system, produce sufficient heat. No extra energy is required for heating and cooling. But in most new houses, and in existing, well-insulated houses, energy is still needed for heating in the winter and cooling in the summer. How can these needs be satisfied sustainably? Actually, it's not that hard when you consider the following:

- in the summer you are hot and you want to cool down
- in the winter you are cold and you want to warm up

If we now transfer the summer's surplus heat or energy to the winter and, conversely, transfer the winter's surplus cold to the summer, then, in principle, we would have no need for extra energy. It's all a matter of storing heat and cold, and having a sustainable energy system for heating and cooling.

In the future our buildings and homes will be much more energy-efficient. We will heat and cool them with sustainable heat sources, heat pumps and efficient heat storage.

So, if we store the summer's heat in the ground and recover it in the winter, we'll solve the problem. Of course we will lose some energy, but with a heat pump that uses a small amount of electricity, we can always keep the house at the right temperature. This technique, which is already used in many places, is known as ATES (aquifer thermal energy storage).

Naturally, the heat or cold can also be transported from another source to buildings through a pipe network. But the heat must be sustainable, from a geothermal source for instance, or be industrial residual heat – as long as it also comes from a sustainable energy source. Thanks to heat exchangers, and especially to heat pumps, we can also maintain the heat or cold at the desired levels.

Heat distribution is certainly economically attractive in densely populated areas, but in small country villages the situation is different. A possible option in this case is to convert the gas network into a hydrogen network. Obviously, the buildings and homes first need to be well-insulated, but the demand for heat that remains can be satisfied by fuelling boilers with hydrogen.

Around the equator or, let's say, between the tropics, there is no demand for heat, though there is always one for cold. There is a year-round need to cool buildings and homes, a need that is met by air conditioners powered by electricity. This works fine, but there are often good sources of cold to be found in the vicinity: in the ocean or in surface water for instance. One could for example very effectively cool all the buildings in the Caribbean using water from the sea. The seawater would be pumped up, at a temperature of 6 to 9 degrees Celsius, from a depth of a few hundred meters and, via heat exchangers, directly cool the buildings and homes.

The future therefore consists of much more energy-efficient buildings with sustainable cold and heat sources, in combination with electric heat-pump technology and efficient heat and cold storage systems. But in old cities, villages and in the countryside, hydrogen, distributed through adapted gas pipe networks, could offer a good alternative for sustainable heat.

Transport

To drive, sail and fly today, we depend essentially on oil, which is processed in a refinery into petrol, diesel, LPG, kerosene and other products. The fuel is then transported in large tank trucks to fuelling stations, where we take our cars, boats, busses and trucks to fill up. The technology we use to move our vehicles and boats has not changed over the last hundred years, namely: an internal combustion engine, which has an efficiency of only around 25%. Over the last couple of decades, a lot of work has been put into introducing natural gas as a transport fuel, in the form of compressed natural gas (CNG) or liquified natural gas (LNG), because of their lower carbon dioxide (CO_2) emissions. Biofuels have also been brought to the market: biodiesel, ethanol, bio-CNG and bio-LNG, all of which produced from plants or plant residues. This is all fine in itself, but we're still working with low-efficiency combustion engines.

In the future we will be driving, sailing and flying autonomously and electrically, using electric motors, batteries and hydrogen fuel cells.

This is why a huge effort has been made over the last few years in developing the electric car, because an electric motor's efficiency is around 95%. But the big question is: How do you transport the electric power with you in your car or boat? Batteries are one option, but to drive, say, one to four hundred kilometres, you'll need a heavy load of batteries to store the electricity you require. And it then takes a considerable amount of time to recharge these batteries. Nonetheless, this is certainly an acceptable solution for cars that are not driven many kilometres on a daily basis. But what do we do about the cars, busses, trucks, boats and trains that do clock up great distances?

The fuel cell is emerging solution for these cases. A fuel cell converts hydrogen into electricity at an efficiency of 60% [22], and an electric motor then propels the vehicle. This means of transport is known as a Fuel Cell Electric Vehicle (FCEV). One fills its tank with hydrogen, just as one now does with natural gas (CNG).

We see another key development in the future for the transport sector, and that is autonomous driving or sailing. It is anticipated that such a development would mean fewer cars, which would also be more energy-efficient, because the car itself, and not humans, will be doing the driving.

Autonomous, electric driving, sailing and flying – with batteries, but also certainly with fuel cells and hydrogen – are what lies in the future when it comes to transport.

Feedstocks and steam in industry

Industry uses energy to produce the steam it needs to conduct specific processes. This is the case of the paper, food and chemical industries, among others. Huge opportunities still exist in a large number of processes to save energy by improving energy efficiency. The electrification of industrial processes can also make them more efficient and, more importantly, cleaner.

In the future we will see more and more electrical production processes and new production techniques, such as 3D printing. Industry will be using hydrogen and biomass as feedstocks.

In addition, the chemical industry in particular makes use of energy as a feedstock in the production of other chemical materials. This industry uses energy – which today means fuels like oil and gas – as a feedstock. Thus a large number of chemical materials, such as ethylene, plastics, nylons and polymers are made from oil. Natural gas is also a feedstock for chemical materials, like methanol and ammonia (artificial fertiliser).

In a green economy, we will no longer make these chemical materials from fossil fuels, but from green feedstocks and 'waste'. We can derive these green feedstocks from biomass, such as wood, straw, or algae and seaweed. We can also recycle various chemical feedstocks from waste. But a very interesting green feedstock can be made from biomass, and more particularly from electricity, namely: hydrogen. If the electricity used comes from a sustainable source, we would therefore have green hydrogen.

Many production processes are still large-scale processes. Through the increased use of additive manufacturing, or 3D printing, these processes can be radically changed. 3D printing would enable the manufacture of a personalised product on-demand and on-the-spot. This would mean less waste, less transport and lighter products, all of which would deliver considerable energy savings. 3D printing can also play a big role in the circular economy, since products can more easily be repaired, modified or partially recycled on-site.

The future consumption of energy for the production of steam can in part be reduced by improving efficiency, and by electrifying the processes and implementing new production techniques like 3D printing.

Light and power for our devices

We use electricity to power all our devices, machines, pumps, compressors, lighting, computers and telephones. Naturally we can make many of these a lot more energy-efficient – certainly in the case of lighting, through the use of LED lighting.

In the future electricity consumption will increase for new devices like 3D printers, drones and robots.

But the future will also bring us many new devices and systems that will use electricity; take for instance 3D printers, robots, drones, transmission masts, data centres, the internet of things and the cloud. The demand for electricity will grow with the extension and penetration of such technologies.

All final consumption of energy will be in the form of electricity

In the future the final consumption of energy in our society will be electric. Not only for our power and light, but also for all the other energy functions. The electric heat pump will play a big role in heating and cooling. Electricity will become increasingly important in industry as well. The same applies to the transport sector, since all cars will be equipped with an electric motor. Increasingly, the electric motor, heat pump, battery and fuel cell will take over the functions of the internal combustion engine, boiler, generator and steam turbine.

The final consumption of energy for heating and cooling, transport, feedstock and steam in industry, and for power and light will increasingly be electric.

Solar Power to the People **Future developments in energy consumption**

Energy consumption	Future developments
Heating & cooling	Energy-saving, thermal storage, heat pumps, hydrogen boilers
Transport	Electric, autonomous, batteries, hydrogen fuel cells
Feedstock & steam in industry	Electronic processes, heat pumps, digital processes, 3D printing, bio-based, hydrogen
Power & light	New devices (robots, 3D printers, internet of things), heat pumps, hydrogen fuel cells

2.2 Sustainable energy production will become all-electric and cheap

The energy we need in a sustainable society must of course only come from sustainable energy sources. This is not at all a problem since, as we have seen, the sun provides us with more energy in one hour, than we consume worldwide in an entire year. We have numerous ways of converting the sustainable energy sources into useful energy carriers. However, the most important energy conversion technologies convert sustainable energy into electricity. We have long done this through hydro and geothermal power, and now we are increasingly doing so using the wind and sun.

Although hydroelectricity was and generally remains the cheapest form of electricity production, in 2017 we observe that the combination of sun and wind, at locations where the sun shines the wind blows a lot, is – or in a couple of years will become – the cheapest way of producing electricity. In 2020, solar energy, in areas in the Middle-East, Brazil, Chile, Mexico, India, China, Australia and Africa will be able to produce electricity for 2 to 3 US cents per kWh. Wind energy in places like Morocco, Mexico, Argentina, the United States, China, India, parts of Africa, Mongolia and Kazakhstan, will also be able to produce electricity for 2 to 3 US cents per kWh in 2020. When it comes to offshore wind, we see that the first tender offers in Germany and Denmark include costs below 4 Euro cents per kWh.

In 2040 we will produce large-scale solar and wind electricity for less than 2 US cents per kWh – and for even less than 1 US cent per kWh at prime locations.

As was made clear in a study by Lazard in January 2017, wind and solar electricity in the United States can also compete with electricity produced by gas and coal. Electricity can be produced from the wind for 3 US cents/kWh, from the sun for 4.5 US cents/kWh, from gas for 5 US cents/kWh and from coal for 6 US cents/kWh [23].

Bloomberg New Energy Finance, in their Energy Outlook Report 2017, forecast that the cost of solar energy will drop by about 66% by 2040, that of wind onshore by 47%, and of wind offshore by no less than 71% [24]. All sustainable forms of electricity production (solar, wind onshore, wind offshore and also hydro) will be able by 2040 to produce electricity for less than 2 US cents per kWh – and even for less than 1 US cent per kWh at several prime locations around the globe.

3 SOLAR POWER TO THE PEOPLE WORLDWIDE

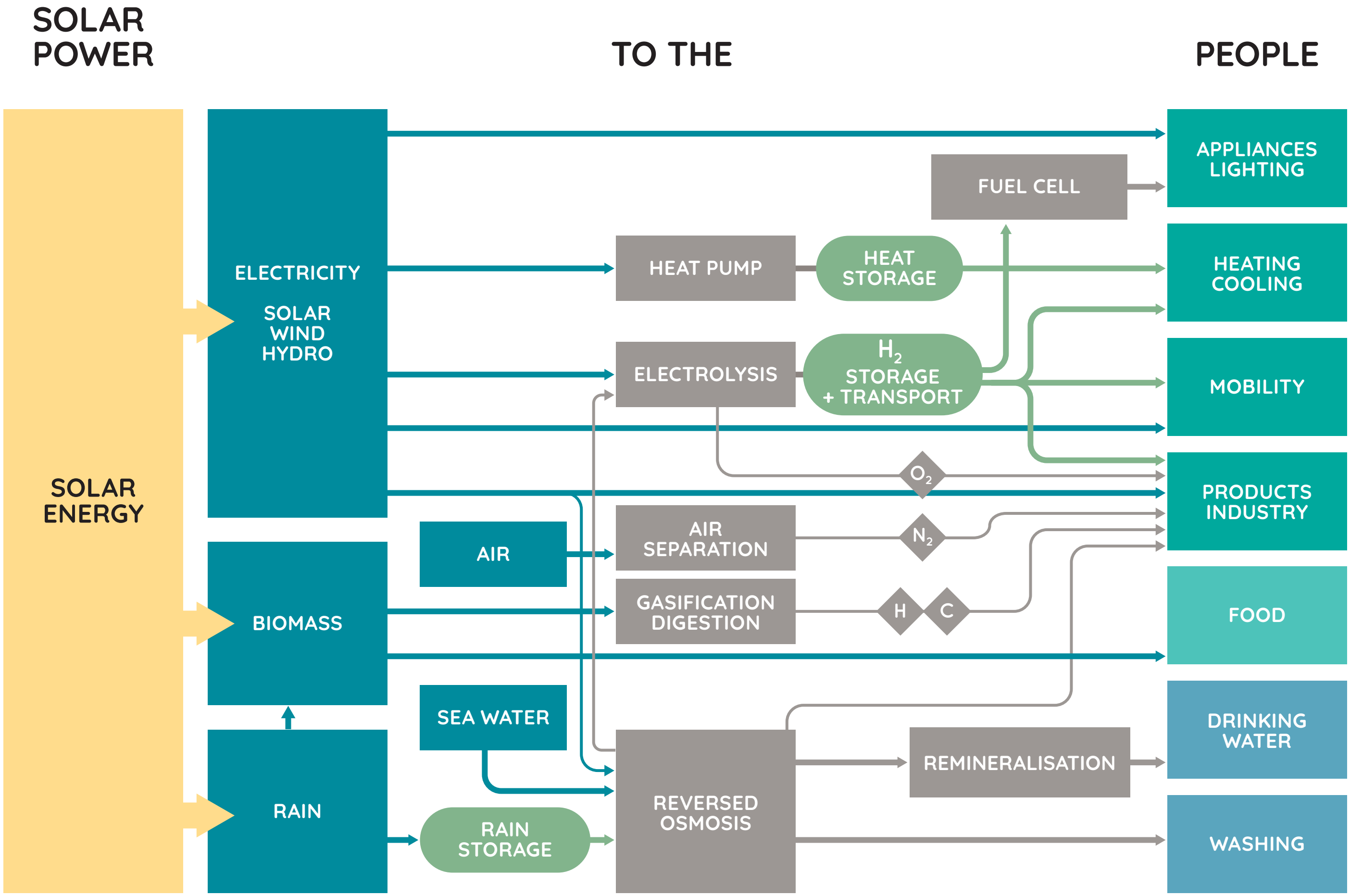
We produce electricity from our sustainable energy sources. We transport this electricity via hydrogen all over the world to use it at every moment, at the place we need it.

Providing everybody with clean and affordable energy and water is an enormous challenge. Fortunately, the methods of producing energy and drinking water from the sun, wind and water, are becoming more and more inexpensive, thanks to technological developments and especially to mass production. Ultimately it will even become cheaper to produce energy and water from sustainable sources than from fossil sources. But the challenge is not met yet: we still have to get the energy and the water to the people.

The production of energy from the sun, wind and water depends both on where you are in the world and at what time. In general, we don't live and work in areas where the sun shines the brightest (deserts) or where the wind blows the hardest (oceans). Moreover, we also want to use energy at night, when the sun doesn't shine, or at times when the wind doesn't blow. This also applies to our freshwater. It doesn't rain uniformly all over the world, and it certainly doesn't rain all the time. Therefore, in a sustainable energy and water system, we have to be able to transport energy and water over distances and time, and we have to be able to store them.

It is true that energy and water are, together with food, primary basic needs, but ultimately it is a matter of how we use the water and energy, what we use them for, and what quality we require. When it comes to energy, what we want is not simply energy, rather, what we want is energy to perform certain functions: prepare a good meal, have a comfortable home, or to read a book in the evening. This also applies to water: we want to drink it, shower ourselves with it, and water our gardens with it. In other words, we need to convert the sustainable energy and water into the right energy and water functions, services or products.

In a sustainable energy system, it is primarily electricity that we produce from the sun, wind and water. This means that we ultimately have to be able to bring this sustainable electricity to the people at the time that they need it. Moreover, we want to be able to convert this electricity into all those energy functions, services and products people demand. Let's first take a closer look at how we can transport and store this sustainable energy (primarily electricity) all over the world, and how we can use it to make basic products, such as chemicals and metals, and even, who knows, drinking water.



SOLAR POWER
TO THE
PEOPLE
SOLAR ENERGY
ELECTRICITY
SOLAR
WIND
HYDRO
BIOMASS
RAIN
AIR
SEA WATER
RAIN STORAGE
HEAT PUMP
HEAT STORAGE
FUEL CELL
ELECTROLYSIS
H2 STORAGE + TRANSPORT
O2
AIR SEPARATION
N2
GASIFICATION DIGESTION
H
C
REVERSED OSMOSIS
REMINERALISATION
APPLIANCES LIGHTING
HEATING COOLING
MOBILITY
PRODUCTS INDUSTRY
FOOD
DRINKING WATER
WASHING

3.1 Hydrogen for transport and storage of sustainable energy

As mentioned, the production of electricity from the sun and wind depends on the amount of sunshine and wind. And this amount varies from one place to another on earth and fluctuates strongly in time. This is why the transport and storage of electricity all over the world is a key challenge.

We can of course store electricity in batteries, but given the limited energy density of batteries, this is only a solution for the transport of small quantities of electricity and for short-term bridging purposes. This is why the conversion of electricity into another form of energy is often a better option for the longer-term storage and transport of larger volumes of electricity.

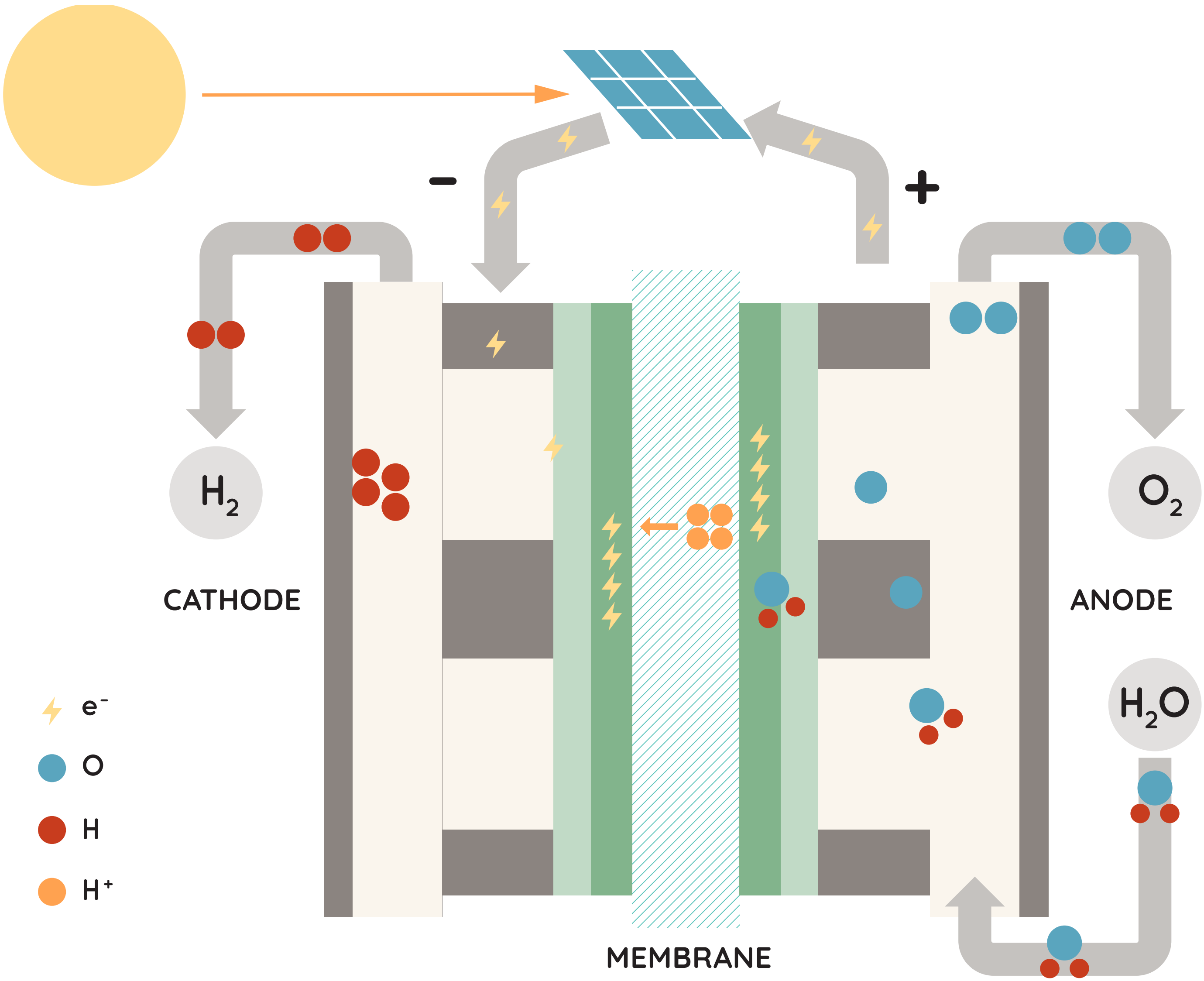
One conversion-storage technique has been applied for decades. It consists of pumping up water into a reservoir using electricity. Whenever electricity is needed, the water is made to flow down through the turbines which generate the electricity. We thus convert electricity into so-called potential or gravitational energy, and then reconvert it back to electricity.

The problem is that this doesn't allow you to transport energy from one continent to another. The only way of transporting electricity over long distances and storing it on a large scale is to convert it into a fuel. And that fuel is hydrogen!

Hydrogen production from electricity

The conversion of electricity into a fuel – i.e., into chemical energy – does offer the possibility of large-scale energy storage, and of transporting energy over large distances. How can we then convert electricity into a fuel? Actually, there is only one way of doing this on a large scale: through the electrolysis of water. The electrolysis of water is the decomposition of water (H_2O) into hydrogen (H_2) and oxygen (O_2), caused by the flow of electricity through the water.

There are different forms of water electrolysis, of which alkaline electrolysis and PEM electrolysis are by far the most important. The application of PEM (polymer exchange membrane) electrolysis has grown very rapidly over the last few years. The electrolyser contains a membrane responsible for the conduction of the protons (H+), the splitting of the gases and the electrical insulation of the electrodes: anode (+) and cathode (-). The PEM electrolyser reacts particularly well in cases of fluctuating electricity production, which of course characterises solar and wind electricity.



PEM electrolyser [25].

Hydrogen is produced through the electrolysis of water (H_2O), splitting it into hydrogen (H_2) and oxygen (O_2).

PEM electrolysis techniques are developing at lightning speed, both in terms of efficiency and costs. While the efficiency of a PEM electrolyser in 2010 was about 65%, in 2017 it is about 80%, and the expectation is that it will reach 86% by 2050.

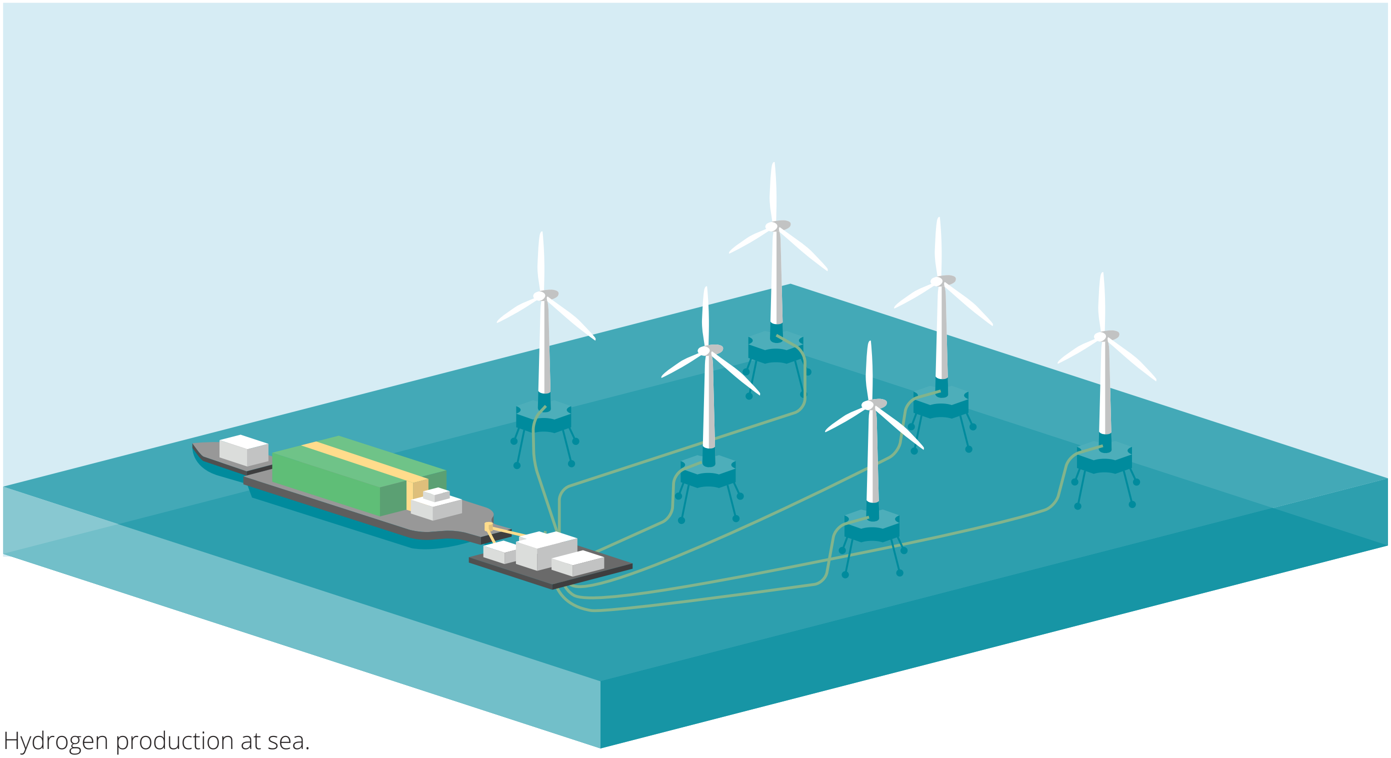
Additional energy is needed to produce demiwater, and to clean and compress the hydrogen. With this in mind, in 2050 a total of 49 kWh of electricity will be required to produce 1 kilo of hydrogen with an energy content of 39.4 kWh. The costs of PEM electrolysers are dropping even faster than the efficiency. In 2015 the technique still cost about € 2000 per kilowatt (kW); in 2020 this should drop to € 600 per kW, and the expectation is that costs will drop to € 350 per kW in 2030 and even to € 250 per kW in 2050 [26].

Solar Power to the People **Hydrogen production with PEM electrolysis** Source: [26]

Component	Energy consumption (2050) kWh/kg H_2
PEM electrolyser	45.8
Hydrogen cleaning	1.1
Compression (500 bar)	1.9
Cooling (-40 degrees Celsius)	0.15
Reverse osmosis of seawater + pumping	0.05
Total	49.0

Electrolysis costs are expected to continue to drop sharply, from € 2000 per kilowatt in 2015 to € 600 per kilowatt in 2020.

One can now generate electricity at locations anywhere in the world where good wind conditions, solar radiation, geothermal sources or hydroelectricity resources exist. With PEM electrolysis one can then convert it into hydrogen and transport it to wherever it is needed.



Hydrogen production at sea.

Compressed hydrogen transport

Hydrogen is a gas, the lightest of all elements, so its energy density per unit of volume is not high. A cubic meter of hydrogen, at atmospheric pressure, contains only about 3 kWh (10.8 megajoules) of energy. In order to transport considerable amounts of energy in the form of hydrogen, one way is to highly compress the gas.

In the large-scale production of solar or wind electricity, we can produce and compress hydrogen, store it in hydrogen tanks in a container rack, and transport it directly to the end-user.

The development of tanks – known as tubes – to transport compressed hydrogen is advancing rapidly. Hydrogen can be stored and transported by road with tubetrailers. In 2015, it was common to transport hydrogen in tubes under a pressure of 120 to 200 bars. The latest tubetrailer system (2017), made with carbon fibres, can store hydrogen at 500 bars and can therefore transport 1,100 kilos of hydrogen at once. Since one kilo of hydrogen contains 39.4 kWh, a trailer of this type transports 43.3 MWh. These tubetrailers measure 40 feet and weigh almost 30 tonnes, so that the energy density per weight unit is 1.46 kWh per kilo.

Hydrogen transport by truck [27].

We can now use a variety of methods to produce electricity from the sun, wind and water in very remote areas. We can then convert the electricity into hydrogen through electrolysis. In all of these cases, the hydrogen can be compressed and stored in tubes in a container rack. These containers can then be placed on a large container barge and be towed by tug to a harbour, where they can be directly loaded onto trucks and taken to a hydrogen fuelling station. From the production site to the fuelling station, the hydrogen does not have to be transferred or handled at all.

Liquid hydrogen transport

We can transport even more energy in a ship by liquifying the hydrogen and pumping it into slightly modified tanks. This is actually what we do with natural gas, which is transported in large LNG (liquified natural gas) tankers over the oceans. Methane is liquified at a temperature of -162 degrees Celsius. Hydrogen, however, has to be cooled further, to -259 degrees Celsius, which is close to absolute zero. One can transport 800 times more hydrogen in liquid form, per volume unit, than in gas form at atmospheric pressure. Liquid hydrogen is currently only produced on a small scale for use as rocket fuel. The liquefaction of hydrogen requires about 10 kWh per kilo of hydrogen. It is expected however that this would be cut by about half if liquid hydrogen were to be produced on an industrial scale [28].

Liquid hydrogen occupies 800 times less space than does hydrogen gas. In 2030 it will cost about 5 kWh in energy to produce 1 kilogramme of liquid hydrogen.

The Japanese company Kawasaki Industries, among others, is currently developing an entire logistical chain for hydrogen liquefaction, ship transport, tank storage, before it is delivered by tank trucks to a fuelling station. This chain should be operational in 2020, with a view to importing liquid hydrogen to Japan from Australia. Japan wants to make hydrogen a major theme of their 2020 Olympic Games.

Liquid hydrogen transport by ship [29].

From hydrogen to ammonia

We can thus transport compressed or liquid hydrogen over the oceans by ship. But we can also convert hydrogen into another chemical, which is liquid and easy to transport. In the world's remote areas, such as deserts and the middle of oceans, air, sand or seawater are the only raw materials at hand. In fact, air is the most available source, because it contains nitrogen (78%) and oxygen (21%). And from the air's nitrogen (N_2) and the hydrogen (H_2) from electricity and water, we can make ammonia (NH_3).

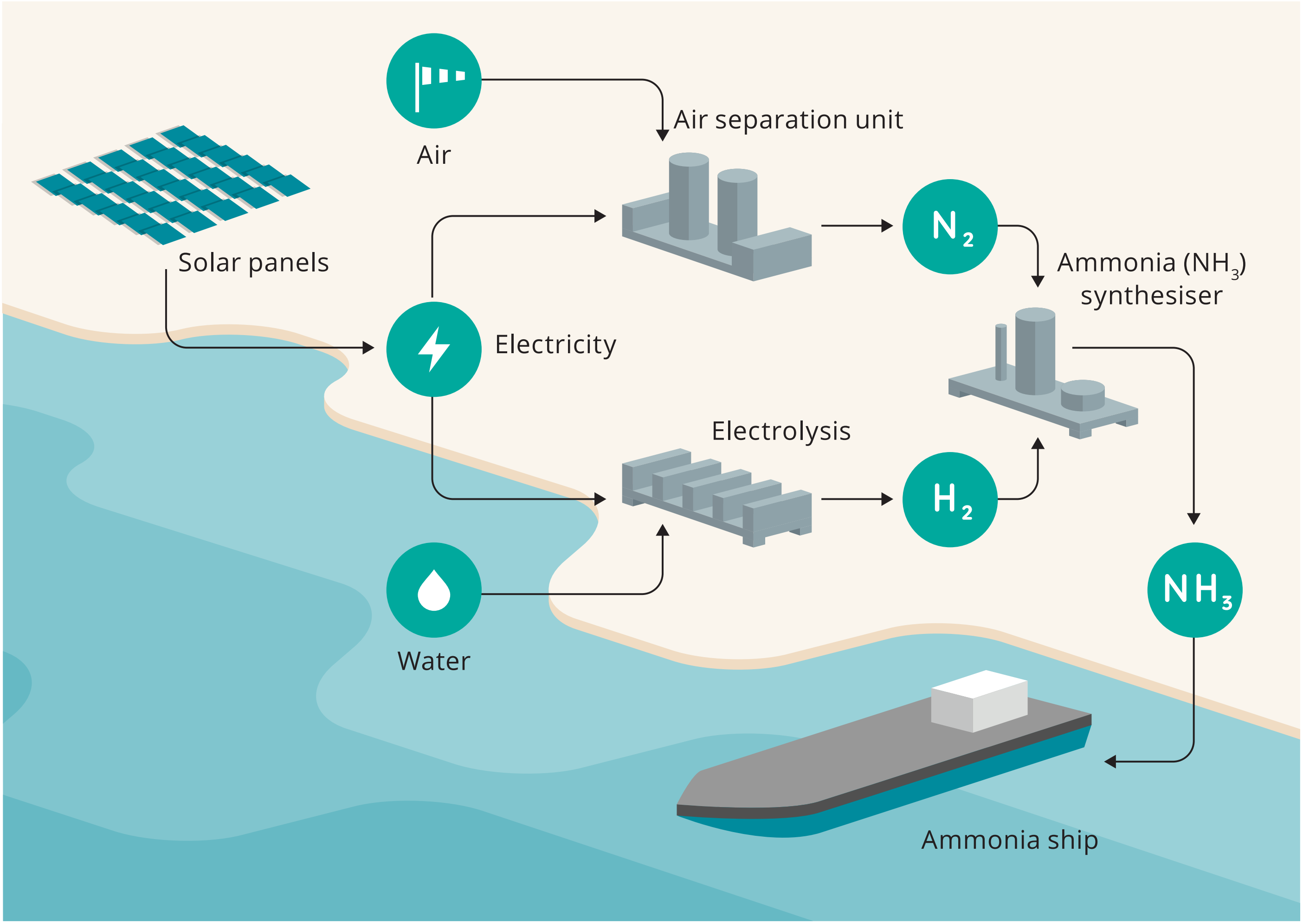
Ammonia is formed by combining hydrogen with nitrogen from the air. Ammonia liquifies under a pressure of 10 bars and is easy to transport.

In these remote areas we can't produce fuels that contain carbon, such as methanol (CH_3OH) or formic acid (CH_2O_2). Oxygen is available, but the problem is carbon. Ammonia is the only chemical that we can produce in such areas with the raw materials available, namely, nitrogen from the air and hydrogen. Moreover, ammonia is not only a practical means of transporting energy, but we also make wide use of it for other applications. Together with phosphate, ammonia is for instance the main component in artificial fertilisers. Indeed, of all the ammonia produced in the world, which in 2015 amounted to 150 million tonnes, 80% is used in artificial fertilisers. Thus ammonia is both an energy carrier and a product that can itself be directly used.

Other fuels that require carbon can't be produced in the desert or on the oceans, since these are places where no carbon is available.

The process and the installations required to obtain nitrogen from air already exist. And the process of producing ammonia from hydrogen and nitrogen is also being implemented at many locations throughout the world. In addition, the complete logistics chain for the transport of ammonia by ship, train and truck, and its storage in tanks, already exists. The only difference is that the hydrogen in this case isn't produced from natural gas, but from solar, wind or hydroelectric power.

The transport of ammonia by ship, as is being planned in Japan, is one means of first converting solar energy into hydrogen, and then converting it into ammonia which would then be transported. The ammonia can be directly used in industry to, for example, produce artificial fertiliser. But the Japanese also intend to crack this ammonia to remove its hydrogen, and then use the hydrogen as a transport fuel.



Solar-hydrogen-ammonia cycle [30].

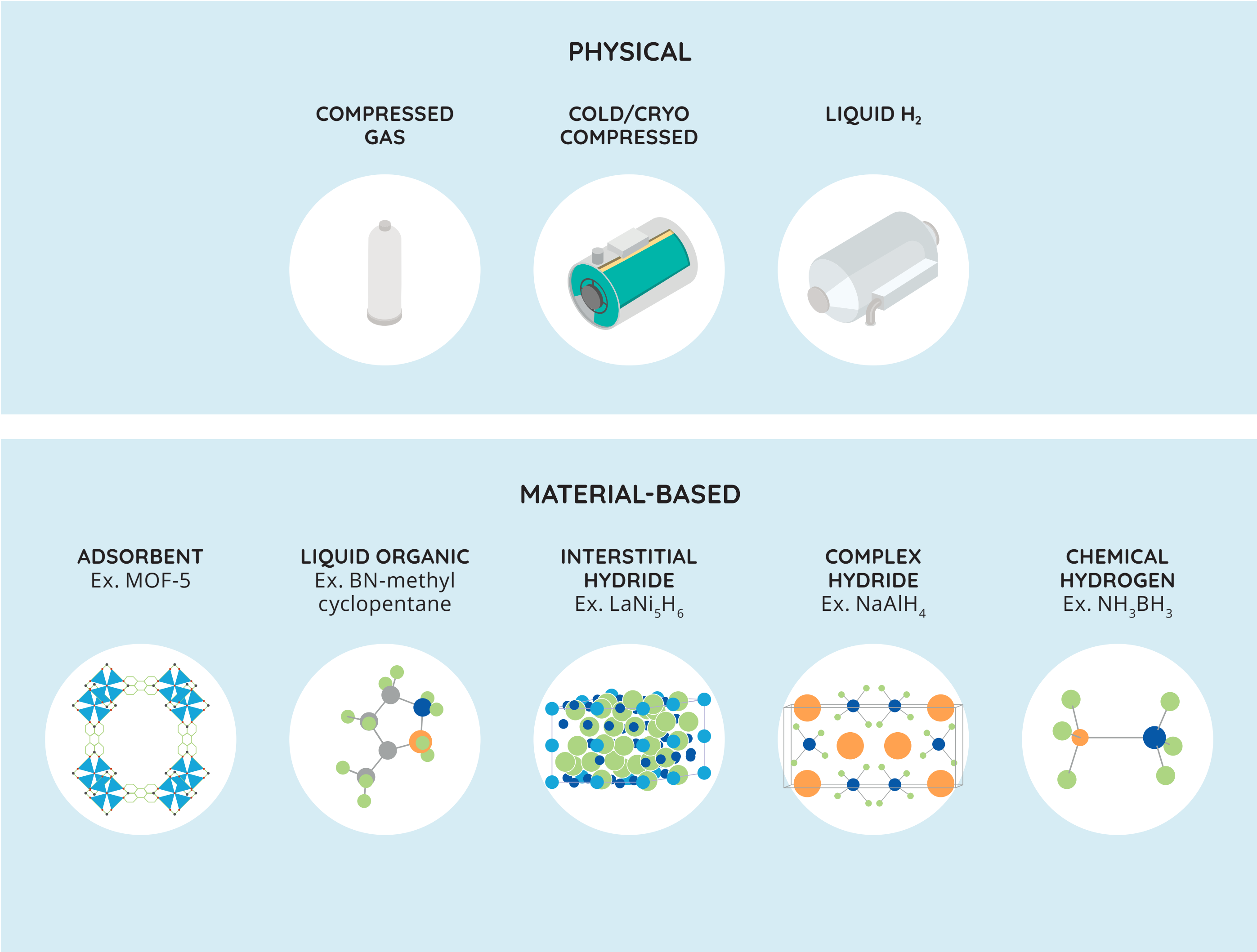
Hydrogen for large-scale storage of energy

We can store hydrogen in compressed or liquid states or in the form of ammonia. But there are still other storage methods. We can for instance bind hydrogen with metal hydrides, with organic chemical hydrides like toluene, or we can adsorb hydrogen on a solid or liquid surface. Metal-hydride storage is used to store small amounts of hydrogen safely, for example for use in scooters or bicycles. Binding with toluene is currently being done in a joint Brunei-Japan project for the transport and storage of hydrogen between the two countries [31].

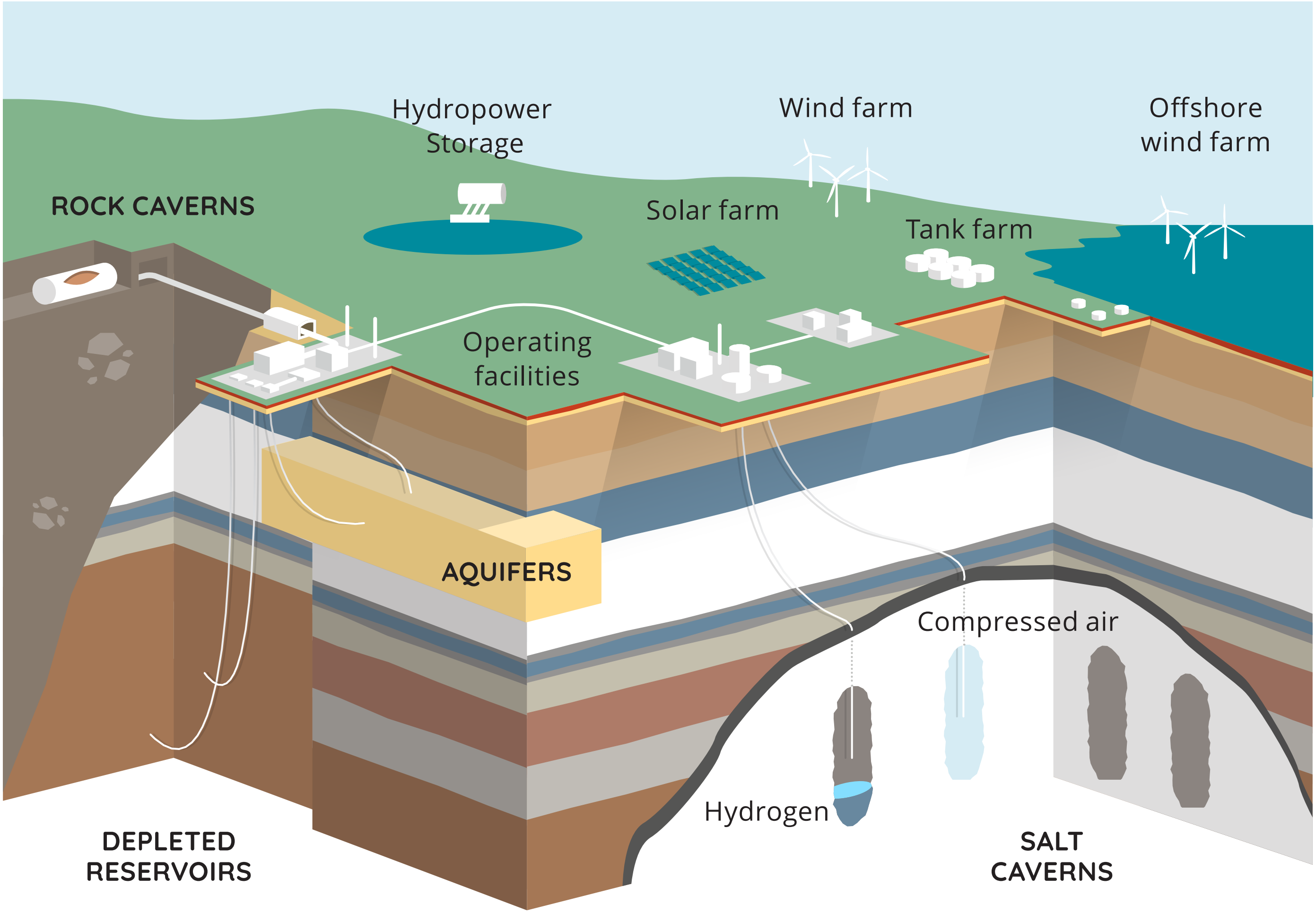
Compressed or liquified hydrogen can be stored as a gas, or bound with another chemical element.

Hydrogen storage in salt caverns is a proven, safe and inexpensive technique. There are many salt caverns available worldwide.

As mentioned, we can store compressed hydrogen gas in tanks, but another option is to store it underground, as we do with natural gas, in salt caverns or depleted gas fields. Hydrogen can be stored in very large volumes in salt caverns, and thus can be done as easily and safely as natural gas storage and is a proven technique. There are many salt caverns available in the world for hydrogen storage, allowing for the storage worldwide of large volumes of compressed hydrogen gas. Air Liquide already has put salt-cavern hydrogen storage into operation in the United States [33].



Forms of hydrogen storage [32].



Hydrogen storage in salt caverns [34].

3.2 Hydrogen and biomass as feedstock in the chemical industry

Hydrogen is a feedstock in the production of chemical products such as ammonia, methanol and hydrogen peroxide. It is also frequently used in refineries to crack heavy oil fractions, and the food and glass industries also use hydrogen.

In a sustainable energy system carbon is scarce. It can economically only be extracted from biomass. This is why we only want to use carbon when there is no alternative, that is, as feedstock for products in the chemical industry.

But to make chemical products such as polymers, plastics, nylon and ammonia, apart from hydrogen, one often needs oxygen, nitrogen *and* carbon. Oxygen and nitrogen are in the air, but not carbon. Currently, both hydrogen and carbon are obtained from fossil sources, which we call hydrocarbons. But this can't be done in a sustainable energy system. It is possible that in the distant future we'll be able to remove carbon dioxide from the air, but the only real source of carbon that we now have is biomass.

As crazy as it might sound, in a sustainable energy system carbon is a scarce resource, because it can only be obtained from biomass. And we want to use biomass essentially as food, as building material or to manufacture products – and of course simply to enjoy as nature. Thus we want to use carbon only in the case where there is no alternative, that is, as feedstock in the chemical industry. This means that, in principle, we no longer want to use any biomass for electricity production, any biofuels or biogas for transport fuel, or any wood pellets or biogas for heating.

Electrolysis and biomass gasification offer an interesting combination for the production of sustainable hydrogen and oxygen, as well as carbon for the chemical industry. The hydrogen and oxygen are produced through electrolysis. While through the biomass gasification of torrefied biomass one can produce so-called syngas, which consists mainly of hydrogen, carbon monoxide and carbon dioxide. The nitrogen is still taken from the air. In this manner, we can make all bulk chemical products using a sustainable energy system.

The technology for the biomass gasification of torrefied biomass is under development. Torrefaction is the process of making a standardised biomass product out of all sorts of solid biomass residues, such as wood waste, straw and coconut shells. Torrefaction breaks down the biomass fibres and produces a biomass that repels water – it is the same process used to roast coffee beans. Gasification of torrefied biomass is therefore a lot easier than the gasification of the biomass itself.

We can now realise a completely green chemical industry cluster wherever the following conditions occur: biomass is available or can be shipped in; cheap sustainable electricity is available (or hydrogen and oxygen can be brought in by ship or pipeline); and a chemical industry cluster is already established. In the Netherlands, one suitable site would be the Eemshaven-Delfzijl area in Groningen.

3.3 Electricity and hydrogen for metal production

A lot of energy is needed to produce metals like iron, aluminium and copper from the metal ores which are extracted from the ground. The metal ore usually contains the metal in oxidised form, that is, it's bound with oxygen. When it's iron, we call it rust. A lot of energy is needed because a redox process – i.e., the removal of oxygen from a metal – requires high temperatures. In addition, an energy feedstock is needed to bind with the oxygen. Let's take a look at the two most commonly used metals.

Aluminium is made from bauxite. To begin with, the alumina is freed from the bauxite (aluminium oxide compounds). Then we need large amounts of electricity to remove the oxygen and produce the aluminium. To make aluminium from aluminium oxide requires about 15 kWh per kilo of aluminium [37]. This is why aluminium is produced at sites in the world where cheap electricity is available. Interestingly, these tend to be places where there is lots of cheap hydroelectricity. A good example is Iceland, where there is a huge hydroelectricity and geothermal energy potential. Several big aluminium companies have set up their plants over the last few decades. Iceland currently produces about 800,000 tonnes of aluminium annually [35] and has plans to further increase its output.

Iron and aluminium are made from ores in which metal is bound to oxygen. To separate this oxygen from the metal requires high temperatures as well as an energy feedstock to bind with the oxygen. Electricity and hydrogen can easily replace fossil fuels and carbon in this task.

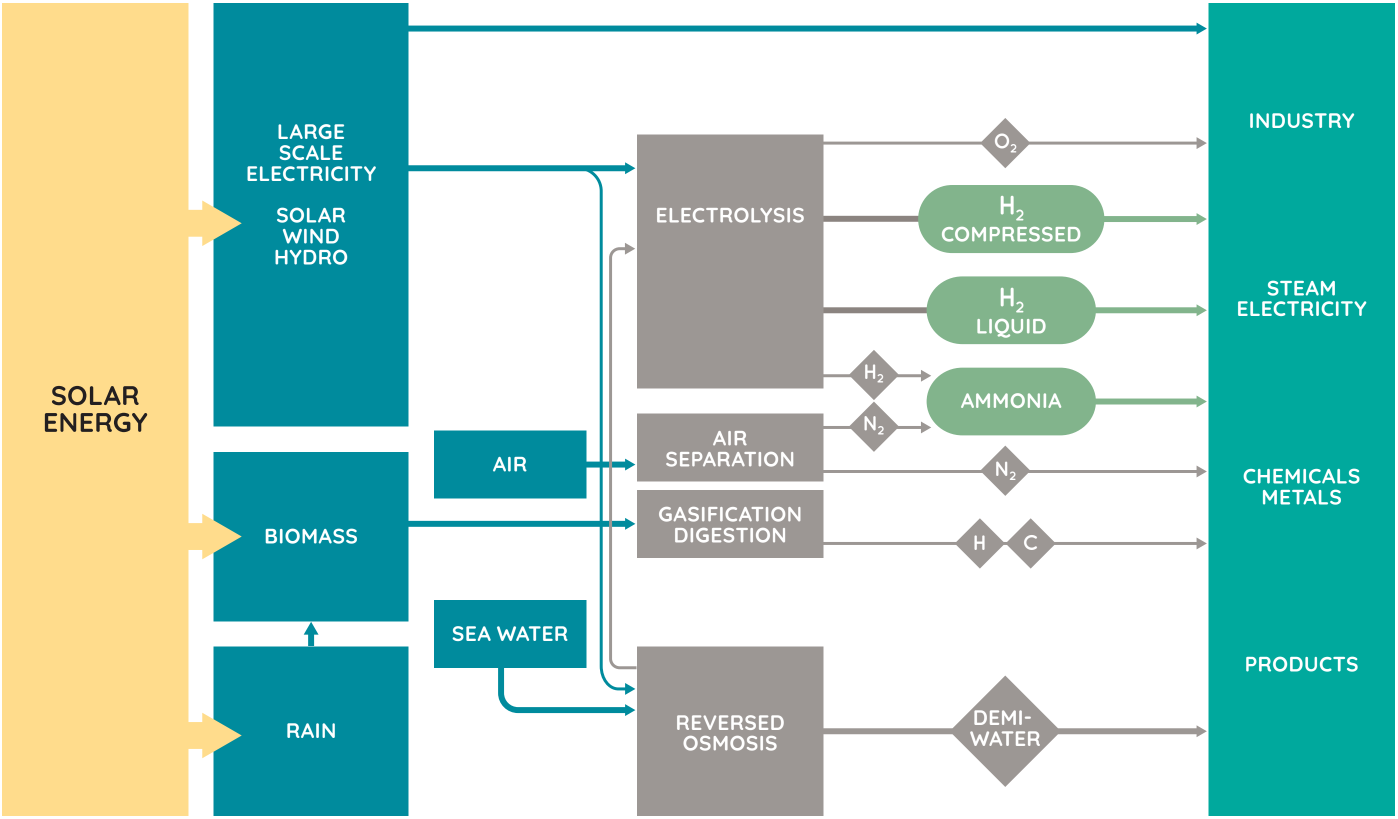
To make iron from iron ore, which is a mixture of various iron oxides, the ore is reduced (freed of oxygen) at high temperatures in blast furnaces using coking coal – which is degassed coal, that is, carbon. The high temperatures are achieved by burning coal. The process thus depends on a fossil fuel, in this case coal. But in the future we would also like iron production to be sustainable. This is possible in principle. We can easily achieve the high temperatures using electricity or hydrogen. Today's reduction process uses carbon to make iron (Fe) from iron oxide (FeO) with carbon (C), and generates carbon dioxide (CO_2) as waste. But the reduction process could also work with hydrogen. Then iron oxide with hydrogen would also produce iron, with water (H_2O) rather than CO_2 as the waste product.

Current process: $2FeO + C \longrightarrow 2Fe + CO_2$

Future process: $FeO + H_2 \longrightarrow Fe + H_2O$

In the case of other metals, such as copper, lithium and silicon, we can also develop production processes that make use of electricity or hydrogen to provide the required high temperatures, and in which the reduction process is carried out with hydrogen instead of carbon.

SOLAR POWER TO THE PEOPLE'S PRODUCTS



3.4 The hydrogen cycle for energy and drinking water

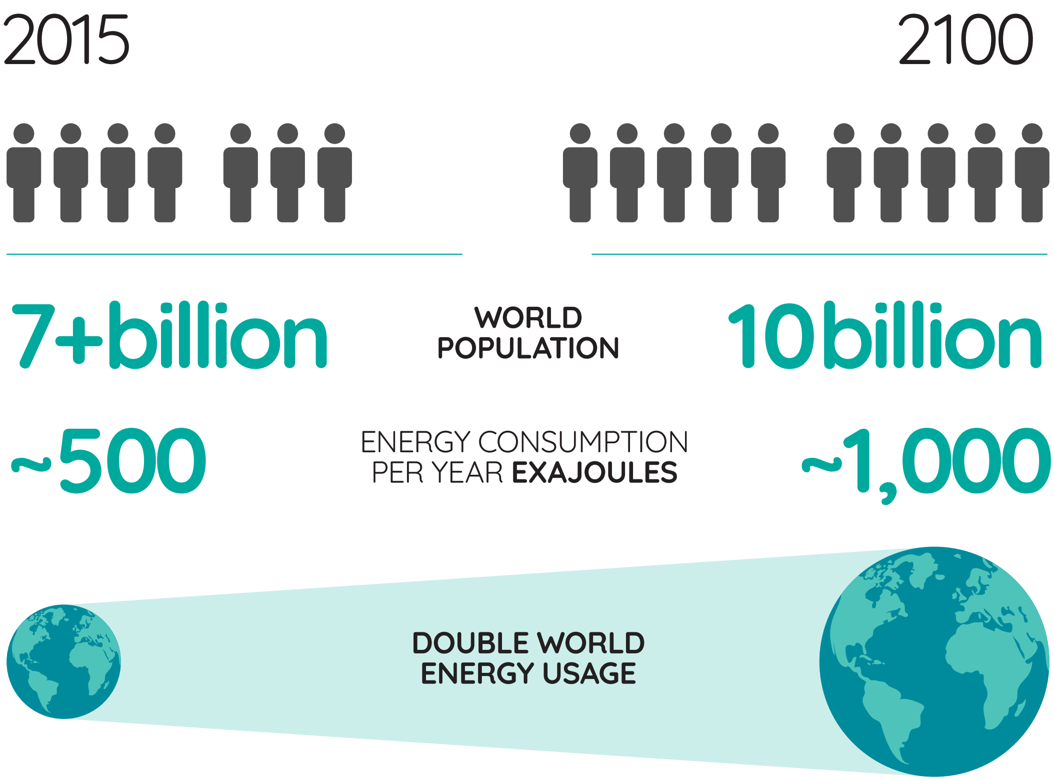
Let's do a global analysis of a worldwide sustainable energy system. First and foremost: What do we expect energy demand to be in the future? Shell has conducted scenario analyses for over forty years, and in its 2016 scenarios projected that in 2100 the world's population will be about 10 billion, with a primary annual energy consumption of 1,000 exajoules (EJ, 1,000*10^{18} J) [36].

In a sustainable energy system large amounts of energy will be transported as hydrogen all over the world. But in doing so we will also be transporting a source for clean water.

Let's assume this to be our starting point and let's look at how we can generate this 1,000 EJ sustainably. We'll approach our task with a so-called 'backcasting method'. We have four big sources of sustainable energy: solar, wind, hydroelectricity and biomass. We want to touch biomass as little as possible, because of the competition with agriculture and nature. But we do need to use some biomass for its carbon, particularly as a feedstock in the chemical industry – this, in a context where no carbon is available from fossil energy sources. Let's make a generous assumption that the biomass energy we need for our carbon feedstock in the chemical industry will be 50 EJ per year. We'll produce this 50 EJ in the form of syngas (biomass gasification) and biogas (biomass fermentation). The remaining 950 EJ must therefore be produced from solar, wind and water sources, which, in principle, produce electricity. The 950 EJ electricity is about 265*10^{12} kWh (265,000 TWh), which is more than ten times the electricity produced in 2016.

In a fully sustainable energy system it is all about costs and not energy efficiency.

The production of solar and wind electricity in areas where the sun shines strongly and the wind blows hard is very inexpensive. A cost of about € 0.01 per kWh is clearly possible. But the cost of producing solar and wind electricity in areas with less sunshine or wind, is significantly higher. The cost of solar or wind electricity produced in inhabited areas will



Energy consumption in 2100 according to Shell [36].

also be higher because the land is more expensive, only relatively small systems can be installed and supplementary measures are required. Moreover, the placement of large-scale wind farms near homes and buildings is a sensitive issue because of noise nuisance and visual pollution concerns.

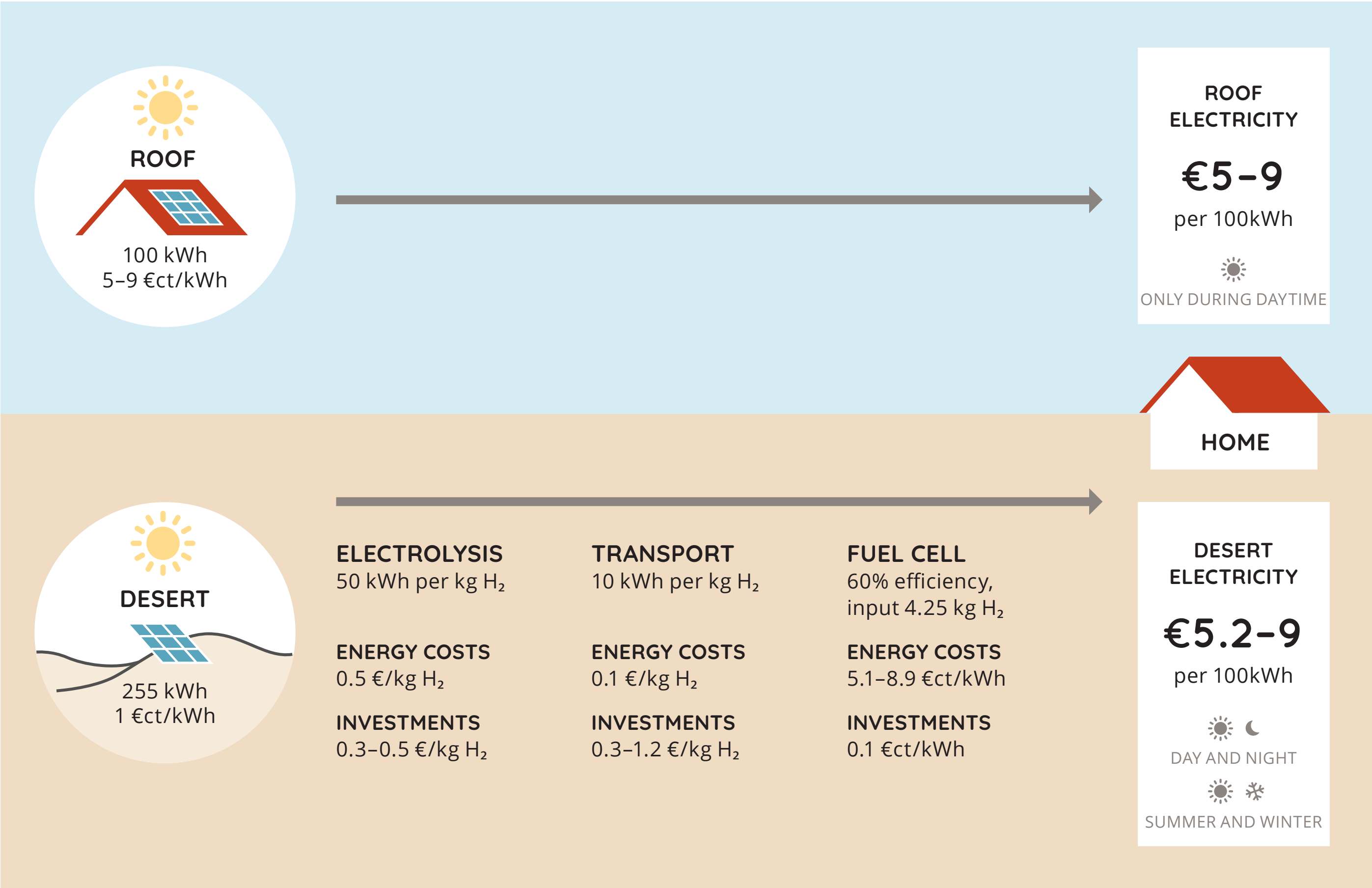
We can now of course install solar panels on houses and buildings and, in the vicinity of industrial sites, we can build wind and solar farms with no problem. Nonetheless, the expectation is that we will be producing the bulk of our sustainable energy in areas in the world where the sun shines strongly, the wind blows hard and no people live. This means that we have to incur the costs for hydrogen conversion, transport and storage, and the reconversion of part of the hydrogen back to electricity. This need not be a problem, as long as the costs are lower than those of producing and storing electricity in the vicinity.

It is therefore our assumption that in the future a very large portion of our electricity will be transported in the form of hydrogen to places where we will consume it. Specifically, we assume that this amount is 75% of the 1,000 EJ. We will consume about 200 EJ (55,000 TWh) directly as electricity, which is self-produced or is transported to individuals or companies through an electricity grid. These 200 EJ come from rooftop solar panels on houses and buildings, solar farms and wind farms, located relatively close to the consumer and connected to a grid. 750 EJ will be produced on a large-scale, in areas where the sun shines strongly, the wind blows hard or very large hydroelectricity stations can be built. Such areas are far from where we live: in the middle of the ocean, in the desert or in other very

Desert electricity versus rooftop solar power

Let's do the calculations to show that the cost price of desert electricity is comparable to that of rooftop power. A solar energy system on our roof costs roughly 2 to 3 times more per panel than a very large-scale solar energy system in the desert. In addition, this desert system produces 2.5 to 3 times more electricity than the one on our roof. Let's assume that a solar energy system in the desert can produce 1 kWh of electricity for 1 Euro cent. This means that a solar energy system on our roof produces the same amount of electricity for 5-9 Euro cents.

We need to first apply electrolysis to convert the desert solar electricity into hydrogen, then liquify or compress the hydrogen, transport it by ship and feed it into a hydrogen pipeline and then, by means of a fuel cell, convert it back into electricity. Thus, to receive 1 kWh of electricity in our home, we need about 2.55 kWh of desert electricity: a chain efficiency of less than 40%.
So, what's the outcome? Despite all the extra investment costs for electrolysis, compression, transport and fuel cells, the desert electricity has a cost that is comparable to that of our rooftop power. And, furthermore, the desert electricity is available whenever we want it, day and night, summer and winter. This illustration shows that, when it comes to a sustainable energy system, what matters ultimately is not the chain's efficiency. Only the costs matter.



Solar power – rooftop versus desert.

remote places in the world. The 750 EJ is equivalent to 210,000 TWh of electricity. We can't transmit this power by electric cable, so that we convert into hydrogen which we can of course transport over large distances by ship or pipeline, as well as easily store.

If we want to convert electricity into hydrogen, apart from the electricity we also need demiwater (or demineralised water) which is ultra-pure water. We can produce demiwater by applying reverse osmosis to seawater or surface water. The demiwater is then split into hydrogen and oxygen in an electrolyser. We need about 50 kWh to produce 1 kilo of hydrogen, which includes the electricity used to make the demiwater. This means that to produce the 210,000 TWh we need 4.2 billion tonnes of hydrogen.

Hydrogen transport becomes as big as oil and gas transport worldwide.

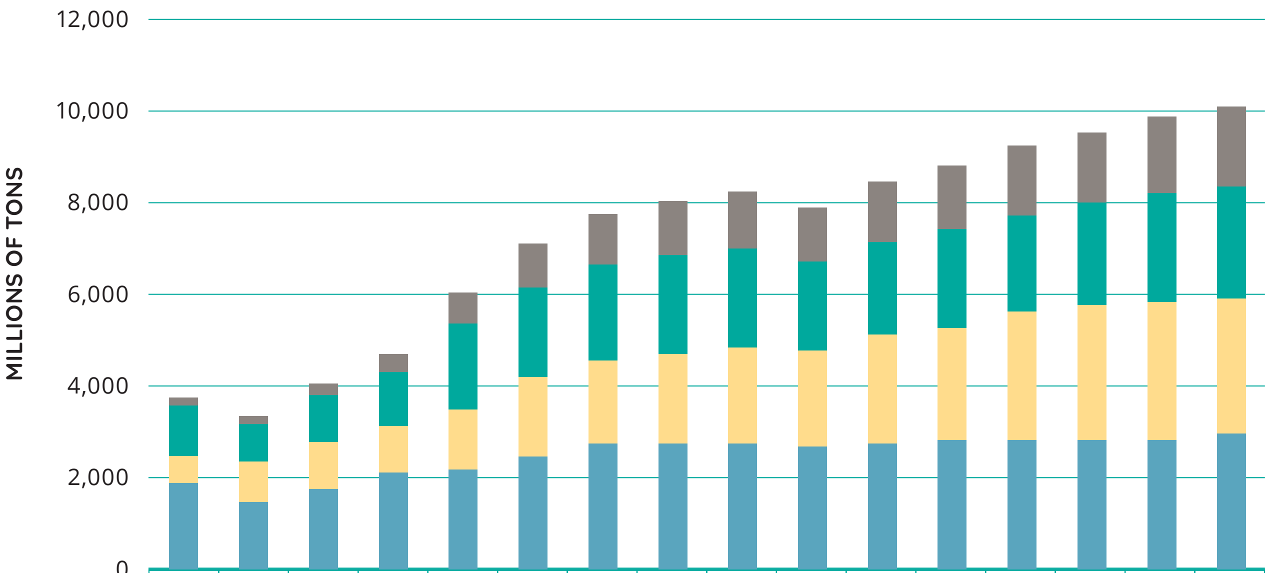
We will transport this hydrogen – in compressed or liquid form, or possibly converted to ammonia – by ship or pipeline to places in the world where it will be used. We need to transport around 4.2 billion tonnes of hydrogen, most of which, say, about 3 billion tonnes, will be transported by ship. This is the same tonnage of oil and gas that we transport today around the world [37]!

Solar Power to the People **Sustainable energy production worldwide**

	Technology EJ	Production EJ	Production TWh	Production tonnes H_2
Biomass	Biomass gasification (syngas) Biomass fermentation (biogas)	50		
Electricity Direct consumption	Rooftop power Solar farms Wind farms Small-scale hydroelectricity	200	= 55,000	
Electricity Hydrogen	Large remote solar farms Large remote wind farms (onshore + offshore) Large-scale hydroelectricity	750	= 210,000	= $4.2*10^9$
Total		1,000		

Following transport, the hydrogen will be used:

- in industry as feedstock, but also to produce steam;
- in the transport sector as a fuel;
- in buildings and homes for heating and cooking;
- naturally also for the production of electricity at times that too little sustainable electricity is available.



	1980	1985	1990	1995	2000	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Containers	102	152	234	371	598	1,001	1,076	1,193	1,249	1,127	1,280	1,393	1,464	1,544	1,640	1,687
Dry cargo other than main bulk commodoties	1,123	819	1,031	1,125	1,928	1,975	2,112	2,141	2,173	2,004	2,022	2,112	2,150	2,218	2,393	2,463
Main bulk commodoties	608	900	988	1,105	1,295	1,711	1,814	1,953	2,065	2,085	2,335	2,486	2,742	2,923	2,985	2,951
Oil and gas	1,871	1,459	1,755	2,050	2,163	2,422	2,698	2,747	2,742	2,642	2,772	2,794	2,841	2,829	2,825	**2,947**

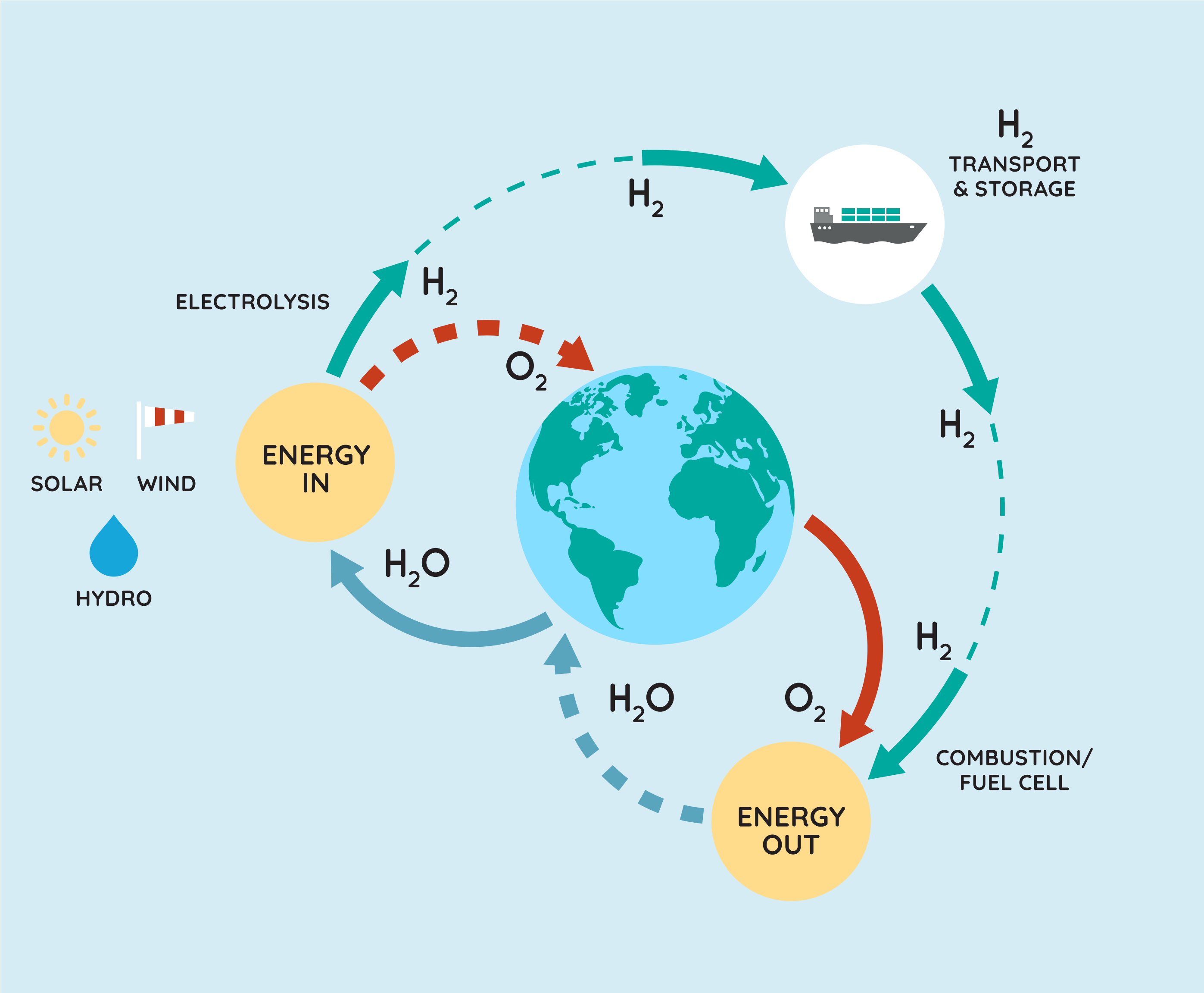
Worldwide seaborne transport [37].

But if we use the hydrogen in a (car's) fuel cell or in a boiler for energy production, then the resulting 'waste' product is again very pure water. In fact, this water is so pure that it wouldn't be crazy to see it as a source of drinking water. We would of course have to add some minerals and salts to it to make it potable. In short, we would not only produce energy, but possibly drinking water as well – and, again, we'd do it where the people are.

But how much water are we in fact talking about? We can produce about 9 kilogrammes, or 9 litres, of pure water per kilogramme of hydrogen. Therefore, by reusing those 4.2 billion tonnes of hydrogen we can produce 37.8 billion m^3 of clean water, which in principle could be made suitable for drinking. But we won't dispose of all of this water, since part of it will be used as a feedstock, part will be released in places where it can't be collected (or only at a high cost), and so on. But a third of it – say, 12.5 billion m^3 – should be available as drinking water in places we can use it. And, hey: 10 billion people, each of whom drinks 3 litres of water per day, that's 11 billion m^3 per year. A sustainable hydrogen cycle for energy and for drinking water! And even if it isn't made into drinking water, they're plenty of other useful applications for such pure water.

Sustainable hydrogen cycle for energy and drinking water.

Solar Power to the People **Hydrogen for energy and drinking water**	
Total world population	**10 billion**
Primary energy consumption per year	1,000 EJ
Drinking water consumption per year	11 billion m^3
Hydrogen production	4,2 billion tonnes
Drinking water production from hydrogen	1/3 of 37.8 billion m^3 = 12.5 billion m^3



The hydrogen cycle [38].

4 SOLAR POWER TO THE PEOPLE IN OUR CITY OR VILLAGE

The sun and the rain provide energy and water via solar cells, reverse osmosis, batteries, electric motors, fuel cells and electrolysers.

Providing everybody with clean and affordable energy and water is more than a global challenge. It is also something that affects our own immediate living environment, our cities, villages and the countryside where we live, work and enjoy recreational activities. How can we provide a healthy and clean living environment? How can we ensure that our homes are comfortable and pleasant to live in? How do we move about, and how do we access our products and services? Let's try to sketch a picture of our sustainable energy and water provision in our immediate living environment.

What will our city or village look like in 2050?

Let's imagine what the future could bring us.

Our houses and buildings are comfortable; they are well-insulated and perfectly ventilated. We no longer need lots of energy for heating or cooling. But any heating needs we might have are met by a heating network or by electric heat pumps. In the countryside, in small villages and, sometimes, in old city centres, the natural gas network is still in place, but has been adapted to transport hydrogen to meet the heating and cooking needs of homes and buildings.

All the roofs of homes and buildings have solar panels that produce electricity and are also equipped with a rainwater harvesting system. We are surrounded by many more electric devices, including intelligent LED lighting, screens, digital TV, internet, tablets, computers, smartphones, robots, drones, cameras and 3-D printers, besides out fridge, washing machine, dishwasher and cooking appliances. The internet of things is well established, so that we can also monitor and operate our devices remotely. Since these devices have become much more efficient and, thanks to the internet of things, we can use them efficiently and economically, our electricity consumption is not that much higher than it was in 2017.

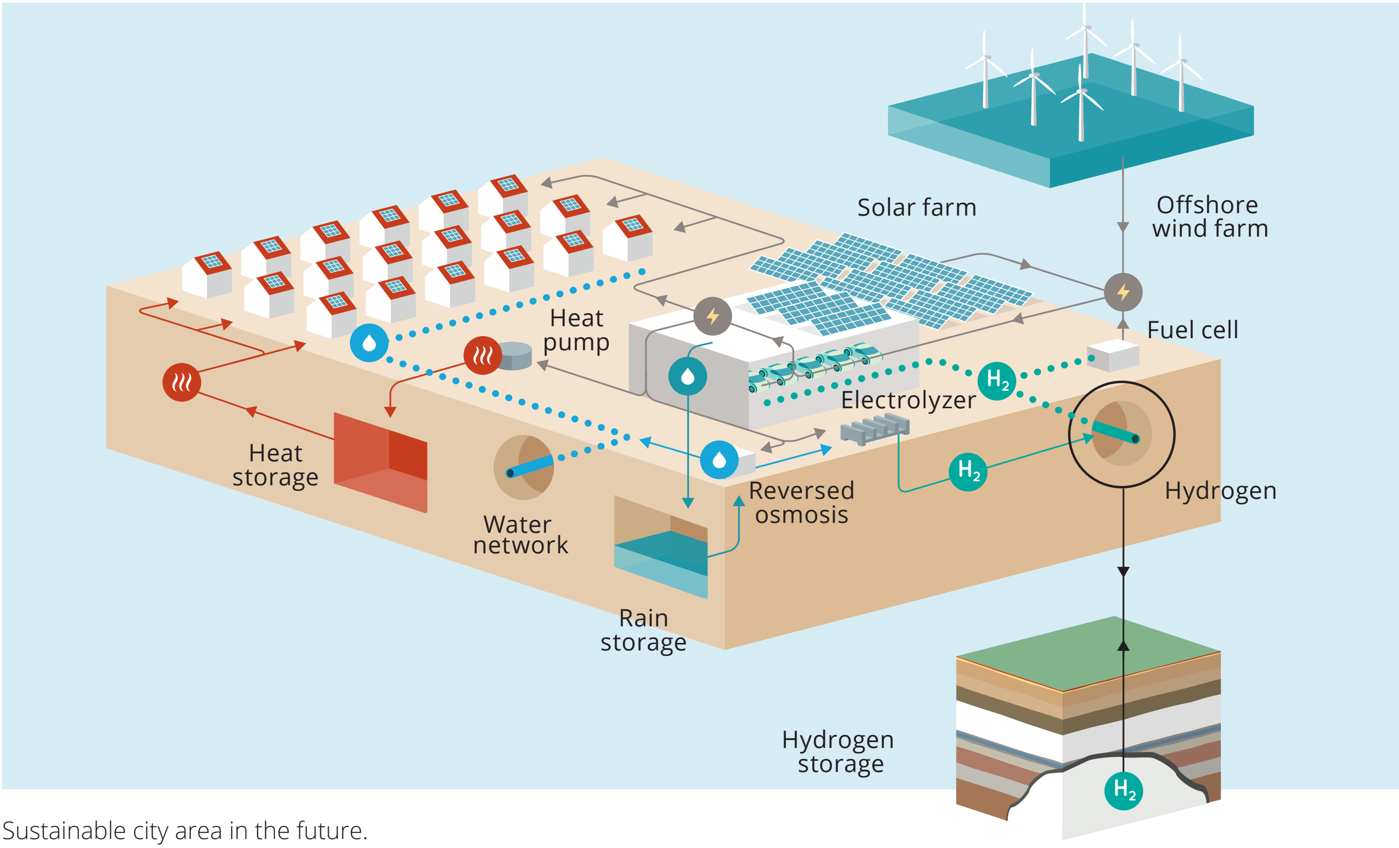
We do our purchasing and shopping digitally, from our easy chair; robots and drones look after the delivery. Robots clean the windows and do the vacuuming. If an appliance or something in our house breaks, the 3-D printer makes the replacement part needed. Garbage is, as much as possible, directly transformed into new raw materials that are taken away by robots and drones.

We move around in electric vehicles that run on batteries or are equipped with an electric fuel-cell hydrogen system. Of course, our vehicles are autonomous and we've gone from vehicle ownership to vehicle usage. We order the vehicle we want by smartphone. What does this vehicle look like? It doesn't need a steering wheel, nor headlights, and does it still have a windshield? And what do our roads look like; do we still need road signs, traffic lights and lighting?

We don't park our vehicles in front of the door: they park themselves in large parking garages, where they are connected to the electricity grid, hydrogen network (adapted natural gas network) and water distribution network. They can be 'filled up' with electricity and/or hydrogen in the garage. But they can also supply electricity to the grid; hydrogen fuel-cell electric vehicles can also supply water to the water distribution network.

These parking garages have an energy and water conversion unit. Batteries and flywheels store short-term fluctuations in electricity from the solar panels and then supply the electricity to meet peak demands. In the summer – or when electricity is cheap – electrolysers make hydrogen from the surplus power from the solar panels; the hydrogen is then fed into the hydrogen network. Fuel cells can also supply electricity from hydrogen taken from the hydrogen network whenever a structural electricity shortfall occurs or is forecast. Heat pumps produce heat, ranging from 40 to 60 degrees Celsius, from surplus solar energy – or when electricity is cheap – and store it in the subsurface for use in the winter. A reverse osmosis unit makes demiwater from the rainwater that has been harvested and then stored in the subsurface; the demiwater is then used to produce hydrogen as well as drinking water, which is fed into the water distribution network for use in homes and buildings.

The energy and water conversion unit is connected to a larger electricity grid, hydrogen network and water distribution network. These can transport the electricity produced by wind turbines, hydroelectricity plants or solar farms. There is also a connection to the hydrogen network, the adapted natural gas network. This network is actually used in both ways: when there's an over-production of hydrogen in the neighbourhood, city, village or rural area, the hydrogen is pumped to a large-scale hydrogen storage complex. There, the hydrogen can be stored – for instance in compressed form in salt caverns – liquified, or converted into ammonia and stored in tanks. The water distribution network essentially constitutes a back-up network or water reserve, because most water is made from rainwater.



Sustainable city area in the future.

4.1 From electricity to hydrogen

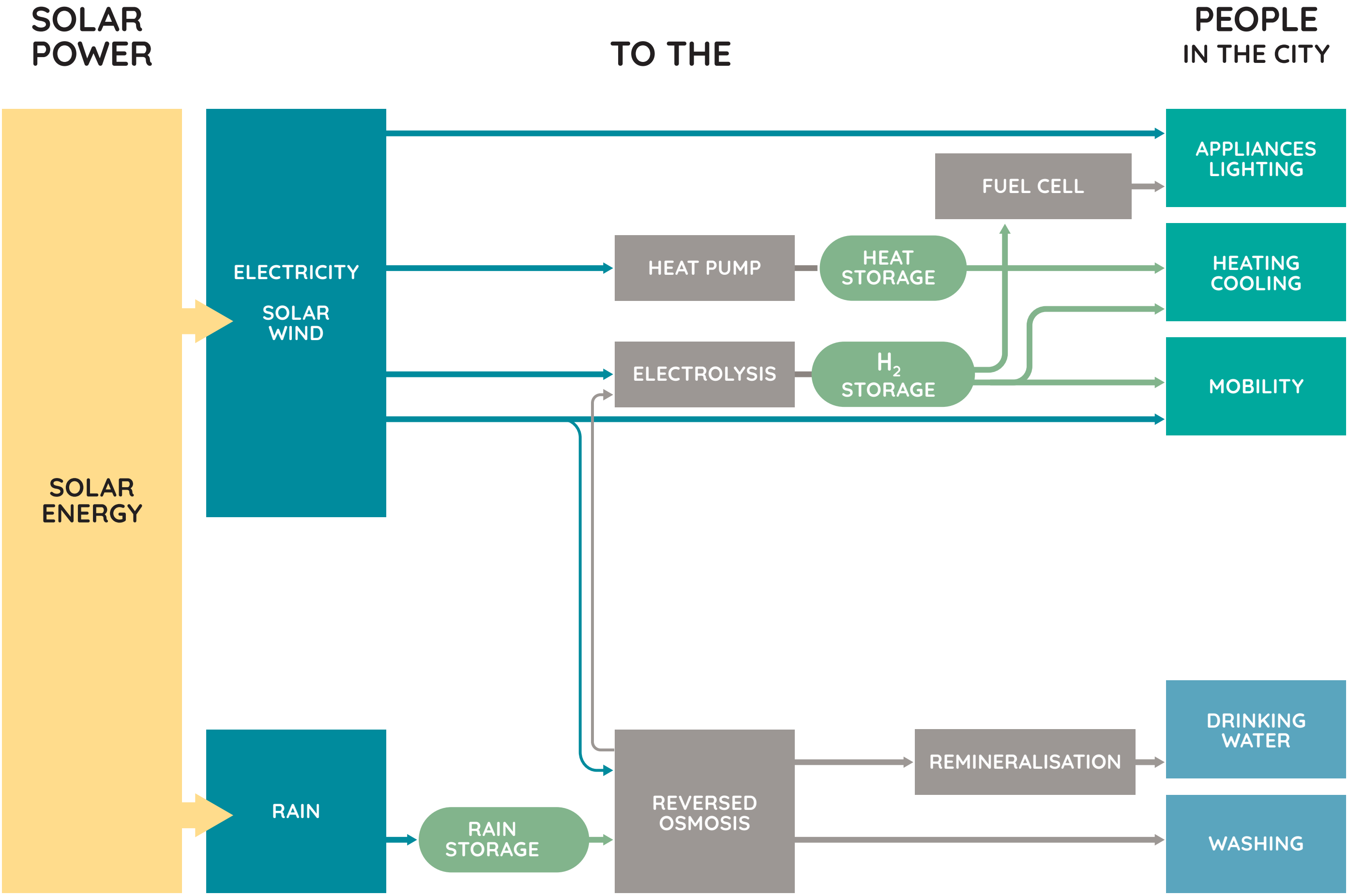
We will produce electricity in our cities and villages using solar cells, which we set up everywhere and integrate into everything. Solar panels on walls and roofs, solar cells integrated into roof tiles, windows, bridges, roads, benches and lighting, or solar-cell paint on our walls, window frames and doors.

In 2017, the surplus solar panel electricity of a neighbourhood, city or village is fed into the electricity grid. Given the moderate penetration of solar panels, the surplus electricity can always be used elsewhere.

But in the future, when every house is equipped with solar panels, there will be a huge surplus of summer electricity production everywhere: in every neighbourhood and city, in every village and also in the countryside. Of course, at first we'll use batteries to store the electricity for use at night. Those batteries will absorb part of the surplus, but far from all of it.

We store solar-panel electricity in batteries for day-night storage, and convert it into hydrogen for summer-winter storage.

This summer electricity will therefore have to be absorbed somewhere in the system. One obvious option is to convert it into hydrogen, which is after all much easier to store than electricity. We can do this with electrolysers, but where should we set them up? Do we decentralise them, placing them in the neighbourhood, next to the large parking garage, as described above? Or do we take a more regional or centralised approach? In the first case, that is, a decentralised location in the neighbourhood, the electricity network does not need to be adapted, reinforced or even made two-way. We solve the overproduction problem in a decentralised manner, and actually use the hydrogen network – i.e., the adapted natural gas network – for the transport of the surplus solar power; of course, only after as much of the hydrogen as possible has first been used to fill up our vehicles. In any case, a good economic system analysis will provide an answer to whether a decentralised or centralised location of the electrolyser is most sensible. Regardless, it is clear that a decentralised solution is clearly a robust solution.


SOLAR POWER
TO THE
PEOPLE
IN THE CITY
SOLAR ENERGY
ELECTRICITY
SOLAR
WIND
RAIN
APPLIANCES
LIGHTING
FUEL CELL
HEAT PUMP
HEAT STORAGE
HEATING
COOLING
ELECTROLYSIS
H2 STORAGE
MOBILITY
DRINKING WATER
REMINERALISATION
REVERSED OSMOSIS
RAIN STORAGE
WASHING

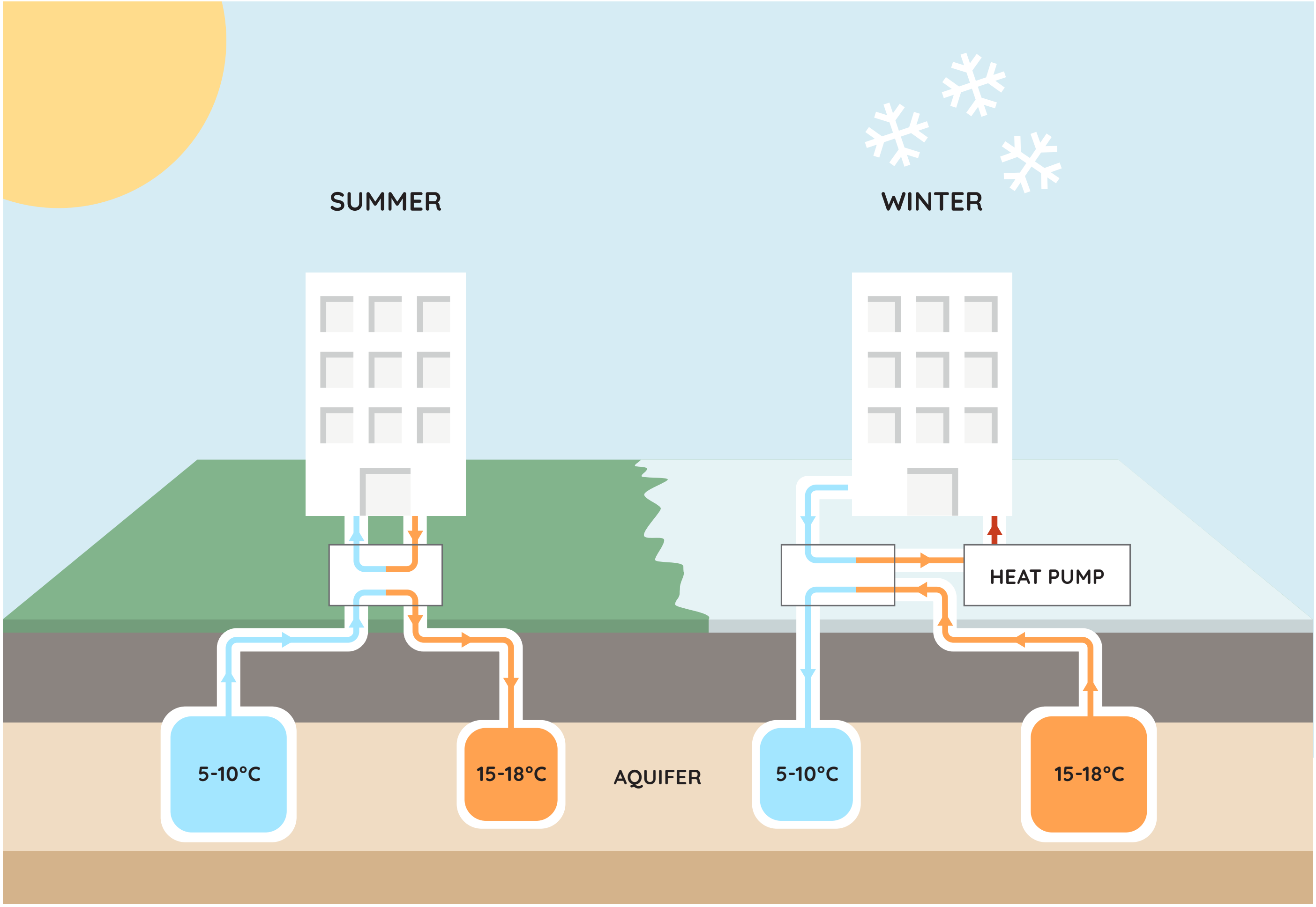
4.2 From electricity to heat

In 2017, when energy supply is not yet fully sustainable, there are two different possible heating systems for areas where a heat network is an option. The first possibility is a large-scale heat network, which distributes the heat at a temperature of 70 to 90 degrees Celsius. Such city heating systems have existed in several cities for a few decades. As a heat source they use the residual heat of fossil power plants or of waste incineration plants, but this is not renewable energy. These large-scale heat distribution systems can also be fed by a geothermal source, which means that the heat is of course renewable.

With a heat pump and solar power, we can produce heat at 40 to 60 degrees Celsius in the summer, store it in the subsurface and then use it in the winter.

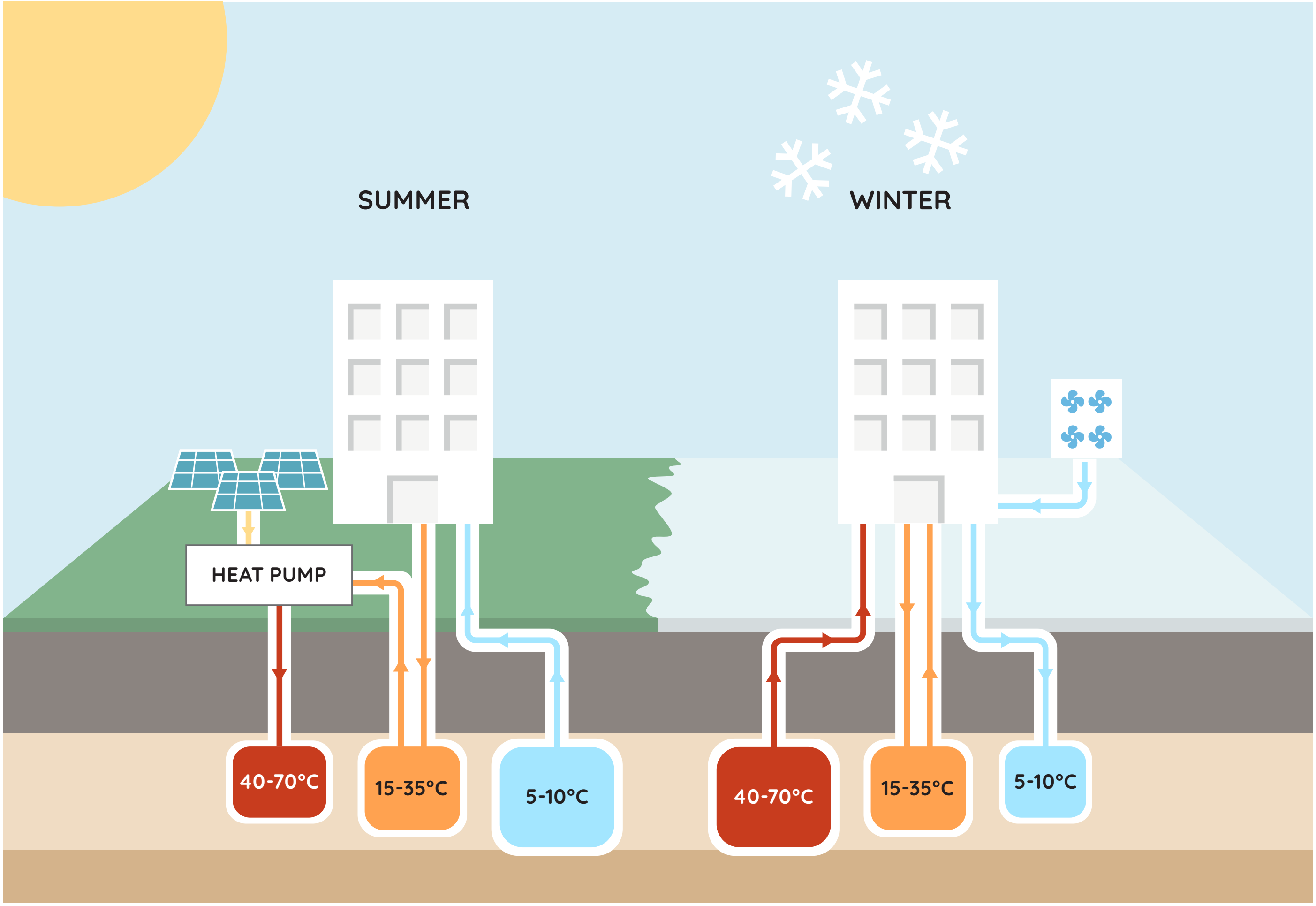
The second possibility involves an ATES (aquifer thermal energy storage) system. The system stores summer heat in the subsurface in a well at a temperature of 15 to 20 degrees Celsius, while in the winter the cold is stored in a second well at a temperature of 5 to 10 degrees Celsius. In the summer we can now directly cool buildings or homes from the cold well. But in the winter we can't directly heat buildings or houses from the warm well because it is not hot enough. To achieve a desired temperature of about 30 to 40 degrees Celsius in the winter, the building or house needs to have a heat pump to raise the temperature of the water pumped up from the well. In the winter the pump consumes electricity. But in a sustainable energy system, with solar panels on every roof, we now in fact produce far too little electricity in the winter. Moreover, the connected load of all those heat pumps means that the electricity grid's capacity in the area certainly needs to be doubled.

This is why, in a fully sustainable energy system, it is of interest to study whether we can actually produce this heat in the summer using a large central heat pump, instead of doing it in the winter. We can then store this heat, at a temperature of 40 to 60 degrees Celsius, in a subsurface aquifer in the summer. In the winter we can then pump it up from the aquifer into the heat network, which directly heats the building or home. We can also easily cool the buildings in the summer by storing the cold in the winter in a cold well in the subsurface. Now we have three sources in the subsurface: a cold well at 5 to 10 degrees Celsius, a



Low-temperature heat storage in the subsurface.

hot well at 40 to 60 degrees Celsius, and a balancing well at 15 to 35 degrees Celsius [39]. This means that heat pumps would not be needed in the homes and buildings, no electricity would be consumed during shortage periods in the winter and, above all, there would be no need to reinforce the electricity grid.



High-temperature heat storage in the subsurface.

An example of a home in the Netherlands

Let's look in some detail at the example of a Dutch home, which on average houses 2.2 people. The roof of the house covers 60 square meters (m^2), half of which is suitable for solar panels. In the Netherlands these panels produce about 5,400 kWh per year. With these solar panels we therefore produce more than the electricity needed to power a heat pump for our heating and hot tap water, as well as for the home's electricity consumption. Average rainfall in the Netherlands exceeds 800 millimetres per year, which means that a 60 m^2 roof annually receives about 50 m^3 of rainwater, some of which naturally evaporates. Each of us consumes about 120 litres of water per day, which adds up to 96 m^3 per year. In other words, we're not quite there with rainwater alone. But we could certainly be a lot more economical with our water – through high-efficiency toilets and recycling showers for instance.

It should be possible therefore, for us to harvest enough sun and rain with our homes to satisfy our energy and water needs. The problem is the storage of this energy and water: a problem that is difficult to solve at the level of the home.

4.3 From electricity and rain to water

In 2017, drinking water is usually produced on a large scale by pumping water from the ground or from surface water. The water is then treated to produce potable water which is transported and distributed through a network to consumers. Coastal countries with insufficient surface water and groundwater resources, pump their water from the sea. The seawater is evaporated in large energy and water installations to produce freshwater that is distributed through a water network. In addition, many hotels and large buildings in these countries have reverse osmosis installations to make their own drinking water.

In 2017 in city areas, rainwater largely falls on our roofs and is then discharged into the sewer system, or finds another course to reach surface water. This is a shame, because rainwater represents a significant source of clean water. We'd therefore like to harvest rainwater with our solar-panelled roofs or at our solar panel farms. We could then store the water in a subsurface aquifer, and recover it when we need it. We can use it directly to water our plants, but we can also, through reverse osmosis, make demiwater from it and, then, using electricity, make hydrogen. We could also make drinking water from the demiwater by adding minerals and salts to it.

Houses in many parts of the world receive enough solar radiation and rain to meet their own electricity and drinking water needs.

The sun provides most places in the world with sufficient energy. At the same time, enough rain falls to meet our own energy needs for heating, cooling and electricity, but also for drinking water.

4.4 From hydrogen to electricity for back-up

We store any surplus electricity in batteries or convert it into hydrogen. But solar panels will, of course, sometimes fail to produce sufficient electricity – at night, but also during the day in the winter. We can naturally make up for the electricity shortfall by drawing it from the grid. But, in cities and villages, we can also produce the extra electricity ourselves using fuel cells which, with an efficiency of 60 to 70%, can convert hydrogen into electricity and demiwater using oxygen from the air.

Hydrogen fuel-cell electric cars can produce the electricity needed when there's not enough solar electricity.

In principle, these fuel cells already exist, because they're in our hydrogen fuel-cell electric cars. If these cars are parked, which is the case 90% of the time, then we could use their fuel cells to produce electricity when we don't have enough. Each fuel cell in a car has the capacity of about 100 kW, enough in principle to supply one hundred homes with electricity. We therefore only need a fraction of all the cars to produce the electricity we need whenever the solar panels don't produce enough [28].

Producing electricity with those cars that are parked in a parking garage, gives us a fantastic back-up power plant. The hydrogen can be fed into this 'plant' through the hydrogen network. But the cars don't only produce electricity, they also produce demiwater which, following remineralisation, can be fed into the water distribution network. And if you really want a truly robust electricity system, then we can simply set up a stationary fuel cell, just in case [40].

5 SOLAR POWER TO THE PEOPLE IN NIEUWEGEIN-UTRECHT

We can paint an attractive picture of the future, but the question remains: How do we get from here to there? How do you transition from today's fossil energy system to a sustainable energy system? How will our technology and our needs evolve? And how can we give shape to the desired or wished-for development toward a sustainable energy and water provision? In Nieuwegein-Utrecht we will attempt to create a first phase of a sustainable *Power to the People* energy and water system.

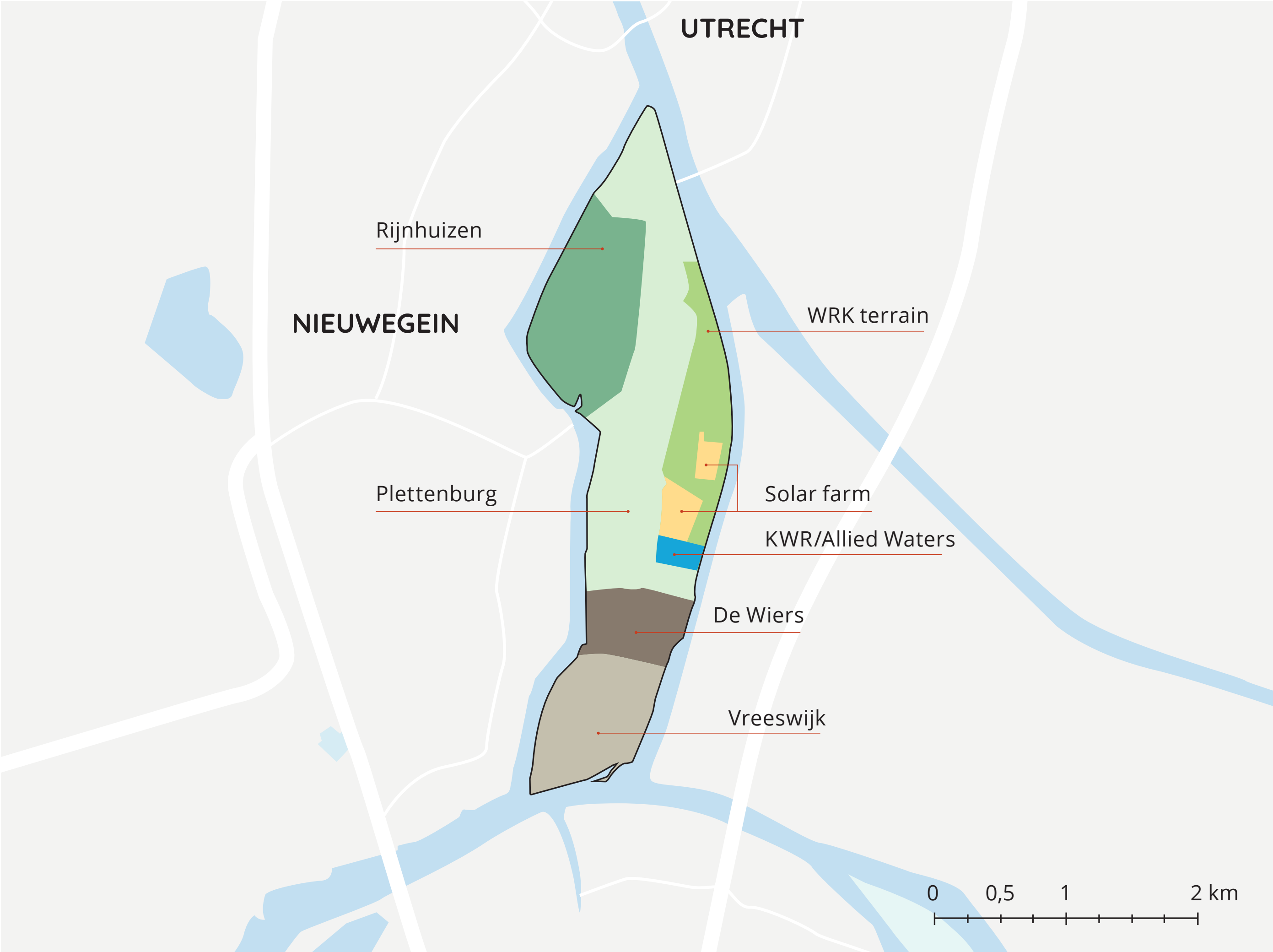
5.1 What does our Nieuwegein-Utrecht area look like?

The area is bounded by the Lek river on its southern side and by two canals: the Lek canal on its eastern side and the Merwede canal on its western side. The historic village of Vreeswijk is situated on the Lek river in the area's southern side and, above it, the small De Wiers residential district. Above De Wiers is the Plettenburg industrial area, where, along the Lek canal, the Amsterdam and North-Holland drinking water companies are situated, as is the new, attractive and sustainable building of KWR Watercycle Research Institute. Between the N408 and the Merwede canal, in north-western Plettenburg, is Rijnhuizen, with its old historic Waterline fort.

A new housing development is being built in the Rijnhuizen area, where office space is also being converted into homes. Altogether, this involves a total of about nine hundred new homes. The Plettenburg industrial area also contains a bus depot and various transport-sector training institutes. On their site, the drinking water companies draw surface water from the Lek canal. They pre-treat the water and then pump it, through large pipelines, to a dune area where it undergoes further purification. This water is ultimately destined to become drinking water to supply the city of Amsterdam. The Amsterdam drinking water company is also developing a couple of large solar farms on the site: a 3 megawatt-peak (MWp) farm is under construction, and its electricity will be used primarily for the pumps on the site; and a second farm, which will be built in 2018 and producing just under 9 MWp.

Nine hundred homes and an 8.6 megawatt-peak solar farm will be built in this area in Nieuwegein-Utrecht.

Naturally this solar farm's electricity can be fed into the public power grid, but this would require a reinforcement of the network connection. This



Where it's all going to happen in Utrecht-Nieuwegein.

prompted us to study how we could use this farm's electricity to realise a sustainable energy system for the area. **How can we bring this Nieuwegein-Utrecht Solar Power to the People?**

5.2 The Solar Power to the People system in Nieuwegein-Utrecht

The solar farm supplies electricity, but we need electricity for more than just lighting and powering our devices. We want to have a comfortable home, to drive here and there, take showers or enjoy a great meal. Moreover this solar farm produces a lot of electricity in the summer, but not much in the winter. This is why the solution is to convert part of the electricity into other energy carriers, which can fulfil other energy functions. Let's look at what we're going to do.

From electricity to heat

The neighbourhood of Rijnhuizen, where about nine hundred new homes are being built, is 2 kilometres away from the solar farm. The ambition is to build homes that are as sustainable as possible. This implies a sustainable heat supply. If we accomplish this with a classic aquifer thermal storage system, it would mean that each home would have its own heat pump, which would increase the heat extracted from the subsurface to the desired temperature. The heat pump would therefore consume electricity in the winter, when solar electricity production is low.

There is a better way to do this. In the summer, when we actually have lots of solar electricity, we can use a heat pump to heat water to about 40-60 degrees Celsius. We can then store this water in an aquifer and then use it in the winter to heat the homes. The novelty involved is not only the production of heat with solar electricity, but the storage of this heat in the subsurface. Normally, heat is stored in the subsurface at temperatures that don't exceed 20 degrees Celsius, while we want to do it at a temperature of around 40-60 degrees Celsius. The optimal termperature level is being investigated.

The solar panels on the roofs and the solar farm supply electricity and harvest rainwater. We can convert electricity into heat and hydrogen, and rainwater into demiwater.

The heat is transported to the homes through a heat network. All that the home needs to be heated is a heat exchanger; although a maybe little extra energy is needed to the heat the tapwater. This not only means that the homes don't need heat pumps, but also that the neighbourhood's electricity grid doesn't need to be extended to accommodate them.

From electricity and rain to hydrogen

We want to convert part of the solar farm's electricity into hydrogen using water electrolysis. Besides electricity we therefore also need water, indeed ultra-pure water, or demiwater. To this end, we will harvest rainwater with the solar panels. We'll then use a reverse osmosis installation to make demiwater from the rainwater.

At first, we will use the hydrogen to run fuel-cell vehicles. Actually, we'd like to have it run the hydrogen fuel-cell electric cars of the new housing development's residents. But because there is as yet no nationwide hydrogen fuelling station network – and thus no sales of private fuel-cell cars – we will in practice let other cars and vehicles use the fuel. These would be the fuel-cell cars of a number of companies in the vicinity, taxis and the municipality's fuel-cell vehicles, like street sweepers and the landscape service's carts. Besides producing hydrogen, we'll also need to set up a hydrogen fuelling station in the vicinity.

From rain and electricity to demiwater

To produce hydrogen we need demiwater, which we will make from the rainwater harvested by the solar panels. But the volume of rainwater harvested by the panels is many times greater than what we need for hydrogen production. So, what else can we do with this demiwater?

In the new housing development, besides the ordinary drinking water pipe, we're going to connect a second, demiwater pipe to the homes. This demiwater will be used in the dishwasher and washing machine, among others. By using this very pure water in these machines, we will be able to reduce the consumption of detergents. This has an impact on costs, of course, but it is also good for the environment.

By capturing the rainwater in the solar farm, but also on the roofs of the new housing development homes, we avoid discharging this water into the sewers. This is beneficial because it allows for the use of smaller-diameter sewer pipes, but it also means that the wastewater treatment plant receives much more concentrated influent, which facilitates the extraction of biogas and residuals. Furthermore, less energy is needed to treat the wastewater, simply because it no longer contains the rainwater.

.A smart DC electricity network

Solar panels produce electricity, but this electricity is in the form of direct current, or DC. An inverter is therefore needed to convert it into alternating current, or AC. The electricity grid delivers alternating current, which is what all our devices used in the past; today almost all of them work on direct current, so they are equipped with an inverter that makes this direct current from the alternating current.

Our system includes a reverse osmosis installation, heat pump and electrolyzer, which all run on direct current. We will therefore install a direct current network between the solar farm and this installation, so as to avoid the inverter losses, from DC to AC and back to DC.

We would also like to install a direct current network in the new housing development as well, to begin with only in its public space. The LED lighting system will be connected to it, as will the charging stations for battery electric cars. After all, LEDs and batteries both run on direct current. The solar panels on the homes can also be directly connected to such a direct current network. In the future, a direct current network in the home would also be more practical and efficient.

5.3 Demand and supply of energy and water in Nieuwegein-Utrecht

What can we now do with the amount of electricity that the solar farm produces? And how can we ensure that we can satisfy, at every moment, the demand for electricity, heat, hydrogen and demiwater?

The supply of electricity and the demand for energy for electricity, heat, demiwater and hydrogen are balanced on an annual basis, but not at every moment.

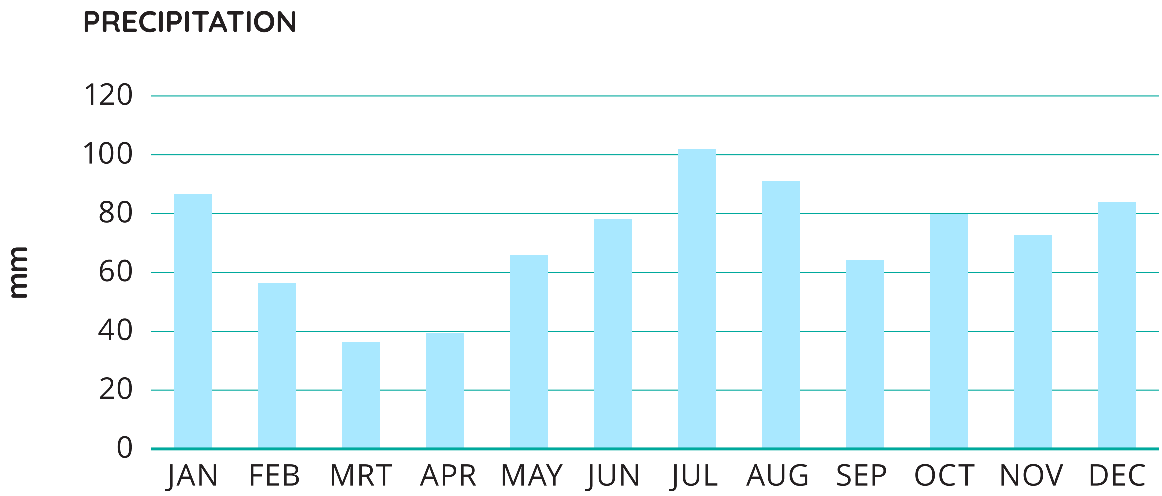
The supply of sun and rain

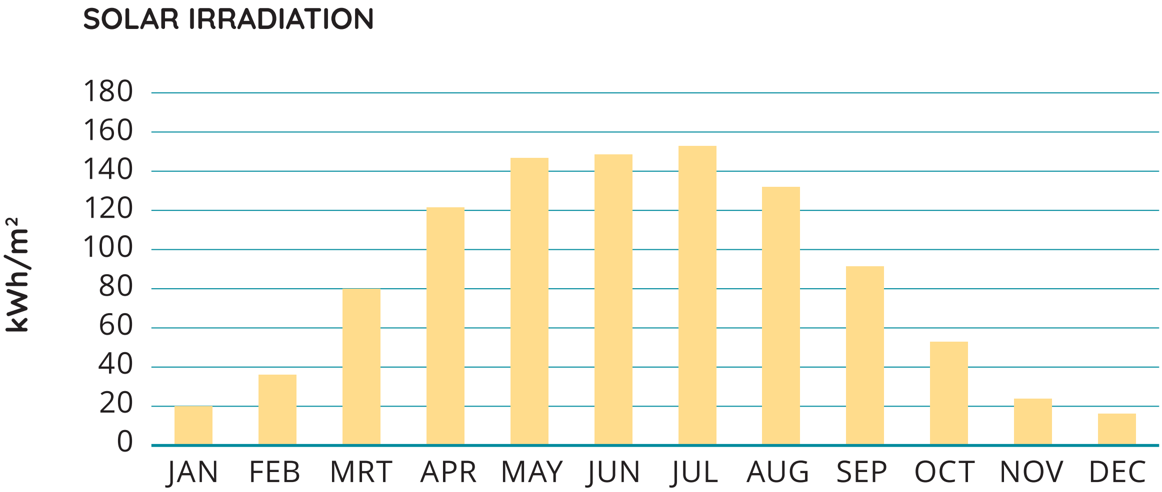
The planned solar farm will have a peak capacity of 8.6 MWp. Given its east-west orientation, we estimate that the farm will produce about 7 million kWh per year. The solar panels also function as rainwater captors and should harvest about 40,000 cubic meters (m^3) per year. This rainwater will be stored in a subsurface aquifer.

Solar panels will also be installed on the homes in the new housing development, and they too will harvest rainwater. The solar panels should produce enough electricity to achieve a balance of supply and demand over the course of the year. If we assume an annual average consumption of 3,300 kWh per year for a home, then an output of 4 kWp from the solar panels on each home would suffice. In total, the neighbourhood will have an established solar panel capacity of 3.6 MWp. The rainwater that falls on the roofs will be harvested and transported by pipe to the solar farm area. We assume that each home will have a rain catchment surface of about 30 square meters (m^2). This means that all the homes together will harvest roughly 20,000 m^3 of rainwater. We will store this water underground, together with that from the solar panels.

The demand for electricity, heat, hydrogen and demiwater

Our fundamental aim is to supply the new housing development as a whole with sustainable energy. These homes will produce their own electricity from the solar panels on their roofs. However, although this electricity's supply and demand will balance over the course of the year, it won't at every moment of the year. This is why we want to use the solar farm's electricity to supply heat for the homes, as well as fuel,





Sun and rain in Nieuwegein-Utrecht (2011-2016 average) [41].

in this case hydrogen, for the cars. This is how that system will work:

- The electricity consumption of a new home in this area is estimated at about 3,300 kWh per year [42]. So, in total, the homes will consume 900*3,300 = 3 million kWh of electricity.

- We pump up water from a cold source at a temperature of about 25 degrees Celsius. Using a heat pump powered by the solar farm's electricity, we heat this water up to 40-60 degrees Celsius. We then store the water in the hot source underground. This heat pump should be able to achieve a coefficient of performance (COP) of 3. This means that with 1kWh = 3.6 MJ of electricity the pump will produce 10.8 MJ (3*3.6 MJ) of heat. The heat demand of these well-insulated new homes is estimated at 12 gigajoules (GJ) for heating and 9 GJ for hot tapwater: a total of 21 GJ of heat. The nine hundred homes will thus consume a total of 19,000 GJ of heat. In round figures, this will require 1.75 million kWh of electricity.

- In average terms, practically every household in the Netherlands has a car (0.93 cars per household). We assume that half of the households will have a hydrogen fuel-cell electric car and the other half a battery electric car. A car in the Netherlands is driven an average of about 13,000 kilometres per year [43]. A hydrogen fuel-cell car consumes 1 kilo of hydrogen per 100 kilometres. This means that a household will consume 130 kilogrammes of hydrogen. In total, 450 households will therefore consume 58,500 kilogrammes of hydrogen. If we assume that we currently need about 55 kWh to produce 1 kilogramme of hydrogen, then we'll need a total of 325 million kWh. In addition, we need about 9 litres of demiwater to produce a kilo of hydrogen. That adds up to a total of 500 m^3 of demiwater, which we will make from rainwater using reverse osmosis. The electricity consumption per m^3 of demiwater is about 1 kWh; the total needs would therefore be 500 kWh: a negligible amount. We will also lose some water during the conversion from rainwater to demiwater, but our total rainwater needs won't exceed 1,000 m^3. This is only a small fraction of the rainwater we will harvest. The battery electric car is also driven 13,000 km per year. With 1 kWh one can drive about 5 kilometres [44], which adds up to 2,600 kWh per car per year. In total therefore 450*2,600 = 1.17 million kWh will be used by these cars.

- Apart from the normal drinking water distribution network, a demiwater network will be installed in the neighbourhood for the water use of washing machines, dishwashers, and others. The per capita daily consumption of water is 120 litres, of which 50 litres for washing machines and dishwashers and others [45]. Homes in the Netherlands have an average of 2.2 people, so that the total daily consumption of water in these new homes will be 2.2*50*365 = 40,150 litres per year, or about 40 m³ per year. The nine hundred homes will thus consume a total of 36,000 m³ of demiwater. To make demiwater from rainwater using reverse osmosis, we need 36,000 kWh. We will of course lose some water; let's assume this loss to be about 10%. This means that we will need a total of 40,000 m³ of rainwater. We also need to supply an additional 70 litres of drinking water per person per day. In total, for all the homes, this amounts to 2.2*70*365*900 = 50,000 m³ (rounded) drinking water per year. This will be supplied externally by the drinking water company.

- In any neighbourhood, besides energy for heating and tapwater, electricity for all in-house devices and lighting and energy for mobility, electricity is also used in the public spaces. Public lighting consumes about 65 kWh per household per year [46], [47]. The pumps in the heat network consume about 50 kWh per household per year [48], while the sewer system and rainwater network together consume an average of 0.5 kWh/m³, which adds up to about 40 kWh per household per year [49]. Broadly, these uses amount to a total of 200 kWh per home, that is, 180,000 kWh for this new housing development's nine hundred homes.

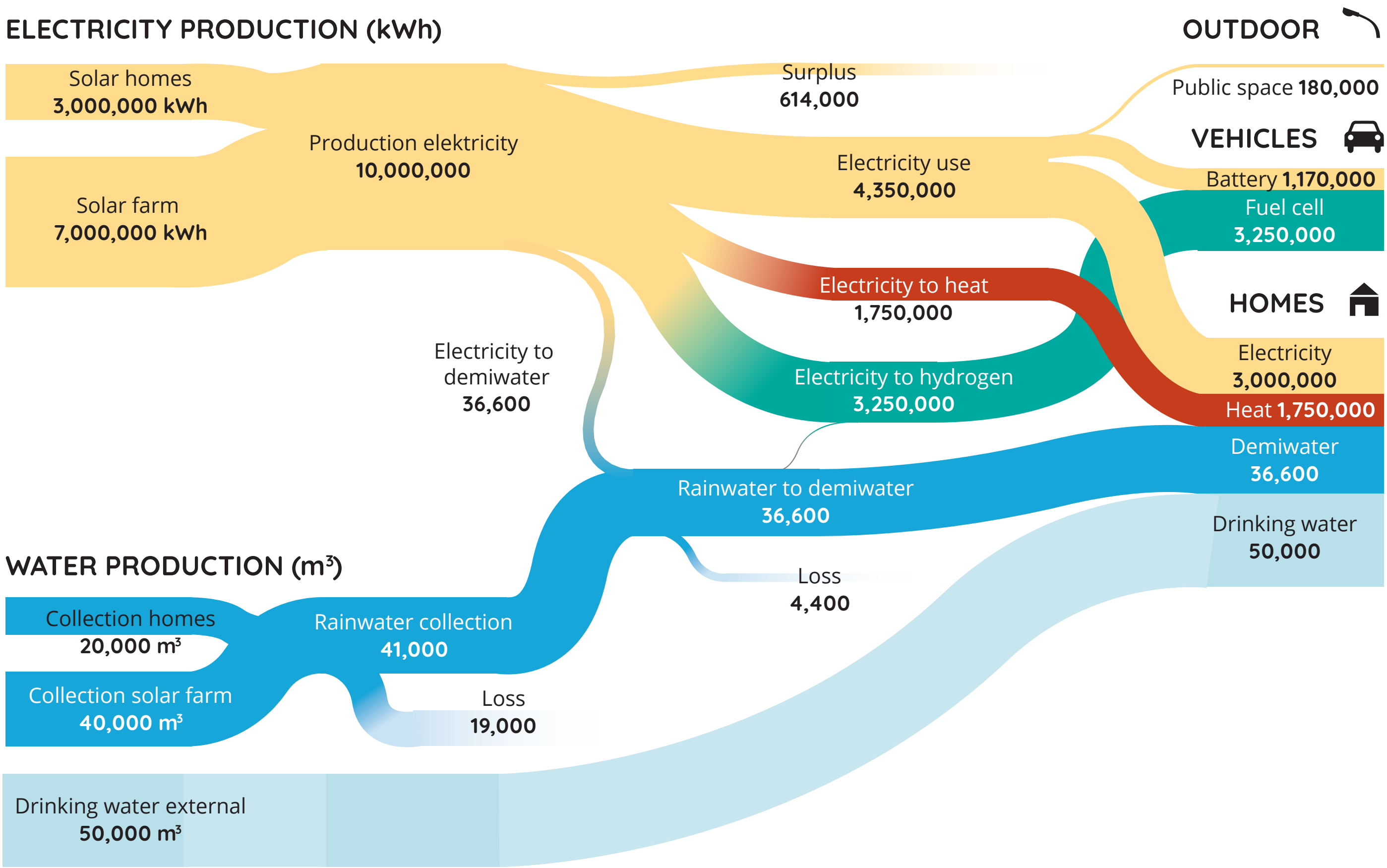
The annual energy budget and energy balancing

If we now place the energy budget of this new housing development with nine hundred homes in the context of an 8.6 MWp solar farm, we see the following. A total of 10 million kWh of solar electricity will be produced (7 million by the solar farm, 3 million in the neighbourhood), while electricity consumption will be 9.4 million kWh. In other words, such a system including homes and a solar farm can achieve a balanced annual energy budget. But this does mean that one needs a solar farm that is approximately 2.5 times larger than the 'solar farm' on top of the homes.

The car is the biggest energy consumer, followed by the in-house electricity consumption and then by its heat consumption. Compared to the heat consumption, the electricity consumption is almost two times larger, and the energy consumption for cars almost three times larger.

Although the electricity produced and consumed are in balance on a yearly basis, this is not the case at every moment of the year. In the summer there is an electricity surplus and in the winter a shortage. Similarly, at night no electricity is produced, while during the day even too much can be produced. This imbalance is resolved in this system as follows.

- We will convert part of the surplus electricity produced in the summer into heat. We can store this heat underground, for use in the winter. In this way, heat production and heat demand can be brought into balance at every moment of the year.



Solar Power to the People in Nieuwegein-Utrecht.

- We can convert part of the electricity surplus into hydrogen for direct use as transport fuel. This would of course mean that a small hydrogen buffer would be required at the fuelling station. But this does not mean that we will have produced enough hydrogen for all the hydrogen fuelling needs – particularly for the winter hydrogen needs.

- The nocturnal shortages in the summer months can be effectively offset by the batteries of the electric cars. Even an ownership rate of one battery electric car for every two houses should make this possible.

- Then we still find ourselves with a shortage of electricity and hydrogen during the winter. Let's start with the hydrogen. At times when the grid electricity is cheap – that is, when the wind blows hard – we can buy electricity and use the electrolyser to make the hydrogen we need to fill up our cars. In this manner we can always absorb the electricity grid's surpluses.

- We can also resolve the hydrogen shortages in other ways. We can make use of tube-trailers which can transport the hydrogen by road. If there is a hydrogen network – i.e., an adapted natural gas network – connected to the hydrogen fuelling station, we can use it whenever we need to offset a shortage. This hydrogen would be produced cheaply somewhere in the world and then taken elsewhere – in this case the Netherlands – by ship or hydrogen pipeline transport.
- We can also solve the electricity winter shortage thanks to the electricity grid. When the wind blows hard, there is no problem, because we can draw electricity directly from the grid. But when it isn't windy, then the electricity has to be taken from storage, for example, from pumped-up water. Or by converting hydrogen into electricity in power plants or fuel cells. After all, hydrogen can always be stored in very large quantities.

The annual water budget and water balancing in Nieuwegein-Utrecht

If we now place the water budget of this new housing development with nine hundred homes in the context of an 8.6 MWp solar farm, we see the following.

The amount of rainwater is more than enough to satisfy the demand for demiwater for hydrogen production, and to feed a neighbourhood demiwater network to supply water for the dishwashers, washing machines and others. The demiwater used for hydrogen production is only a fraction of the total consumption. Lots of rainwater is left over for other water uses, irrigation or drinking water production.

Besides demiwater, ordinary drinking water is also needed for drinking, cooking and showering. This drinking water will in this case be supplied by external sources. The rainwater could supply a significant fraction of this drinking water, but could in no way supply all of it.

The buffering of water above-ground would require enormous, expensive tanks. The subsurface storage of rainwater in aquifers is therefore a better and cheaper option, and sufficient rainwater – and thus demiwater – will be available any time of the year.

There is more than enough rainwater to satisfy the demand for demiwater for hydrogen production and in-house use for the i.e. dishwashers and washing machines. By storing the rainwater underground, enough demiwater will be available at all times.

Solar Power to the People will start in Nieuwegein-Utrecht

We are carrying out this unique project in Nieuwegein-Utrecht, in which we will bring solar power to the people. We will produce solar electricity through solar cells on the roofs of the homes and in a solar farm. Part of the summer solar electricity will be converted into heat with a heat pump, and into hydrogen with an electrolyzer. We will store the heat in a subsurface aquifer, at 40 to 60 degrees Celsius, for use in the winter. We will use the hydrogen as fuel in hydrogen fuel-cell electric cars and other vehicles for mobility. Besides electricity, the production of hydrogen also requires demiwater, which is ultra-pure water. For this, we will harvest rainwater with the solar panels by means of catchment gutters below the panels. We will also buffer this rain underground and use it to make demiwater through reverse osmosis. But the rain will provide us with much more demiwater than we will need for hydrogen production. This is why we will connect the homes to a demiwater network for them to use the demiwater for exemple in their washing machines and dishwashers, which will moreover reduce their detergent use.

With this system we have taken a first important step toward a fully sustainable energy and water system. To be sure, further development will be needed to enable the buffering of hydrogen and to produce sustainable electricity at times when the sun does not provide enough. We also have to develop energy and water systems of this kind for existing buildings and homes. But in Nieuwegein-Utrecht we are now taking the first steps in bringing *Solar Power to the People*!

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