OUR CAR AS POWER PLANT

Ad van Wijk & Leendert Verhoef

Authors: Ad van Wijk & Leendert Verhoef
Contributions: Chris Hellinga, Freerk Bisschop, Charlotte de Jong, Kumayl Sarwar
Illustration: Snoei Vormgeving, Schwandt Infographics, TU Delft a.o.
Design/layout: Made in May

www.thegreenvillage.org
twitter: @thegrnvillage #grnv
www.linkedin.com/company/thegreenvillage
www.facebook.com/thegrnvillage
www.youtube.com/thegrnvillage

ISBN 978-1-61499-376-6 (print)
ISBN 978-1-61499-377-3 (online)
doi 10.3233/978-1-61499-377-3-i

Published by IOS Press under the imprint Delft University Press

Publisher
IOS Press BV
Nieuwe Hemweg 6b
1013 BG Amsterdam
The Netherlands
tel: +31-20-688 3355
fax: +31-20-687 0019
email: info@iospress.nl
www.iospress.nl

PRINTED IN THE NETHERLANDS

An initiative of The Green Village and TU Delft University of Technology

www.thegreenvillage.org www.tudelft.nl

OUR CAR AS POWER PLANT

AD VAN WIJK & LEENDERT VERHOEF

TABLE OF CONTENTS

THE VISION

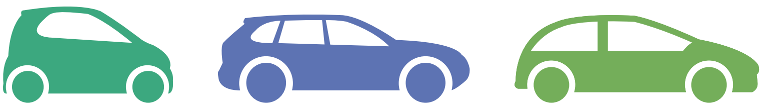
Fuel cell cars: efficient and clean transportation AND clean and efficient production of electricity, heat and water.

Fuel cell cars can provide more efficient and cleaner transportation. However, we use our cars for transportation only 5% of the time. So when parked, the fuel cell in the car can produce electricity from hydrogen. Cleaner and more efficiently than the current electricity system – with useful 'waste' products heat and fresh water. The produced electricity, heat and fresh water can be fed into the respective grids or be used directly in our house, office or the school of our kids. The required hydrogen can be produced from gas (natural gas, biogas) or electricity (hydro, wind, solar, etc.). In the end these fuel cell cars can replace all power plants worldwide. As a result, the 'car as power plant' can create an integrated, efficient, reliable, flexible, clean, smart and personalized transport-, energy- and water system.

REASONS TO BELIEVE

The change towards a sustainable transport and energy system is ongoing and inevitable. Our cars become more efficient, clean and safe. A major trend is electric driving. We see this trend in electric bikes, fork lifts, scooters and the car also. Electric cars with battery packs to store electricity for driving. Such an electric car has two main limitations. Driving distance is limited, between 100 and 300 km. And the charging time of batteries is too long. About 8 hours for normal charging and above 10 minutes for fast charging, which is longer than the 1 to 2 minutes to fuel your tank now. Of course for many of our transport needs this is not a problem, but to drive to your work, going on holidays and visiting clients or friends, it is not that comfortable.

For that reason hybrid cars are entering the market. Electric driving, batteries and an electricity-producing engine using gasoline, diesel or ethanol. But the energy efficiency of the present car engines is not very good, about 25 to 40%. Therefore many car manufacturers are developing the fuel cell car. A PEM fuel cell (Polymer Electrolyte Membrane or Proton Exchange Membrane) that can produce electricity using hydrogen. The efficiency to produce electricity with a PEM fuel cell from hydrogen is about 60%. Of course we have to produce hydrogen, for example by reforming gas into hydrogen. We can produce hydrogen from gas with an efficiency of 70-80%. So, with a fuel cell we can produce electricity from gas with an efficiency of about 45%. This is a higher efficiency than the system efficiency of our electricity production, which is below 40%.



We use our cars only for a very limited time. If we drive 20,000 km per year with an average speed of 50 km per hour, the time we use our cars is 400 hours – less than 5% of the time. Our car, a major asset for us all, that we use less than 5% of the time? So what else can we do with our car; when it is parked? Once we build fuel cells into cars it is possible to produce electricity, with a high efficiency. That is interesting: the fuel cell in our car has a capacity of 100 kW, which is more than sufficient to produce all the electricity for about 100 European houses. So our future fuel cell cars can produce all the electricity that we need – with a better energy efficiency than the present power plants.

The idea that the fuel cell car is not only used for transportation but also for production of electricity, heat and water, is a paradigm-changing concept. It will certainly change our energy-, water- and transport system dramatically. Let us explore this concept.

OUR CAR AS POWER PLANT **REASONS TO BELIEVE**

EFFICIENCY	• Fuel cell in the car has an efficiency of 60% to convert hydrogen into electricity • Hydrogen production from gas or electricity has an efficiency of about 70-80%
BETTER	• Car engines at present have an efficiency of 25-40% • Power system efficiency is below 40%
TIME	• Cars are in use for transportation less than 5% of the time • Over 90% of time, cars are parked at home, at work, in a car park, on the street
AVAILABLE	• Power plants are used between 5% and 90% of the time
CAPACITY	• Worldwide 1 billion cars on the road; with an average engine capacity of 50 kW this represents a power capacity of 50.000 GW
ABUNDANT	• 80 million cars were sold in 2011; with an average engine capacity of 100 kW this represents a power capacity of 8.000 GW • Worldwide the electricity production capacity of all power plants is about 5.000 GW

OUR CARS

Our cars are important for many of us. It gives us the possibility to go to our work, to bring our kids to school, to visit our friends, go shopping or on holidays. It gives us freedom of mobility. Over the past 100 years our car has developed tremendously. Comfort, safety and speed have increased considerably. But what about other technology aspects? And what is the energy efficiency to go by car from A to B? How many vehicles and cars do we have on the road? And what will the future bring?

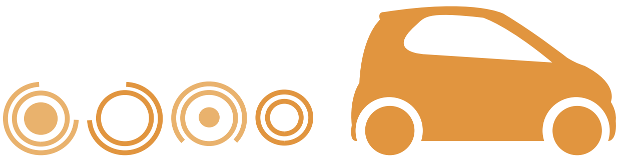
100 YEARS OF CAR DEVELOPMENT

Our modern cars have developed considerably over the past 100 years. The first automobiles were produced by Karl Benz in 1888 in Germany. In the United States, brothers Charles and Frank Duryea founded the first American automobile manufacturing company in 1893. Mass production actually started at the beginning of the twentieth century when the Olds Motor Vehicle Company (known as Oldsmobile) started production in 1902. Many others followed, including Henry Ford. He founded his company in 1903, producing cars in the thousands per year.

Steam-, electricity- and petrol/gasoline-powered cars competed for decades, but in the 1910s the internal combustion engines on petrol/gasoline achieved dominance. Henry Ford became the icon of the automobile industry with his mission: building cars for everyone.

From 1908 to 1927 the Ford Model T was the most widely produced and available 4-seater car of the era. 15 million Ford Model T's were produced and sold in this period. T-Ford was proclaimed to be the most influential car of the 20th century in the international Car of the Century awards. The T-Ford had a four-cylinder engine, used a planetary transmission, and had a pedal-based control system. The T-Ford weighted about 550 kg. The engine was capable of running on gasoline, kerosene, or ethanol. The Model T was capable to produce 20 horse powers (15 kW), for a top speed of 64–72 km/h. According to Ford Motor Company, the Model T had a fuel economy on the order 11–18 liter/100 km [(1)].

Nowadays our cars do not look like the old T-Ford and of course we have made a lot of technological progress. But the technology basically is the same. In our present cars we still use a combustion engine, a planetary transmission and pedals to control the gas and brake system. And the combustion engine is still capable to run on gasoline and/or ethanol.



If we look at the specifications of a modern small family car we see the following. The combustion engine has a capacity of about 100 kW, a top speed of 200 km/h, a weight of about 1,150 kg and a fuel economy in the order of 6-7 liter/100 km. [2] And on top of this, comfort and safety levels have improved dramatically. Indeed impressive technological developments in a 100 year time frame. But if we compare the fuel economy we only do a factor 2 better in 100 years' time! Is that impressive?

TECHNOLOGY **UNCHANGED**

After 100 years

combustion engine, planetary transmission system, pedals for control (gas and brake) unchanged.

T-Ford
1913

- 550 **kg**
- 70 **km/h**
- 11-18 **L** / 100 **km**
- 15 **kW**

Small family car
Present

- 1150 **kg**
- 200 **km/h**
- 6-7 **L**/ 100 **km**
- 100 **kW**

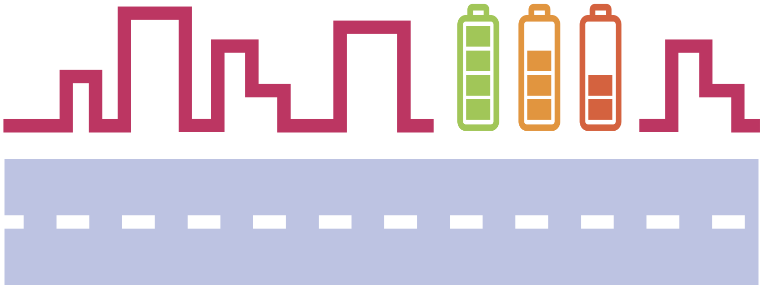
Fuel economy **only factor 2 better!**

ENERGY EFFICIENCY FROM A TO B BY CAR

This fuel economy is even more disappointing when we actually examine the energy efficiency to move ourselves from A to B, using a modern car. Let us try to estimate the various energy losses.

First of all we need a fuel, gasoline in our tank, but we have to produce this gasoline from oil. We drill in the ground and get oil out of it at several places around the world. We treat the oil and put it in a ship to bring the oil to a refinery. In the refinery we refine the oil in several products, one of them is gasoline. This gasoline is then transported by a truck to a fueling station where we put it in the tank of our car. There are losses, but overall the efficiency from well to tank is between 80-85%.

Now the gasoline is in our tank, our engine has to convert the gasoline in a rotating movement. A gasoline car engine has an efficiency of 25 to 40% when it comes to converting gasoline into a rotating motion. The remaining 60 to 75% of the fuel's energy is wasted in the form of heat, which has to be removed through cooling. Everyone is familiar with this phenomenon: the hood of a car will burn your hand – that's the energy loss of your engine.



And if that isn't bad enough: the car is not always moving, it stops for a traffic light, is stocked in a traffic jam or has to be parked. So we have standby- or idle losses, which are estimated to range between 15 to 20%.

And then the rotating motion has to be transmitted to the wheels by the gearbox, at an efficiency loss between 5 and 6%. Besides these transmission losses there is also energy consumption in our auxiliary equipment, such as cooling, lights, fans, heating/pumping and electronics. This consumes about 2 to 5% of the energy.

Our car is moving, but then we have resistance losses from the wind and the road and there are losses from braking and accelerating again. Another 10 to 15% energy loss.

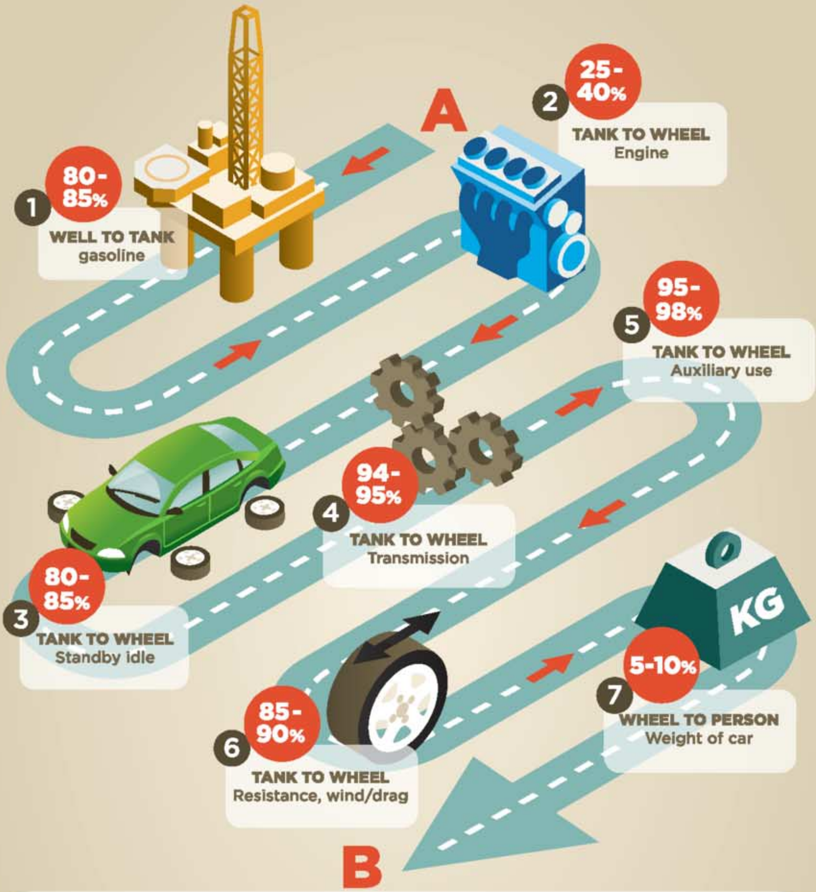
So the energy efficiency to move our car from A to B is between 12 and 24% [3,4,5,6]. Most efficiency calculations stop here, but if we were to continue and take into account the overall purpose of our cars, it becomes even worse. Let's face it, all we're trying to do with a car is move ourselves from A to B, a task for which we deploy a 1,000 to 2,000 kg car to transport about 100 kg of human being. So at the end we only have a lousy 1% (between 0.6 and 2.4%) energy efficiency to move ourselves from A to B in a car. How sad is that!

Can we do better? **Yes we can!**

OUR CAR AS POWER PLANT **ENERGY EFFICIENCY FROM A TO B BY CAR**

		ENERGY EFFICIENCY
WELL TO TANK	gasoline	80-85%
TANK TO WHEEL	engine	25-40%
	standby/idle	80-85%
	transmission	94-95%
	auxiliary use	95-98%
	resistance	85-90%
	Total tank to wheel	**15-28%**
WHEEL TO PERSON	Weight of car	5-10%
CALCULATION	Energy efficiency low	= 80% * 15% * 5% = 0.6%
CALCULATION	Energy efficiency high	= 85% * 28% * 10% = 2.4%
FROM A TO B	**Total**	**0.6-2.4%**

MOVING STOVES



Energy efficiency low 0.80*0.25*0.80*0.94*0.95*0.85*0.05 = **0.006**

Energy efficiency high 0.85*0.40*0.85*0.95*0.98*0.90*0.10 = **0.024**

FROM A TO B TOTAL **0.6-2.4%**

What this means:

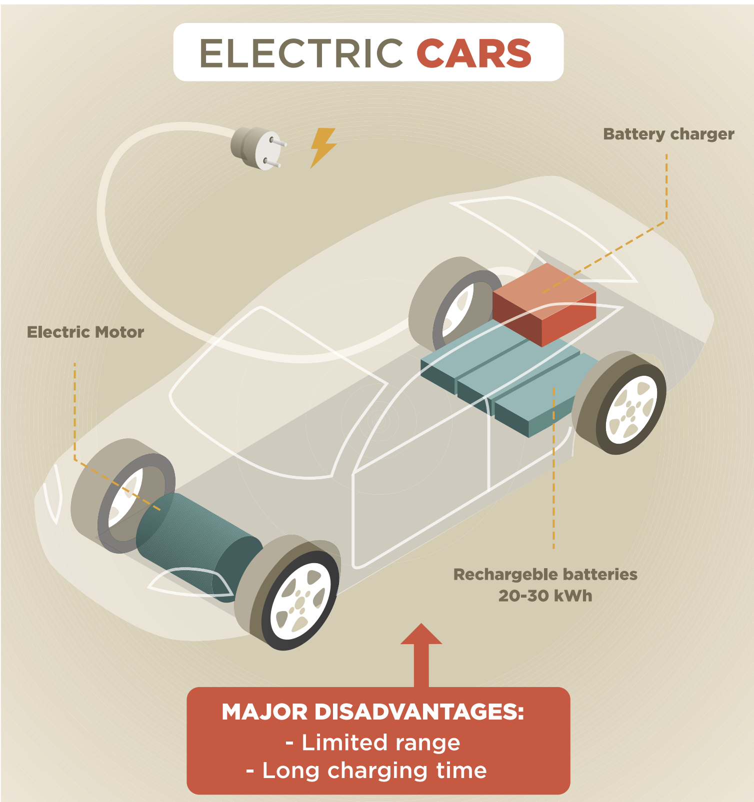
Our traditional car is a moving stove! From A to B more then 97% of the energy gets lost.

FUTURE DEVELOPMENTS IN TRANSPORTATION

The change to electric transport is evident. It causes no local air pollution and no noise. Therefore fork lifts, bikes, scooters or tourist boats are rapidly switching to electric. And now the focus is on our cars, cars with an electric engine and batteries to store the electricity. Indeed, we are now witnessing the introduction of the electric vehicle – so defined by the existence of an electric motor and a large battery pack, but with the remainder of the car largely unchanged – which is already giving us some efficiency improvements.

The electric motor runs at an efficiency of 95%, and charging and discharging the battery has an efficiency of 80%. Which, combined with an average power plant efficiency of 40%, means that the electric car engine has an overall energy efficiency of 30%. About the same as an efficient combustion engine, although this electric car has no standby or idle losses (15 to 20%). Of course the rest of the energy efficiency is the same.

However, electric driving with batteries has two main disadvantages. The range is limited and the charging time long. An electric car has a battery capacity between 20 to 30 kWh. With this electricity such a car can drive between 100 and 300 km. To recharge the batteries at home or near the office you need to be connected to the electricity grid for 6 to 8 hours. There are fast chargers on the market but even then more than 10 minutes for recharging is required [9,10]. A gasoline car has a gasoline tank with 50 to 55 liter and therefore a range of about 700-1,000 km. Such a tank can be fueled in about 1 to 2 minutes. So charging time and range for an electric car are certainly not up to standards.



Therefore hybrid cars are introduced: an electric motor combined with a combustion engine that produces electricity from a fuel. These hybrid cars have a normal combustion engine of about 100 kW and an electric motor of about 60 to 100 kW. The weight of these cars is 1,500 kg. Although our car now has two engines and is therefore heavier, the fuel economy is even slightly better than for the small family car: about 4 to 5 liter per 100 km.

But can we do better and solve also the two main disadvantages of electric driving?

Yes we can!

In the future it will become possible to drive automatically. We'll be able to can read the newspaper while driving. It will certainly lead to a better energy efficiency: driving at a very constant speed, with less distance between cars, which will reduce resistance losses. But there is more to come. Electric motors can be mounted in the wheels, thereby eliminating the losses in the gearbox transmission. We can build our cars from (bio-)plastic with the same comfort and safety standards, which will reduce the weight of cars considerably. And in the future we will replace the combustion engine by a fuel cell that can produce electricity with a much higher efficiency and will allow very long driving distances and short fuelling times.

NUMBER OF CARS WORLDWIDE

But how many cars are there in the world? How many cars do we buy every year? What is the total amount of kilometers we drive per year? What is the capacity of the engines in our cars? And how much time do we use our cars? These statistics will allow us to judge the effects of efficiency improvements and the impact on energy consumption.

Worldwide we exceeded the number of 1 billion cars in 2010. By 2012 there are about 298 million commercial vehicles on the road worldwide, and 711 million passenger cars. Over 80 million new cars were produced in 2012: 63 million passenger cars and 21 million commercial vehicles [11,12]. The expectation is that the number of vehicles in 2050 will be around 2.5 billion cars [13], according to the OECD International Transport Forum.

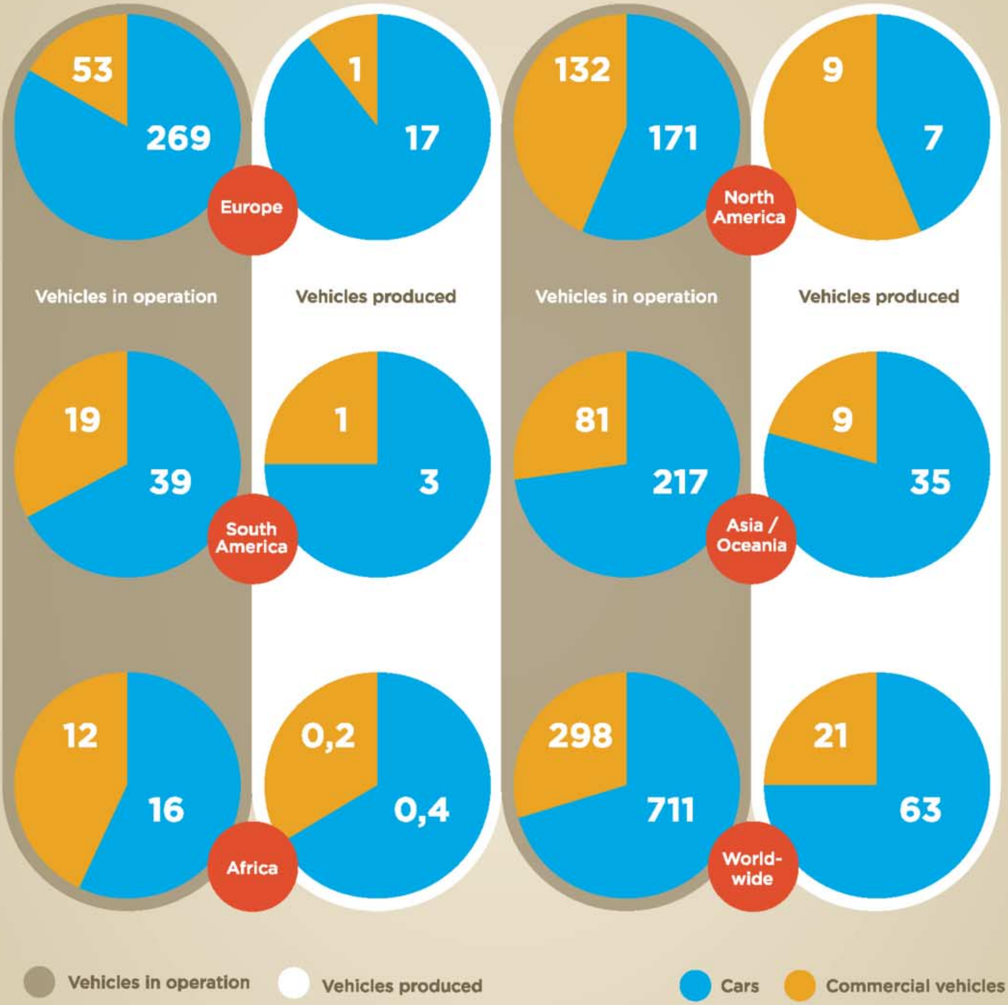
OUR CAR AS POWER PLANT **NUMBER OF VEHICLES IN OPERATION WORLDWIDE 2012 (IN MILLIONS)**

	CARS	COMMERCIAL VEHICLES	TOTAL VEHICLES
EUROPE	269	53	321
NORTH AMERICA	171	132	303
SOUTH AMERICA	39	19	59
ASIA / OCEANIA	217	81	298
AFRICA	16	12	28
TOTAL	**711**	**298**	**1,009**

OUR CAR AS POWER PLANT **NUMBER OF VEHICLES PRODUCED WORLDWIDE 2012 (IN MILLIONS)**

	CARS	COMMERCIAL VEHICLES	TOTAL VEHICLES
EUROPE	17	2	20
NORTH AMERICA	7	9	16
SOUTH AMERICA	3	1	4
ASIA / OCEANIA	35	9	44
AFRICA	0.4	0.2	0.6
TOTAL	**63**	**21**	**84**

CARS WORLDWIDE



Global overall nr. of vehicles in operation

1,009 Million

Global overall nr. of vehicles produced

84 Million

The old Ford Model T had an engine capacity of 15 KW. A modern car has an engine capacity above 100 kW. The North American average engine capacity for cars and light-duty trucks in 2006 was about 220 horsepower or 164 kW [(14)]. In Europe the average passenger car engine capacity in 2008 was 84 kW [(8,9)]. It is obvious that worldwide the car engine capacity has grown, by approximately 2 to 3% per year.

Let us assume that the average car engine capacity in the world is only 50 kW. That would imply that the total car engine capacity in 2012 was about 50 million MW or 50 TW. The new cars brought to the market do certainly have a bigger engine capacity. But let us assume that the average engine capacity for new cars is only about 100 kW. That means that in 2012 a total car engine capacity of 8 million MW or 8 TW has been bought and is driving on the road. And with 2.5 billion vehicles on the road in 2050, assuming still an average engine capacity of 100 kW, the total car engine capacity on the road will be over 250 million MW or 250 TW.

The average annual distance driven per car in the USA is about 18,000 km. If we assume an average speed of 50 km/h it means that in the USA cars are used 360 hours per year. A year has 8,760 hours so we drive our car less than 5% of the time. The rest of the time we have parked our car at home, nearby our work, a shopping area, the school, a restaurant, a car park, or somewhere else. For the world these figures will not be much different. So overall we use our car for driving only 5% of the time.

OUR ENERGY SYSTEM

In our modern life we use energy for almost all the things we do. We use energy to make products, for a comfortable climate in our houses and offices, for lighting, to run our appliances and of course for transportation. A life without energy is almost impossible, certainly not comfortable nor productive.

TOWARDS INTEGRATED ENERGY SYSTEMS

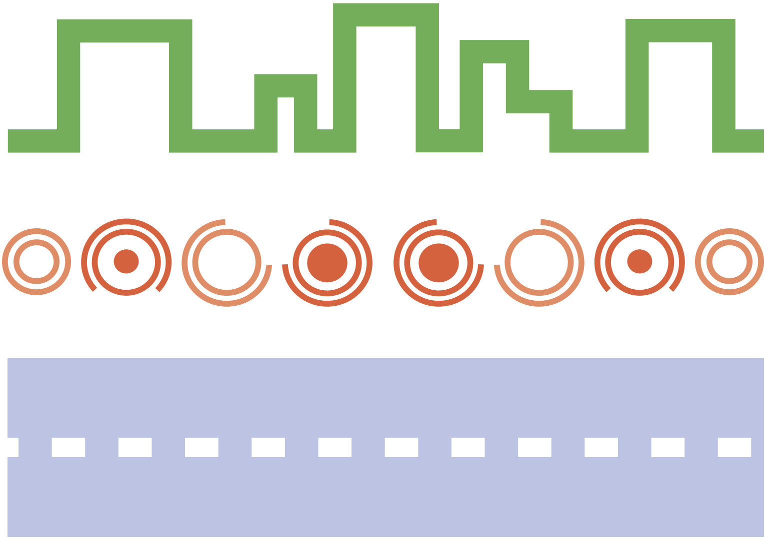
At present we have different and separate energy systems for transport, energy and heating. Our transport system mainly uses oil. We extract oil out of the ground, transport it, refine it into a transport fuel, put it in our car fuel tank and then an internal combustion engine is producing the power to drive. Our electricity system stands separate. We extract coal, gas or oil, transport it, put it into a large power plant to produce electricity and distribute the electricity via a grid to our homes and offices. For heating we use a fuel (gas, oil, coal, wood) that we put into a boiler to produce hot water to heat our houses and other buildings. Sometimes we use electricity to produce heat via a resistance heater or with a heat pump. And finally we use fuels in our industry for high temperature steam. Or as a feedstock, for example to make plastics from oil and fertilizers from gas. Taking a very high level view one may divide the worldwide energy consumption in four quarters: one quarter energy for transport, one quarter energy for heating and cooling of buildings, one quarter for electricity and one quarter for industry and feedstock.

Nowadays we realize that the energy efficiencies for these systems are low, that using fossil fuels is not forever and their use can have considerable environmental impact. Therefore a sustainable energy system needs to be realized: a system with a better energy efficiency and using renewable energy.

There have been many developments in the energy sector and the efficiencies in conversion-, distribution- and end-use technologies have improved considerably. Not only in technology but also in systems we see major efficiency improvements. For example in electricity power plants we produce electricity but also a lot of heat, which is generally 'thrown away' in surface water or the air. Nowadays we try to use the waste heat from our power plants for heating purposes and therefore many cogeneration power plants have been realized. Also industrial waste heat is used for other heating purposes or even to produce some electricity. So we try to integrate the power system with the heating and cooling system.

Although it is very important to make use of excess heat, we have to realize that this is not a sustainable energy system in the end. Let us have a look at how we could develop a sustainable heating and cooling system for example. We first have to reduce our energy demand for heating and cooling, by insulation, heat recovery from ventilation air and by using passive solar heating and cooling. For the remaining demand we can use the ground to store heat in the summer time to be used in winter time and the other way around. With a heat pump, which uses a little bit of electricity, we can bring the stored heat or cold to the right temperature. And this electricity may come from a renewable source like wind, solar, geothermal, biomass, etc. So energy-efficiency improvements, renewable energy sources and heat pump application leads to integration of the heating and cooling system with the electricity system.

A similar development towards a sustainable transport system can be envisioned. The change towards more energy efficient cars and towards electric cars has started. The electric car transport sector will consume more and more electricity, although more efficiently. If this electricity will be produced by renewable sources, transportation can evolve into a sustainable system.



But there is another very interesting system change in the integration of the electricity and transport systems. Electric cars not only consume electricity, they can also produce electricity. Its batteries can deliver some electricity back into the grid. Once today's low-efficiency combustion engines are replaced by clean, highly efficient fuel cells, our cars may produce electricity and feed it to our houses, offices, schools or the electricity grid. And the waste product of a fuel cell is hot de-mineralized water which we can use for heating and fresh water.

So the transport system, the electricity system and the heating and cooling system will develop over time into one interconnected system. And our cars will not just consume energy but rather produce electricity, heat and fresh water.

ELECTRICITY SYSTEM WORLDWIDE

The worldwide installed electricity production capacity in 2010 is about 5 million MW (5000 GW or 5 TW). In 2010 more than 20,200 TWh or 20,200 billion kWh electricity was generated with this installed capacity [15,16].

The worldwide installed electricity production capacity consist of fossil-fuel (coal, gas, oil) power plants, nuclear power plants and renewable electricity production capacity. This renewable electricity production capacity consists of hydro power plants, wind, solar, geothermal and biomass/ waste power plants. The largest capacity is that of the fossil fuel power plants, 3,475 GW or almost 69% of the capacity. The installed nuclear power plant capacity in 2010 was 381 GW or 8% of total. Renewables have an installed capacity of 23% or 1,211 GW: 918 GW hydro power, 183 GW wind, 65 GW biomass/waste, 31 GW solar and 10 GW geothermal [15]. However the fastest growing renewable categories are wind and solar. According to the GWEC the wind capacity has grown to about 280 GW in 2012 [17].

With this installed capacity in 2010 more than 20,200 TWh has been generated, 66% by fossil power plants, 13% by nuclear and 21% by renewables. In the renewables, however, hydro power is by far the largest electricity generator. Hydro power alone generates almost 17% of total electricity worldwide [15].

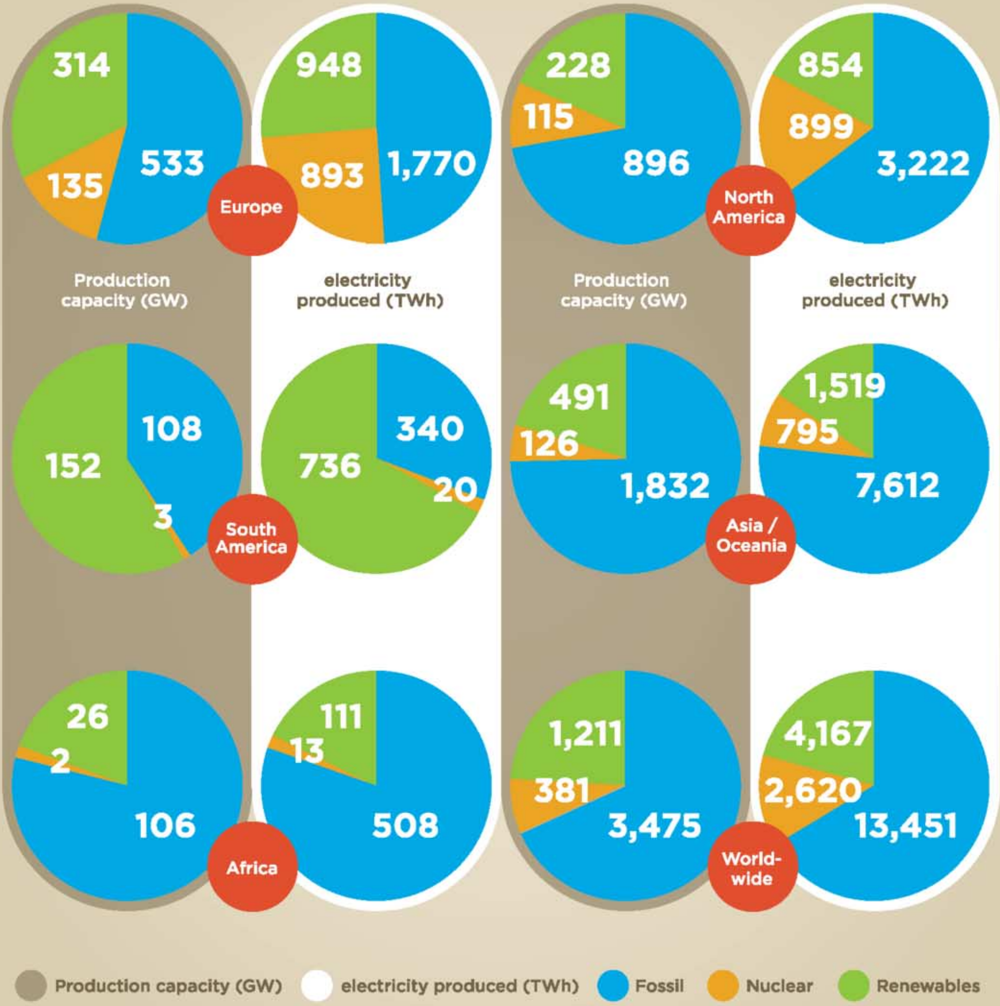
OUR CAR AS POWER PLANT **ELECTRICITY PRODUCTION CAPACITY IN GW WORLDWIDE 2010**

	FOSSIL	NUCLEAR	RENEWABLES	TOTAL
EUROPE	533	135	314	982
NORTH AMERICA	896	115	228	1,238
SOUTH AMERICA	108	3	152	263
ASIA / OCEANIA	1,832	126	491	2,449
AFRICA	106	2	26	134
TOTAL	**3,475**	**381**	**1,211**	**5,067**

OUR CAR AS POWER PLANT **ELECTRICITY GENERATION IN TWH WORLDWIDE 2010**

	FOSSIL	NUCLEAR	RENEWABLES	TOTAL
EUROPE	1,770	893	948	3,610
NORTH AMERICA	3,222	899	854	4,974
SOUTH AMERICA	340	20	736	1,096
ASIA / OCEANIA	7,612	795	1,519	9,926
AFRICA	508	13	111	632
TOTAL	**13,451**	**2,620**	**4,167**	**20,238**

ELECTRICITY WORLDWIDE

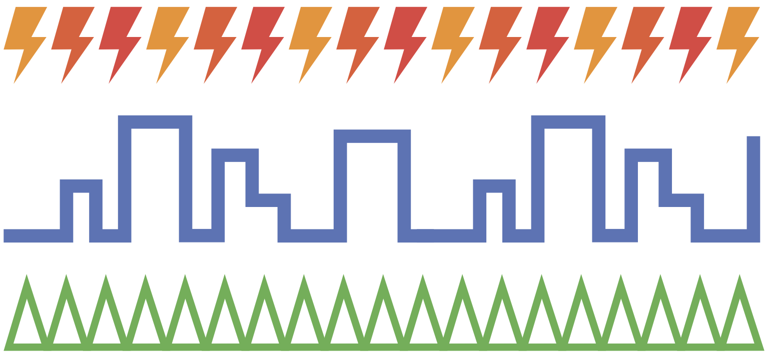


Global overall production capacity

5,067 GW

Global overall electricity generation

20,238 TWh



OUR CAR AS POWER PLANT **RENEWABLES CAPACITY IN GW AND GENERATION TWH WORLDWIDE 2010**

	RENEWABLES CAPACITY	RENEWABLES GENERATION
HYDRO	918	3,402
WIND	183	342
BIOMASS/WASTE	65	325
GEOTHERMAL	10	66
SOLAR	35	31
TOTAL	**1,211**	**4,167**

POWER SYSTEM EFFICIENCY

We need to produce electricity at the moment we need it. Demand and supply have to be in balance at every moment in time. The demand for electricity is not constant. During the day we need more electricity at our offices, schools, industry and for all kinds of appliances. In winter we need more electricity for lighting than in summer. But in summer we need more electricity for air-conditioning, as in winter for heating. And when there are special events, for example an important football match, we all watch television and there is a peak in demand.

How can the supply of electricity deal with these variations? It can be done in several ways. We can for example store electricity by pumping up water to a higher basin. When we need electricity, the water is falling down through a hydro turbine that generates electricity. We can also ask clients to use less electricity and in return they get a better price. This is called load management. Many processes can handle some flexibility, for example our refrigerators. But at the moment, fossil-fired power plants are by far the dominant system to regulate supply of electricity.

The demand for electricity has a certain pattern during the day. During the night there is a minimum demand. In the morning offices, schools and industries start to work and demand goes up. In the afternoon people go home to eat, watch television or do some other activities during the evening. Electricity consumption decreases and when we go to sleep we shut down many of our electronic appliances. Electricity demand during night is at a minimum again.

To be able to follow this electricity demand, we have built a power system with base-load, intermediate-load and peak-load power plants. Base-load plants run almost all of the time. These are our nuclear plants, coal fired power plants and large and modern Combined Cycle Gas Turbine (CCGT) plants. Their characteristics are a long start-up time (many hours), a high efficiency at full load and decreasing efficiency when operated at partial load. Peak-load power plants on the other hand, can start and stop very quickly (minutes). So when there is a sudden fluctuation in demand, these peak-load power plants will produce. But their full-load efficiency is much lower than the base-load power plants. In many cases these peak-load power plants are gas turbines with efficiencies between 25 and 35%. The intermediate-load power plants have indeed intermediate characteristics: start-up in one to two hours and reasonably high efficiencies. Normally these are the older combined cycle gas turbine plants. So in the total power system all the power plants are operated based on a certain merit order.

Next to this merit order there is a system that can react very fast (seconds), for example when a power plant fails to operate because of an accident. Therefore all power plants do not operate at their maximum capacity, but slightly below maximum. If there is a sudden disruption in demand or production, these plants will react and reach their maximum capacity very fast. This system is called spinning reserve.

We can recognise what type of power plant it is by looking to the load factor of the power plant. The load factor is the amount of electricity produced in a year divided by the maximum capacity of that power plant. The load factor has an obvious maximum of 8,760 hours. In that case the power plant runs at its maximum capacity for every hour of the year. From the tables with the electricity production capacity and the electricity generation worldwide for 2010 we can easily calculate the load factors. For nuclear plants in 2010 the load factor was near to 7,000 hours (6,880 hours exactly) which indeed indicates that nuclear plants are base-load plants. For the fossil-fired power plants, coal, gas and oil fired, the average load factor is near to 4,000 hours (3,870). This is a mix of base-load coal fired power plants, intermediate-load plants and peak-load gas-fired plants.

So if we want to study the efficiency of the power system we have to compare power system efficiencies and not only the individual power plant efficiencies at full load. The efficiencies of individual base load power plants are of course much higher than the average efficiency. For example at present, the efficiency of newly built gas fired power plants, combined cycle gas turbine (CCGT), is 60% at full load. Using higher turbine inlet temperatures, this can increase to about 65% in the future [18]. The efficiency of newly built coal fired power, super-critical pulverized coal (SCPC) plants, is about 46% at full load. In the future efficiencies at full load can come up to 52% [19], by SCPC power plants or CCGT fired power plants.

However, because the power system has to balance supply and demand - and must be able to react on disruptions - the system efficiency is much lower. For example the Dutch power system efficiency is about 40%. And the system efficiency in almost all other countries is even lower than 40%. In the US the power system efficiency is 36% and in China 32% [20,21].

FUEL CELL CARS

Both the transport system and the electricity system can be drastically changed by the introduction of fuel cell cars. But what is a fuel cell, how does it work, what are the advantages and disadvantages of fuel cell cars and how can it contribute to a more efficient and cleaner transport- and energy system?

THE FUEL CELL

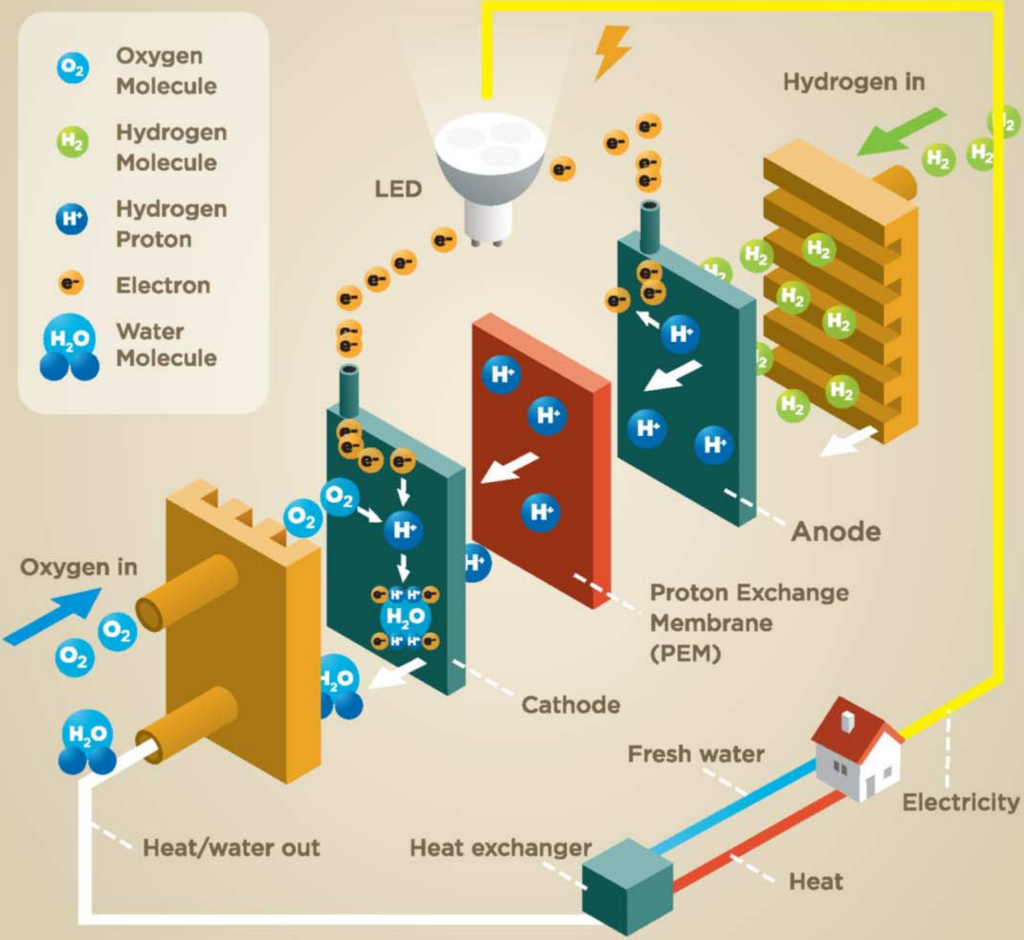
A fuel cell converts the chemical energy of a fuel, in most cases hydrogen, directly into electricity by means of a chemical reaction, with de-mineralized water and useful heat as the only by-products. Hydrogen-powered fuel cells are not only pollution-free, but they can also have more than two times the efficiency of traditional combustion technologies.

There are many types of fuel cells, but they all have the same basic configuration: an anode (negative side), a cathode (positive side) and an electrolyte that allows charges to move between the two sides of the fuel cell. The electrolyte determines the kind of chemical reactions that take place in the fuel cell, the temperature range in the fuel cell and other factors that determine its most suitable applications.

As the main difference among fuel cell types is the electrolyte, fuel cells are classified by the type of electrolyte they use, followed by the difference in startup time ranging from 1 sec to 10 min. Electrons are drawn from the anode to the cathode through an external circuit, producing direct current (DC) electricity. In addition to electricity, fuel cells produce de-mineralized water and heat as a 'waste' product [22,23].

Fuel cells come in a variety of sizes. Individual fuel cells produce relatively small electrical potentials, about 0.7 volts. So cells are "stacked", or placed in series, to increase the voltage and meet application's requirements [24]. The energy efficiency of a fuel cell is generally between 40 and 60% at maximum capacity. Interesting is that the efficiency goes up when fuel cells are operated in partial load. In power plants this is normally the other way around: efficiency goes down when operating in partial load.

FUEL CELLS


Oxygen Molecule
Hydrogen Molecule
Hydrogen Proton
Electron
Water Molecule
LED
Hydrogen in
Oxygen in
Anode
Proton Exchange Membrane (PEM)
Cathode
Fresh water
Electricity
Heat/water out
Heat exchanger
Heat

The first fuel cells were invented in 1838. The first commercial use of fuel cells came more than a century later in NASA space programs to generate power for probes, satellites and space capsules. Since then, fuel cells have been used in many other applications. Fuel cells are used for primary and backup power for commercial, industrial and residential buildings and in remote or inaccessible areas. And nowadays they are also used for transport purposes to power vehicles, including forklifts, buses, airplanes, boats, motorcycles, submarines and our cars.

In cars we use the PEM fuel cell (Proton Exchange Membrane, also called Polymer Electrolyte Membrane). This type of fuel cell starts in a second, has an operation temperature of about 80°C and a full load electrical efficiency of 60% to convert hydrogen into electricity.

OUR CAR AS POWER PLANT **FUEL CELL TYPES AND CHARACTERISTICS**

FUEL CELL	OPERATING TEMPERATURE	SIZE	ELECTRIC EFFICIENCY
PEM **PROTON EXCHANGE MEMBRANE**	50-100°C	1-100kW	60%
AFC **ALKALINE**	90-100°C	10-100kW	60%
PAFC **PHOSPHORIC ACID**	150-200°C	400kW	40%
MCFC **MOLTEN CARBONATE**	600-700°C	300kW-3MW	45-50%
SOFC **SOLID OXIDE**	700-1000°C	1kW-2MW	60%

THE FUEL CELL CAR

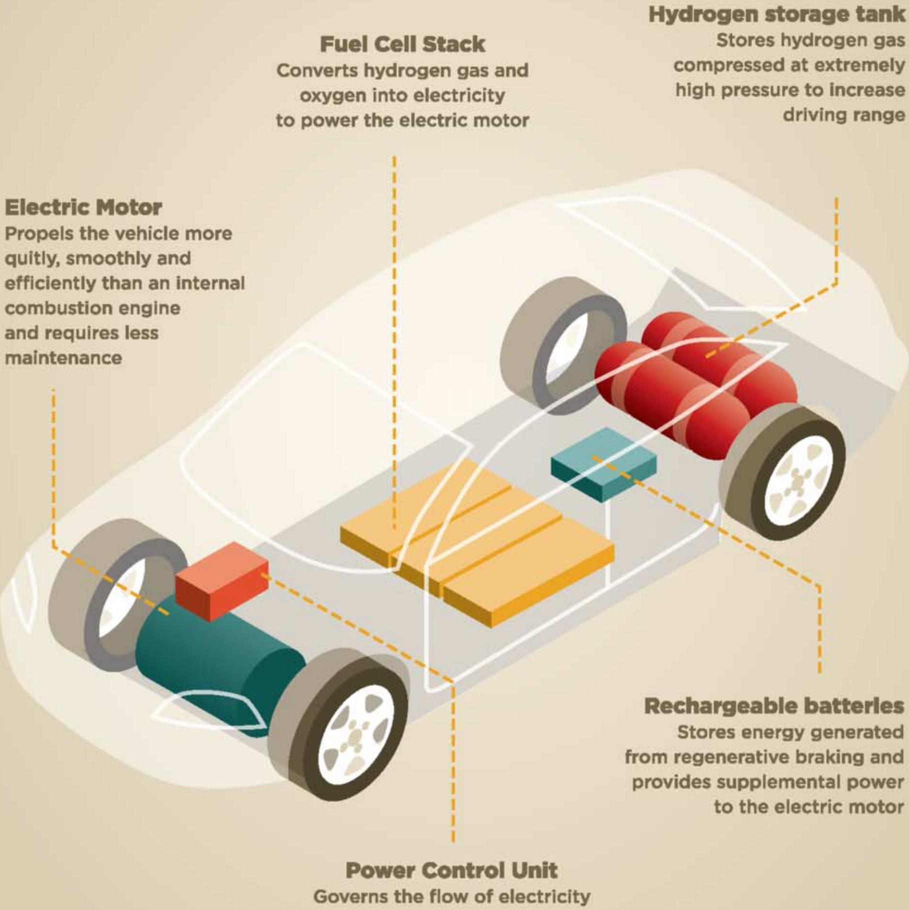
A fuel cell car is a car that uses a fuel cell to power its on-board electric motor. Fuel cells in vehicles generate electricity, using hydrogen stored in the fuel tank of the car and oxygen from the air. At present almost all large car manufacturers develop and demonstrate their fuel cell cars. Government programs in many countries stimulate the development of fuel cells, hydrogen production and -distribution and the introduction and demonstration of fuel cell cars [25,26].

The fuel-cell car set-up has a fuel cell with a capacity around 100 kW, producing electricity from hydrogen and oxygen to power the electric motor. A hydrogen fuel tank at present contains 4-6 kg hydrogen under high pressure, 350-700 bar. With 1 kg of hydrogen you can drive about 100 km. A battery is added to provide extra electricity. The battery can store electricity that is generated during braking [27,28].

OUR CAR AS POWER PLANT **PRESENT FUEL CELL CAR CHARACTERISTICS**

FUEL CELL TYPE	PEM (Proton Exchange Membrane)
FUEL CELL CAPACITY	80-100 kW
FUEL CELL ELECTRIC EFFICIENCY	60%
ELECTRIC MOTOR	60-100 kW
BATTERY	1-2 kWh
HYDROGEN TANK	4-6 kg
DRIVING DISTANCE	100 km per kg H_2
PRESSURE IN TANK	350-700 bar

FUEL CELL **CARS**



HYDROGEN

An important question is how do we produce the hydrogen? Hydrogen is the simplest molecule in the universe, consisting of two hydrogen atoms, or 2 protons and two electrons. It does not exist freely in nature but can be produced in many ways: from natural gas, coal or biomass. But also from electricity, or even direct sunlight. Coal, oil, gas and biomass are hydrocarbons, containing the elements hydrogen and carbon. Natural gas mainly contains methane, CH_4. Electricity or sunlight can produce hydrogen by splitting it from water, H_2O.

Production from coal and biomass can be done by a process called gasification. Gasification transforms these fuels without combustion to a gaseous synthetic gas from which hydrogen can be derived, which can then be reacted into hydrogen. These processes presently have efficiencies of 56% (coal) and 44% (biomass) [24].

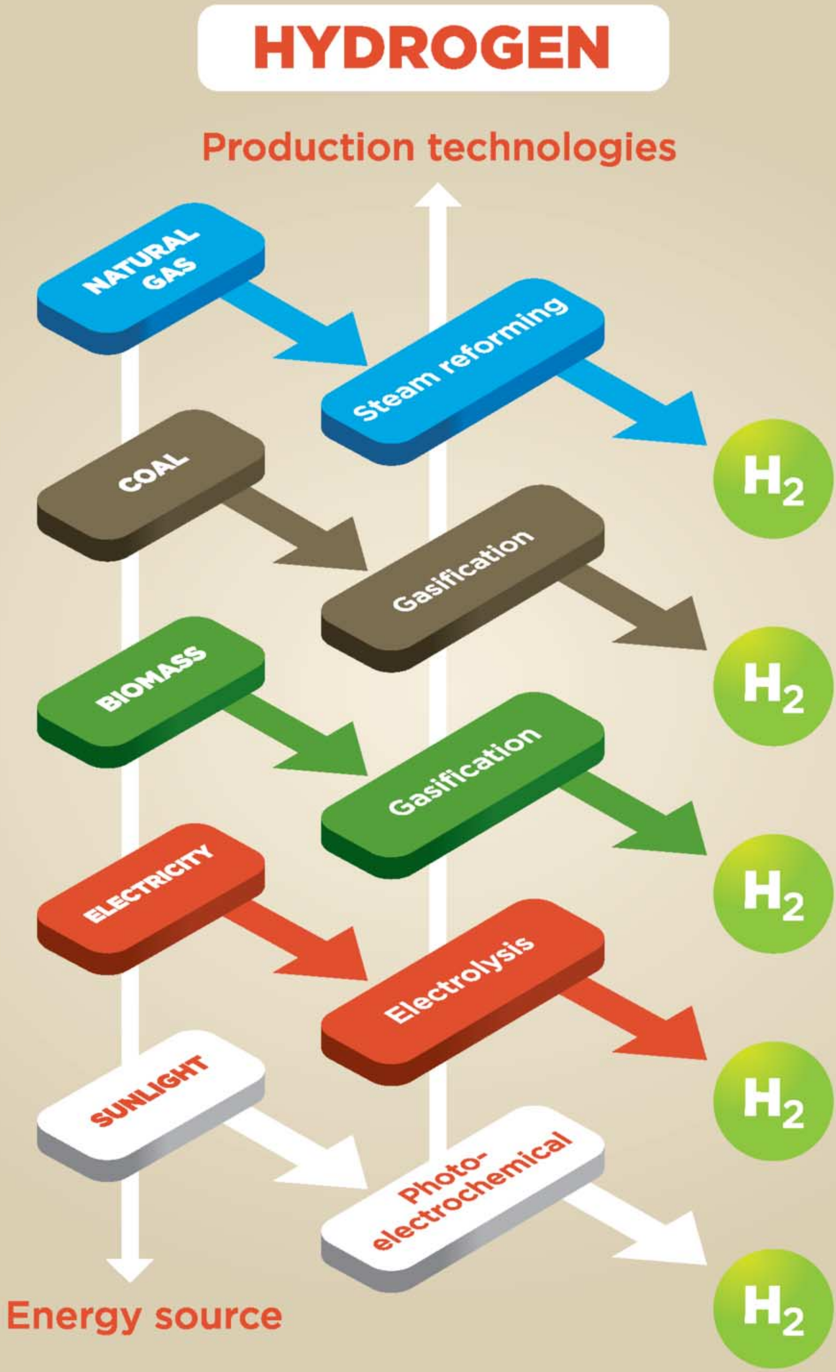
Natural gas can be converted with a much larger efficiency, currently 72%, by a process called methane steam reforming. In this process high-temperature steam produces a synthetic gas containing CO plus H_2 from CH_4 and H_2O in a first step. In a second step the carbon monoxide CO is converted to CO_2 and H_2 (24). Nowadays, most of the hydrogen for industrial purposes is produced by steam reforming, due to easy availability and low prices of natural gas. Currently 30 million kg of hydrogen is produced daily, in refineries and large industrial plants (24).

Production from electricity, by a process called 'electrolysis' has at present an efficiency of 67%. This process is carbon-free, as the only component used is water. A voltage applied over water splits it into H_2 and O_2.

A novel, but promising route is direct conversion from sunlight, inside a solar photo-electrochemical panel. The electrons liberated by photons are immediately used to separate hydrogen atoms from oxygen atoms in the water molecules. A solar-to-hydrogen efficiency of 4.9% has been reached in laboratory based on a metal oxide photo-anode (29).

OUR CAR AS POWER PLANT **HYDROGEN CONVERSION TECHNOLOGIES**

ENERGY SOURCE	PROCESS	EFFICIENCY
Natural gas	Steam reforming	72%
Coal/Oil	Gasification	56%
Biomass	Gasification	44%
Electricity	Electrolysis	67%
Sunlight	Photo-electrochemical	4.9% (lab)


HYDROGEN
Production technologies
NATURAL GAS
Steam reforming
COAL
Gasification
BIOMASS
Gasification
ELECTRICITY
Electrolysis
SUNLIGHT
Photo-electrochemical
H_2
H_2
H_2
H_2
H_2
Energy source

HYDROGEN STORAGE

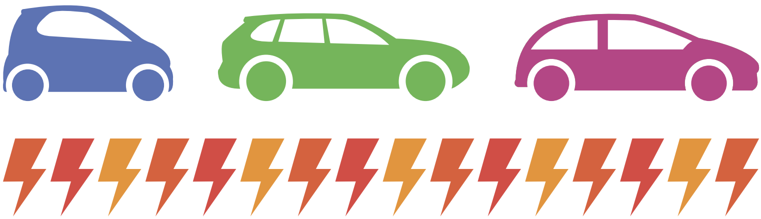
Light-weight, low-volume hydrogen storage systems are needed for the development and viability of hydrogen-powered vehicles. Approximately 5 kg of hydrogen is required to drive 500 km. All emerging commercial fuel cell cars contain compressed-hydrogen gas tanks, with pressures between 350 and 700 bar. Alternatives for storing hydrogen are liquid hydrogen tanks, cryogenic compressed hydrogen, metal hydrides, high-surface-area adsorbents, and chemical hydrogen storage materials [30]. The long-term targets of the US DRIVE research program [31] are 0.075 kg hydrogen per kg storage system and 0.07 kg hydrogen per liter storage volume. With 5 kg hydrogen, this equates to a tank volume of 70 l and 65 kg, comparable to present-day gasoline tanks. The cycle efficiency of storage is important, as energy is lost during the cycle.

The ultimate US target is 90% for the ‘onboard efficiency’ which is delivering hydrogen from the tank to the fuel cell. The target for Well to Fuel Cell efficiency is 60%, which is the efficiency for the total process of hydrogen production, compressing, storage, fuelling and in-the-car decompressing. Next to hydrogen production, compressing and decompressing hydrogen for high pressure storage causes the major loss.

Energy-efficient off-board storage of hydrogen is also needed and developed for stationary and portable applications and throughout the hydrogen delivery infrastructure. For example, storage is required at hydrogen production sites, hydrogen refueling stations, and stationary power generation sites. Temporary storage may also be required at terminals and/or intermediate storage locations.

FUEL CELL CAR FOR TRANSPORT

The fuel cell car is an electric car with on board a fuel cell that produces electricity from hydrogen. That hydrogen is stored on board in a high pressure tank. Of course we need to fuel our tank with hydrogen at a fuelling station. And at the fuelling station the hydrogen will be produced from natural gas, biogas or electricity. So a large-scale hydrogen infrastructure is not needed, we simply use the gas infrastructure and the electricity infrastructure to transport energy. And at the moment we need hydrogen, we convert to hydrogen.



At first we will use natural gas for the production of hydrogen. That technology, steam reforming, is well known and nowadays widely used. Of course we have to improve this technology, especially the conversion efficiency and purity of the hydrogen produced. We expect that in the near future an efficiency of 80% is possible. In parallel we need to scale down the size of these plants in order to place these installations near fuelling stations.

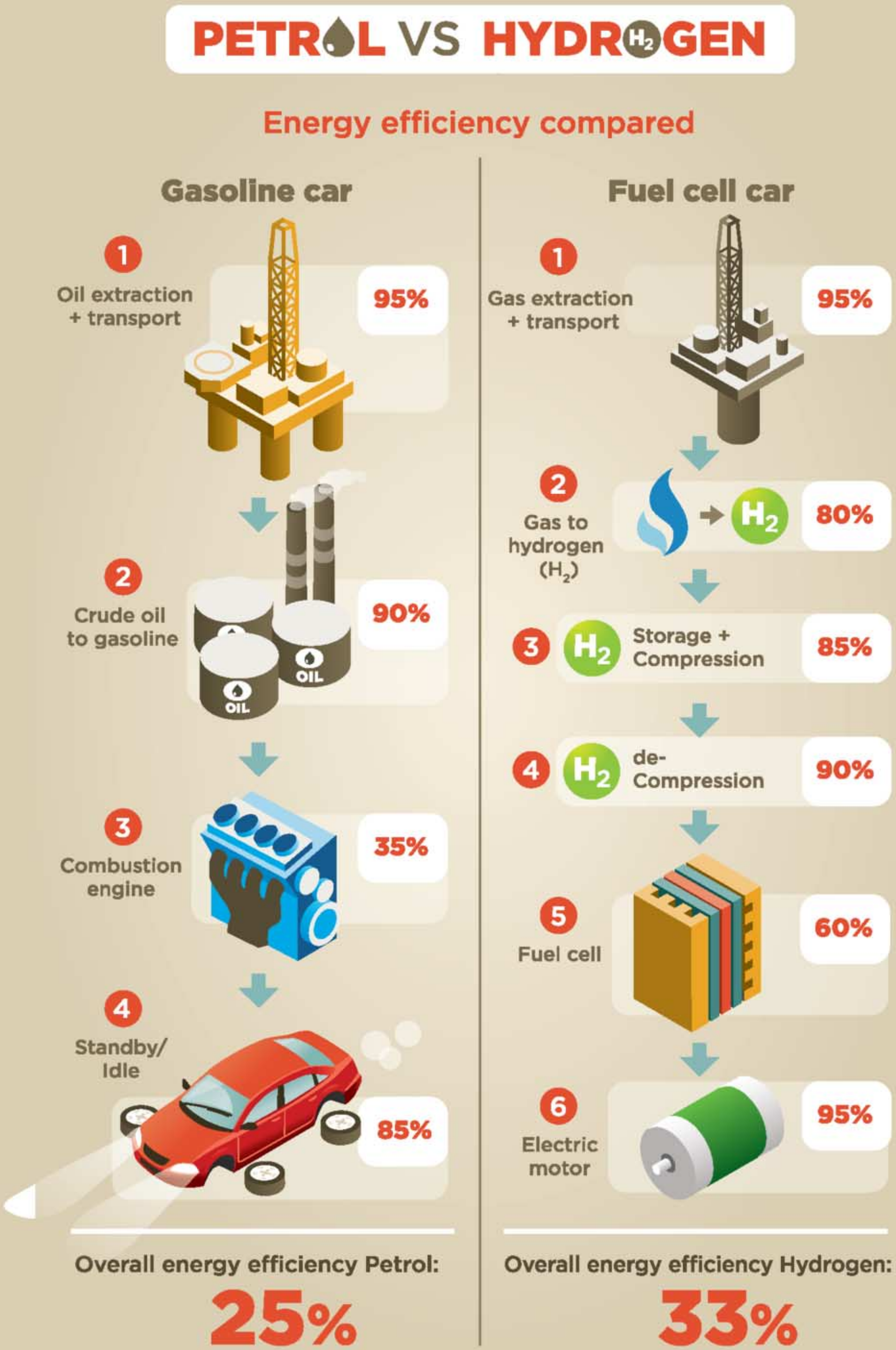
Let us now compare the energy efficiencies of our present gasoline cars and tomorrow's fuel cell cars. Our gasoline cars use oil as the energy input and our fuel cell cars use gas as an input.

We need to produce hydrogen from gas, store and compress it to put it in the tank of the car and decompress it in the car to feed it into the fuel cell. Of course this leads to losses, overall we estimate an efficiency of about 60%. Then we have the fuel cell itself that converts hydrogen into electricity with an efficiency of about 60% also.

Overall the energy efficiency comparison based on the same system components is about 25% for a modern gasoline car and about 33% for our fuel cell car. It means an overall energy efficiency improvement of 30% in our transport system. This would imply also that the carbon dioxide emissions will be at least 30% lower. Additionally, a fuel cell car has no local pollution and is very quiet.

OUR CAR AS POWER PLANT **ENERGY EFFICIENCY GASOLINE CAR COMPARED TO FUEL CELL CAR**

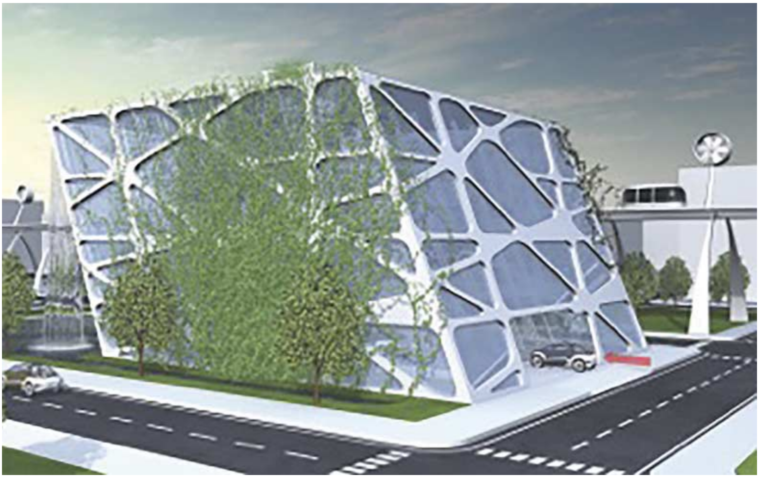
GASOLINE CAR		FUEL CELL CAR	
Extraction oil + transport	95%	Extraction gas + transport	95%
Crude oil to gasoline	90%	Gas to hydrogen (H_2)	80%
		H_2 storage + compression	85%
IN THE GASOLINE CAR		**IN THE FUEL CELL CAR**	
		H_2 de-compression	90%
		Fuel cell	60%
Combustion engine	35%	Electric motor	95%
Standby/Idle	85%		
OTHER SYSTEM COMPONENT EFFICIENCIES THE SAME			
Overall Efficiency	**25%**	Overall Efficiency	**33%**



PETROL VS HYDROGEN
Energy efficiency compared
Gasoline car
1
Oil extraction + transport
95%
2
Crude oil to gasoline
OIL
OIL
90%
3
Combustion engine
35%
4
Standby/ Idle
85%
Overall energy efficiency Petrol:
25%
Fuel cell car
1
Gas extraction + transport
95%
2
Gas to hydrogen (H_2)
H_2
80%
3
H_2
Storage + Compression
85%
4
H_2
de-Compression
90%
5
Fuel cell
60%
6
Electric motor
95%
Overall energy efficiency Hydrogen:
33%

In the future we can produce hydrogen from renewable electricity by electrolysis. When there is an excess of electricity produced by wind, solar, hydro, geothermal, waste or biomass we easily can convert this into hydrogen, store it in the tank of our fuel cell car. Then we effectively do not have any carbon dioxide emissions.

In the future, hydrogen can even be produced at home or at the office where you have a solar system producing electricity, using an electrolyzer to convert this into hydrogen, pressurize it and put it in the tank of your car. Farmers that produce biogas can convert the biogas into hydrogen, pressurize it and put it in the tank of their tractors, combines, trucks or cars. And communities that have wind turbines, solar systems or biogas installations are not only able to produce all their electricity but also the hydrogen for their own fuel cell cars.



THE FUEL CELL CAR AS POWER PLANT

The fuel cell car has a better energy efficiency for transport, has no local air pollution and is quiet. Of course this is an interesting development. But the fuel cell car holds another interesting promise. The fuel cell in our car is a power plant with a high efficiency. And we use our car on average only 5% of the time. So wouldn't it be interesting to use the fuel cell in our car for electricity production?

CAR-PARK POWER PLANT

We can obviously use our fuel cell car as a power plant only when it is not used for driving, when it is parked somewhere. At this parking place we need at least to be able to connect the car to the electricity grid. And if we want to use also the heat and the fresh water that is produced as a waste product, we need to extract the heat and water from the fuel cell and bring this to a heat network and a (drinking) water grid. A logical place to do this, is a place where many cars are parked, a car park!

The idea is that we develop a car park where cars are parked automatically. At the parking place the fuel cell in your car will be automatically connected to the electricity grid, a hydrogen grid, a (hot) water grid and a control system. Hydrogen is produced at the gate of the car park from (bio)gas by steam reforming or from electricity by electrolysis and will be supplied to the fuel cell. The hydrogen under atmospheric pressure will be directly fed to the fuel cell. The fuel cell converts the hydrogen directly into electricity and hot demineralized water.

This hot demineralized water will give its heat via a heat exchanger to a hot water network. The demineralized water will be treated to be used for fresh water for drinking, irrigation or other purposes. A control system will regulate the fuel cell in your car, based on the demand for electricity, heat and fresh water and also based on the preferences and restrict-ions you have given. When you leave the car park, your fuel tank can be automatically fuelled with hydrogen.

Via an app on your smart phone, tablet or computer you can give preferences and restrictions for the use of your car, you can order your car when you want to go, you can pay for the hydrogen you have fuelled in your tank and you will be paid automatically for the use of your fuel cell.

An averaged sized car park with 500 cars with a fuel cell capacity each of 100 kW is a power plant of 50 MW. When we operate such a power plant with a load factor of 4,000 hours such a car-park power plant generates 200,000,000 kWh, which is 200 GWh. In 2010 a German household uses a little over 3,500 kWh per year, while a French household uses over 6,300 kWh and a household in the US uses nearly 12,000 kWh [32]. Let us assume that a typical household consumes 4,000 kWh. Then a car park with 500 cars is able to generate all the electricity for 50,000 houses. Or in other words every fuel cell car with a 100 kW fuel cell can easily produce the electricity for 100 houses.

OUR CAR AS POWER PLANT **CAR-PARK POWER PLANT**

NUMBER OF CARS	500 cars
FUEL CELL CAPACITY PER CAR	100 kW
ELECTRICITY PRODUCTION CAPACITY CAR PARK	50 MW
ELECTRICITY PRODUCED PER HOUR AT FULL CAPACITY	50,000 kWh
HEAT PRODUCED PER HOUR AT FULL CAPACITY	25,000 kWh_{th}
DE-MINERALIZED WATER PRODUCED PER HOUR AT FULL CAPACITY	22,500 liter
HYDROGEN CONSUMPTION PER HOUR AT FULL CAPACITY	83,333 kWh
GAS NECESSARY TO PRODUCE HYDROGEN FOR ONE HOUR	3,300 m^3

CAR-PARK POWER PLANT ENERGY SYSTEM

When we realize an average sized car park with about 500 fuel cell cars with a capacity of 100 kW each, we have built a 50 MW power plant. Such a power plant is a very flexible power plant: almost instantaneously the power output of this car-park power plant can be shut down or brought to full capacity. It is able to operate as a base-load, intermediate-load or peak-load power plant. It can operate as spinning reserve, follow fast fluctuations in demand or act as backup power. And it can switch gradually between full electricity- or water production.

Let us have a look into the electricity-production system-efficiency and compare the system efficiency between our present system based mainly on large fossil fired power plants and a system that basically consists of car-park power plants. The system efficiency based on fossil fired power plants, base-load, intermediate-load and peak-load plants together, is 40% in the Netherlands and much lower in most other countries. The system efficiency based on car-park power plants has all the flexibility to follow the demand and to deal with all kinds of disruptions.

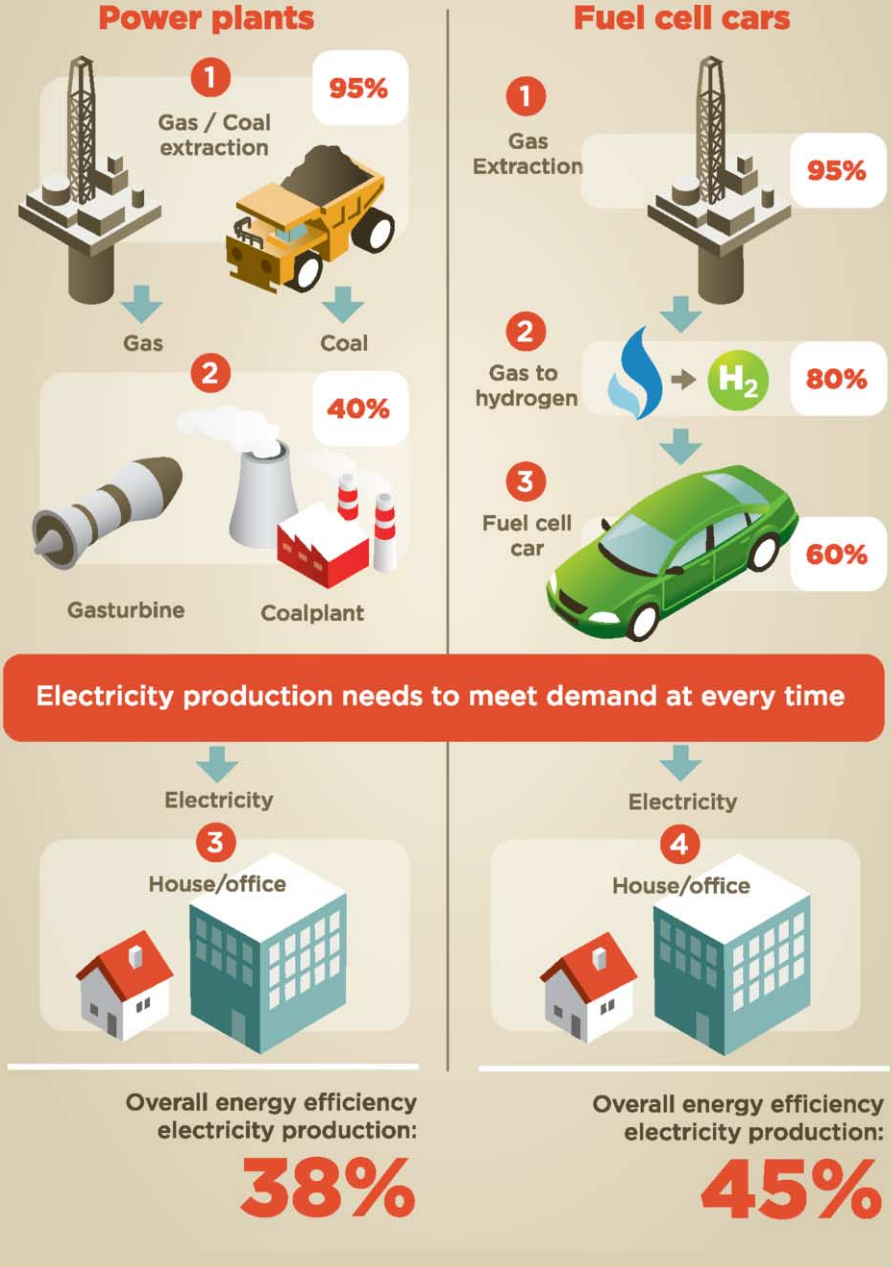
We now compare the system efficiency for the coal and gas power system with the car-park power plant system with gas as fuel. Based on the same system boundaries we see for the fossil-fuel power plant system an efficiency of 38% and for the car-park power plant system an efficiency of 45%. This means an overall energy-efficiency improvement of almost 20% in our electricity system. This would imply also that the carbon dioxide emissions will be some 20% lower. On top of that, a fuel cell car-park power plant has no other local emissions to the air and is very quiet.

OUR CAR AS POWER PLANT **ENERGY EFFICIENCY ELECTRICITY PRODUCTION BY POWER PLANTS COMPARED TO CAR PARKS**

FOSSIL-FUEL POWER PLANT SYSTEM		**CAR-PARK POWER PLANT SYSTEM**	
Extraction coal/gas + transport	95%	Extraction gas + transport	95%
		Gas to hydrogen (H_2)	80%
Power plant system	40%	Fuel cell car park system	60%
Other system component efficiencies the same			
Overall Efficiency	**38%**	Overall Efficiency	**45%**

POWER PLANTS VS CARS

Energy efficiency compared



THE ⊛⊛⊛⊛⊛⊛⊛ FUTURE

Fuel cell cars can bring us from A to B with a higher energy efficiency. And when parked, the fuel cell in our car can produce electricity more efficiently than the present fossil-fueled large-scale power-plant system. But so far the fuel cell car system still uses gas, a fossil fuel, to convert into hydrogen. Although this is more energy efficient and emits less carbon dioxide than with coal and oil, it is not a sustainable energy system.

However, hydrogen can easily be produced from electricity, generated from renewable sources, such as solar, wind, geothermal, hydro or biomass. But it is of course rather stupid when we first produce electricity by a wind turbine, then convert to hydrogen via electrolysis and then use the hydrogen in a fuel cell to produce electricity. So how does the fuel cell car fit in such an energy system? And how can a change towards a fully sustainable energy system take place?

CARS CAN TAKE OVER POWER PLANT CAPACITY

The statistics show that we have over 1 billion vehicles on the road worldwide. With an average engine capacity of 50 kW this represents a total power capacity on wheels of 50,000 GW. The total power-system capacity in the world is only 5,000 GW. So at present we already have 10 times as much power capacity on the road than totally installed in our power system.

The next thing is that every year we buy 80 million new vehicles, with an engine capacity of at least 100 kW. This represents a total power capacity on the road every year of 8,000 GW. So every year we buy more than 1.5 times power capacity on wheels then totally installed in our power system.

Within 30 to 40 years the total number of vehicles on the road is predicted to be 2.5 billion. If the average capacity is still 100 kW it represents a power capacity of 250,000 GW, 100 times as much as the present installed total electricity production capacity worldwide.

If fuel cell cars will come to the market, it certainly will have the potential to take over all the production capacity in large power plants. In the end there will be abundant, very efficient, clean and flexible power capacity available. Which of course raises the question: Will we still need power plants in the future?

OUR CAR AS POWER PLANT **POWER PLANTS AND CAR POWER CAPACITY**

POWER PLANT CAPACITY		CAR POWER CAPACITY	
Installed capacity Worldwide (2010)	5,000 GW	Installed capacity Worldwide (2012)	1 billion
		Average engine capacity	50 kW
		Total car power capacity	50,000 GW
		New vehicles on the road (2012)	80 million
		Average engine capacity	100 kW
		New 2012 car power capacity	8,000 GW

CARS TAKE OVER POWER PLANTS

POWERPLANTS

Total installed capacity (2010)

5,000 GW

CARS

1 car = 50 kW

1,000 million cars (2010)

1,000 million x 50 kW =

50,000 GW

(5% of time in operation)

New cars

1 new car = 100 kW

80 million new cars per year

80 million x 100 kW =

8,000 GW / per year

1 GW =

10,000 new cars

FUTURE ENERGY- AND TRANSPORT SYSTEMS

At present we drive in our car with combustion engine to bring us from A to B, using mainly gasoline, an oil product, as the energy source. The electricity we consume comes in majority from large power plants: coal, gas and some oil and biomass/waste fired power plants, nuclear power plants and large hydro power plants. Geothermal, wind and solar play a minor role. The energy systems, for transport and electricity are separated.

But the world is changing. Our transport becomes more and more electrically driven: bikes, fork lifts, scooters and now our cars become electric. We have seen that all large car manufacturers have introduced electric cars to the market. Cars with an electric motor driven by electricity that is stored in a battery. And because of the short distance you can drive and the long charging time, the car manufacturers have also introduced hybrid cars. Hybrid cars use both an electric motor (driven by electricity from the battery) and a combustion engine (driven by fossil fuel). The result of this change towards electric driving is that we will consume more and more electricity for transport.

Not only the transport system is changing, also the power system is changing. All over the world the capacity in renewable electricity production is growing with double-digit percentages per year. Especially wind and solar capacity are growing rapidly. So the power system is changing towards a renewable power system. This means that especially intermittent electricity production, wind and solar, is coming online.

This intermittent electricity production capacity, wind and solar, only produces electricity when the wind blows or the sun is present. And this implies that we have to design a new power system. We do not longer need base-load power plants, plants that run all the time at full capacity. To balance demand and supply we need capacity that is very flexible, that can react fast on fluctuating supply and demand. And we need energy storage. At moments that there is an excess of electricity production we need to be able to store it somewhere. Classically we can store electricity by pumping up water. But also the batteries in electric cars could store electricity which we can use when the car is parked, so called vehicle-to-grid use.

Charging the batteries of your electric car with electricity and also using your electric car as an electricity storage is the first step in integrating the transport and electricity system. But with the introduction of the fuel cell car we even get more and better possibilities for an integrated transport- and power system. The fuel cell in the car can produce electricity with a high efficiency. For transport it means a higher overall efficiency, a long driving range and short fuelling time. For electricity production it means a larger system efficiency than the present power system efficiency. Moreover: a very flexible and vast amount of capacity that can react on every demand- and supply fluctuation all the time.

At first, when fuel cell cars will be introduced to the market, we still have a power system not fully based on renewable sources. We will therefore produce hydrogen that we can fuel in the tank of our car mainly from natural gas. And at the time we have parked our car we can produce electricity with the fuel cell in our car when there is a need for it. Of course we use first and directly the electricity that is produced by renewable resources, hydropower, geothermal, waste/biomass, wind and solar.

But in the end all the other electricity could be produced by the fuel cell cars. This system change means that we will use more and more gas in our transport system, but also in our power system. And of course not all the cars will be fuel cell cars. There will be certainly a lot of cars that drive electrically with a battery only to provide the electricity. Therefore also the demand for electricity in the transport system will still grow.

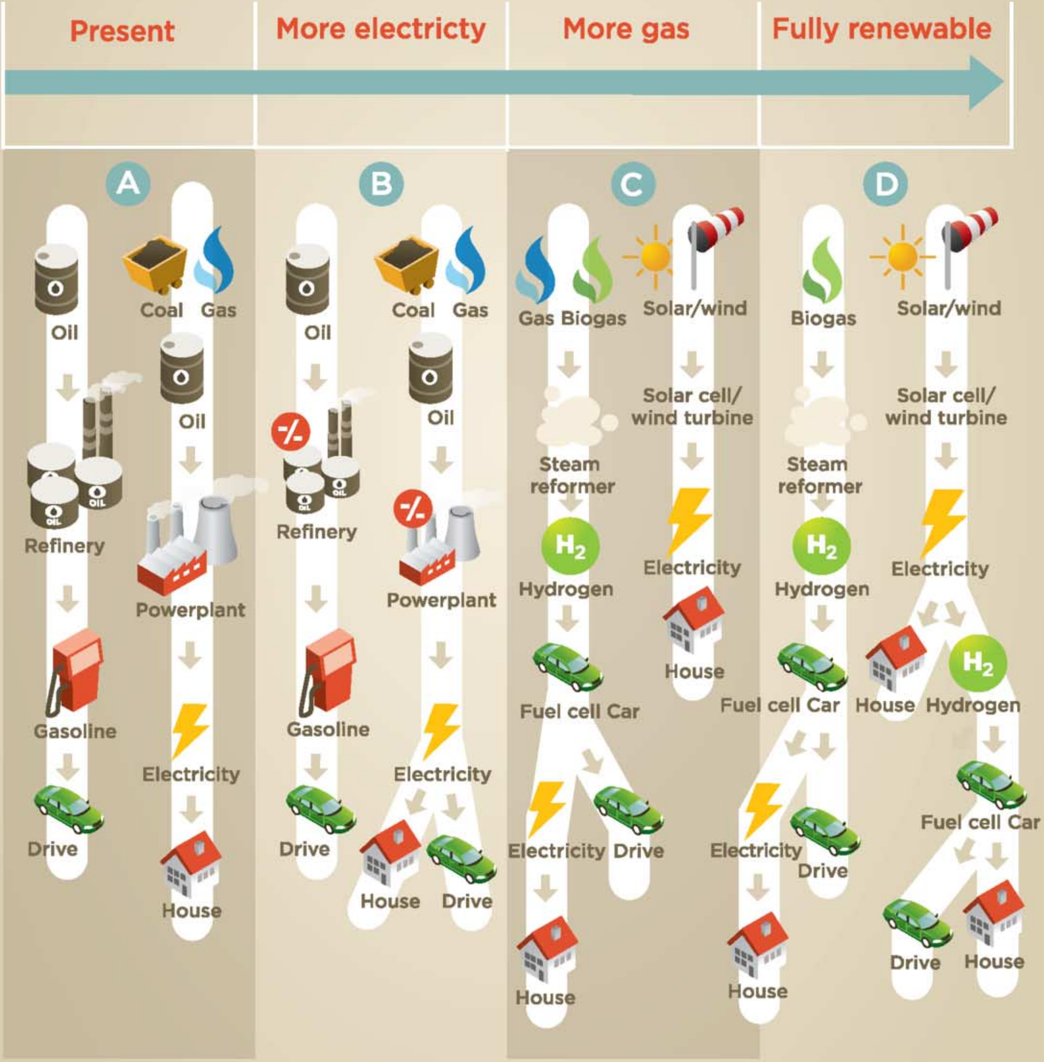
Eventually, the power system will change towards a fully renewable power system. In the end it is able to produce all the electricity we need for our appliances, lighting, industry, heat pumps, etc. But also it will be able to produce the electricity for our transport systems. Electricity to directly charge batteries in our electric cars, but also electricity converted into hydrogen to fuel the tank of our fuel cell cars. Next to electricity for hydrogen production we can still use biogas from the gas grid to produce hydrogen. In such a system we will use the electricity produced by renewable sources directly. And only when there is a shortage of electricity we will use the fuel cell cars to produce this electricity. The fuel cell car will balance the electricity system. It is able to store excess electricity by converting it to hydrogen. And it can produce electricity when there is a shortage of supply by the renewable electricity production sources.

OUR CAR AS POWER PLANT **ENERGY SYSTEM CHANGES**

SYSTEM	TRANSPORT/ELECTRICITY	SYSTEM CHANGE
Present	Transport- and electricity systems are separated	
Electric cars with batteries	Transport system with electric cars consumes electricity and can store electricity	**More Electricity**
Fuel cell car as power plant to produce electricity	Transport system with fuel cell cars produces electricity and will replace power plants	**More Gas**
Fuel cell car as power plant to balance electricity demand and -supply	Electricity will be produced by renewable energy sources; hydro, geothermal, biomass, wind, solar Transport system with fuel cell cars consumes electricity and biogas converted in hydrogen, produces electricity when necessary to balance electricity demand and supply	**Fully Renewable**

FUTURE ENERGY & TRANSPORT

How will this develop in time?



FUTURE CITIES

Our fuel cell car will be used both for transportation as well as to balance electricity demand and -supply. Renewable electricity will be produced by hydropower, geothermal heat, waste and biomass power plants, wind turbines on- and off-shore, tidal power, wave generators, osmotic power plants and solar systems. Biogas will be produced from manure, agricultural residues, waste water, food industry waste, algae's etc. In the end there is not a shortage of energy but a surplus. Because the sun gives the earth more energy in one hour than we consume worldwide in a year. And there is also not a shortage in electricity production- and storage capacity. Because all our fuel cell cars have many times more electricity-production capacity than necessary and storage of electricity can be done both in the batteries of our electric cars or in hydrogen.

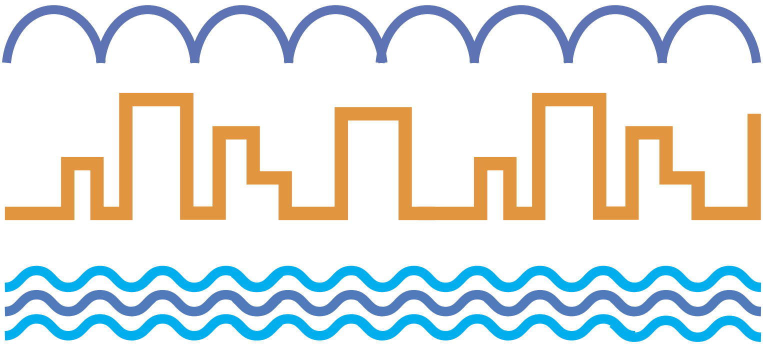
The organization of such an energy system will differ fundamentally from our present system. Everyone can produce renewable energy, locally from solar, wind, hydro or biomass. It can be done at your own house, school, office, within your own neighbourhood or by our own social network. And everyone has a lot of electricity production- and storage capacity available: their own cars and/or cars from lease companies or social network organizations. There will be also large-scale renewable energy production, an electricity- and gas infrastructure and our car parks and other parking places will change into energy production facilities. This will require an internet-based control system in which we have billions of suppliers of energy, billions of capacity providers and billions of consumers of energy. Who will build this intelligent network, develop the architecture and provide all the necessary services and applications? The energy companies, the network operators, the car manufacturers, the software providers or IT companies, the logistic companies or the building industry? Most certainly it will be a combination of all these industries and new companies.

How does such a future sustainable energy system physically look? What will be the changes in our landscape, cities, neighbourhoods, houses, offices, schools, shopping malls and roads? How will we organize such a system? Which products, systems and services will be delivered by whom and what type of regulation is necessary? Of course we cannot predict or design the future but we can give some views about what it might look like.

We can design car-park power plants or E-car parks. The car parks of today, where hundreds of cars are parked, can be changed into car parks that produce electricity, heat and water. With hydrogen fueling stations, where biogas and electricity is converted into hydrogen. These car parks can be a transfer station too, where you change from one way of transport to another. For example from your car to public transport in the city, from your car to an e-bike, or from your large fuel cell car to a small electric car.

We can design E-neighbourhoods with houses, schools, work places/offices and other buildings, that are very energy efficient. Renewable electricity will be generated via solar systems on the roof of the buildings and medium sized wind turbines in the area. Biogas will be generated from the manure, food residues and local biomass. The fuel cell cars parked at home, in the neighbourhood, at school or at the offices can deliver electricity when there is a shortage. And the electricity and biogas can be converted into hydrogen at a neighbourhood fueling station. A smart local grid can control, distribute and balance supply and demand.

We can design E-highways. Electric cars and fuel cell cars will drive automatically as a chain of connected cars in an energy efficient and comfortable way. Along the E-highways we install wind turbines and solar systems to produce electricity, waste water treatment plants to produce biogas, together with hydrogen fueling stations where biogas and electricity is converted in hydrogen.



We can design an E-cloud. Every house, school, building, car, wind turbine, waste water treatment plant, car-park power plant, hydrogen fueling station, energy grid, E-car park, E-neighbourhood, E-highway, can be connected to an E-cloud. Billions of consumers and producers of energy, water and transport with their specifications; energy-, water- and transport demand and -supply, technology characteristics and -preferences can be in the E-cloud. Communities such as neighbourhoods, schools, fuel cell car owners, social networks can exchange and negotiate via the E-cloud how and when they want to supply or demand energy, water, transport, etc.

There is a wide variety of new products, services and systems to come, but who will deliver this? New companies, but also existing companies that develop into new product, system and service providers. Car manufacturers may not only produce the fuel cell cars, but also solar systems, wind turbines, electrolysis equipment and hydrogen fueling stations. Energy companies can be the owners of the renewable electricity- and biogas production facilities but also the owners of the fuel cell cars, supplying energy- and transport services to their clients. IT companies can develop the E-cloud and all kind of related software and social community services. And many more.

OUR CAR AS POWER PLANT **FUTURE SYSTEM EXAMPLES**

E-CAR PARK	• Car park to park your cars • Fuel cell car to produce electricity, heat and water • Hydrogen fueling station, conversion of electricity and biogas in hydrogen • Transfer station, change to another transport system
E-NEIGH-BOURHOOD	• Energy efficient buildings, houses, schools, offices • Renewable electricity production, solar systems, medium sized wind turbines • Biogas production, from manure, food residues, landscape biomass • Fuel cell cars for balancing energy supply and demand • Local hydrogen fuelling stations
E-HIGHWAYS	• Electric cars will drive automatically • Electricity production by wind turbines and solar farms along highway • Biogas production by waste-water treatment plants • Hydrogen fueling stations that convert electricity and biogas in hydrogen
E-CLOUD	• All energy-, water- and transport demand and -supply in E-cloud; billions of houses, schools, fuel cell cars, wind turbines, solar systems, batteries • Communities can exchange and negotiate energy-, transport- and water supply and -demand

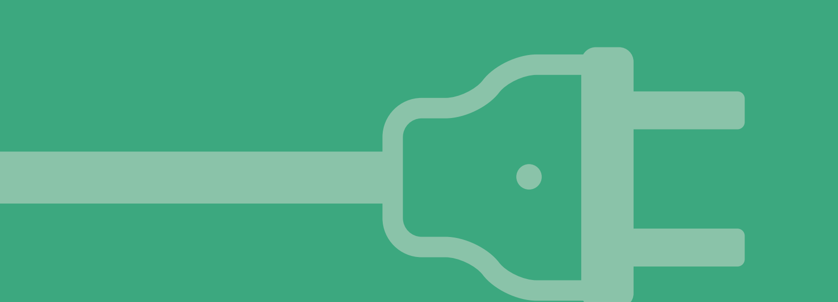
FUTURE CITIES

E-cloud
billions of energy, transport and water consumers, producers, storage and capacity providers (houses, cars, solar cells, ..) in the E-cloud can exchange and negotiate energy, transport and water demand and supply.

E-car parks
cars are parked and generate electricity, heat and water and will be fueled.

E-highways
cars drive automatically, along the road electricity generation (wind, solar), biogas production (waste water, manure) cars can be fueled.

E-neighbourhouds
generate electricity (solar, wind), biogas production (manure, grass,) cars can be fueled or generate eletricity, heat and water.



THE CHALLENGES

A future energy system based on renewable energy sources and the fuel cell car as an intermediate conversion technology for electric driving, energy storage as well as electricity production, promises many economic, environmental and social advantages. But there are huge challenges too. It will require many innovations: technological, organizational, social, institutional, legal and regulatory. Luckily, we can count on innovations driven by the introduction of fuel cell cars themselves, and other energy- and transport trends. For example autonomous driving is on its way. It will make 'automated parking and automated guidance to the nearest parking spot' [(33)] possible, as one of the first applications. Plug-in and electric vehicles with batteries as a power source nowadays deploy vehicle-to-grid options also. And the cost and efficiency of hydrogen production and -storage is progressing independently of the Car as Power Plant concept. But quite some challenges remain to be solved.

TECHNOLOGICAL CHALLENGES

The main technological challenge is evident, and strikes the core of our system: the fuel cell. In our concept, the fuel cell will be used for a much wider operating time than for driving only. The lifetime of the current generation Proton Exchange Membrane fuel cell is about 150,000 km or 4,000 operating hours, sufficient for a transportation-only car. However for the Car as Power Plant, this needs to be improved by at least a factor 5, while at the same time the cost for the fuel cell needs to come down to about $30/kW [34].

Using the car for electricity production, requires maintaining a heat balance in a stationary operational fuel cell in the car. This is a next big challenge: to extract the heat and make use of it, and to generate high power production efficiency but also achieve a high combined system efficiency (power, heat, water). With heat recovery, combined fuel-cell energy efficiencies can be increased considerably. And using the exhaust of the water / steam at the tail pipe, both for water applications and for heating purposes is a parallel challenge.

Since the production of power in a fuel cell is directly coupled to the generated heat, (control) strategies, software and hardware architectures have to be developed that respond flexibly and robustly to various demand signals. For instance when only heat is required, the excess power should be stored or fed away into the power grid.

Hydrogen production- and storage technology is crucial and needs to be improved. Also the conversion efficiencies and hydrogen quality for steam reforming need to be improved, i.e. the conversion of natural gas and biogas into hydrogen. To convert electricity into hydrogen, improved electrolysis systems with higher conversion efficiencies are necessary. Research and development in promising new technologies such as direct methane reforming and direct conversion of sunlight into hydrogen is essential. For all of these hydrogen conversion technologies, the need for small, reliable and safe systems is evident.

The next challenge is the car park geometry and design itself. Cars should be parked and docked automatically and maybe partly wirelessly to four utilities: hydrogen, power, heat and water. This will require new robotic approaches but also access control and densely-packed parking. And safety issues and regulations have to be addressed for hydrogen production and -use, automated parking and the production of energy and water in a car park [35]. For the Car as Power Plant, the main issue of interest is the permission to produce and use hydrogen locally.

Other technological system innovations are important as well. The cars need to be integrated in the larger energy- and transport system. First and foremost challenge is the smart system integration and -control of a system with multiple actors (cars, houses, offices), and multiple fuels and energy carriers (hydrogen, electricity, heat, water). These challenges are on all system levels: from individual cars, to car parks, houses, offices, neighbourhoods, cities and regions.

The physical energy infrastructure needs to be changed and become smart, given multiple production, capacity, storage and conversion technologies whereby the fuel cell cars are not fixed to one specific location. For electricity, gas and heat a grid will be necessary, but with a different topology. However, a physical large scale hydrogen grid is not necessary at any time and hydrogen can be produced locally from gas or electricity.

Although these are massive challenges, we believe it can be done. It does not require fundamentally new technology innovations or breakthroughs, but rather very good product-, system-, software- and hardware development and -engineering.

OUR CAR AS POWER PLANT **TECHNOLOGICAL CHALLENGES**

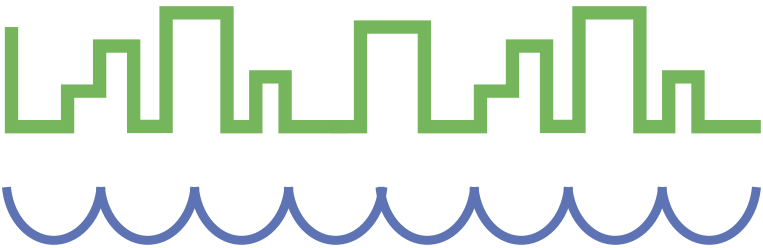
CHALLENGE	FUEL CELL CAR	CAR AS POWER PLANT
Fuel cell life time/cost	Design goals of 5,000 hour and 225,000 km, almost reached Design goal cost $30/kW	Design goal 25,000 hours / 5 years. Design goal cost could be higher than $30/kW
Fuel cell efficiency	Efficiency 60% for electricity production	Combined energy efficiency of electricity and heat 90%, with low-pressure feeding of fuel cells
Fuel cell heat balance and extraction	Fuel cell cooling and aerodynamics are main design criteria	Heat (and cold) at temperature levels for use in buildings. Flexible in producing electricity, heat and water
Fresh water production	None	Extraction and use of exhaust water and steam for fresh water production
Hydrogen production and storage	Efficiency, purity and cost of feeding material (power, gas, biomass); micro installations for home-use	Medium-sized, reliable, safe installations with high conversion efficiencies and high-quality hydrogen needed
System integration and control	Hydrogen fuelling stations available in urban areas and in highway system - mainly conversion and safety issues	Control- and energy management systems on all levels with combined power, heat and/or water demand and supply
Car-park power plant development	None	Automated parking with safe integrated hydrogen production, -storage and -fuelling . Multiple connections and robotics for hydrogen, heat, water, electricity
Energy Infrastructure	No need for hydrogen infrastructure, only conversion technologies to hydrogen	No need for hydrogen infrastructure. Optimizing gas, electricity and water infrastructure

SYSTEM CHALLENGES

The organization of such an energy system will differ fundamentally from our present system. Everyone can locally produce renewable energy, from solar, wind, hydro or biomass. It can be done physically at your own house, school, office, or within your neighbourhood. And everyone has abundant electricity production and -storage capacity available: their own cars and/or cars owned by lease companies or through our social network organizations. There will be also large-scale renewable energy production, an electricity- and gas infrastructure and our car parks and other parking places will change into energy production facilities.

This mobile E-cloud 'energy and transport cloud' will require an internet-based control system in which we have billions of suppliers of energy, billions of capacity providers and billions of consumers of energy. Who will build and operate this intelligent network? Who will develop the architecture and provide all the necessary services and applications? The energy companies, the network companies, the car manufacturers, the software providers and IT companies, the logistic companies or the building industry by building and operating the car parks, or your own social network? Most likely it will be a combination of all these industries and new companies.

Business in transport and energy will change. Business models, assets, products, services and markets will change dramatically. Present car manufacturers, energy companies, infrastructure and logistics providers, technological engineering- and service companies, car sales, garages and many other industries need to change and develop new business models. Car manufacturers, IT companies and energy companies can develop part of the new business, but also have to co-operate to develop such a fundamentally new transport- and energy system.



Organizational innovations need to be addressed. Who will be the owner of the car, the fuel cell in the car, can energy companies lease our car, or will this be organized by ourselves via our social networks with the help of new service providers?

Regulatory, safety and tax issues have to be addressed. It is for example really necessary to get free access to the electricity and water grid. To allow everyone to produce electricity and water anywhere and transport it to the place where we want to use it without any regulatory-, tax- or other market barriers. And what does this mean for government revenues from taxes on transport fuel, electricity, water or parking?

But above all, how will consumers be involved and react to this fundamental change of our energy and transport system? In essence the fuel cell car can socialize our energy system towards the E-cloud, like the internet has done for information. Consumer perception is crucial for the technology- and system changes to catch on. The car owners and -drivers are exposed to totally new functionalities, which can be perceived as energy- and transport freedom. But changes can also cause anxieties and resistance.

OUR CAR AS POWER PLANT **SYSTEM CHALLENGES**

CHALLENGE	FUEL CELL CAR	CAR AS POWER PLANT
E-cloud Energy & Transport Cloud	Billions of cars could be connected to optimize our transport needs for example by sharing	Billions energy suppliers, capacity providers and energy consumers connected. Communities can exchange, control and be self-sufficient.
Business	Business changes not much	Business models, products, services and assets will change dramatically. Business innovation necessary.
Regulations, safety and tax issues	Safety of fuelling stations and fuel cell cars	Free access to electricity and water grid is necessary. Regulatory energy framework has to be changed. Tax system has to be changed.
Consumer perception	Comfort issues, such as safety, reliability, driving distance	Fuel cell car can socialize our energy and water system, gives freedom. But changes can cause anxieties and resistance.

WHY IT WILL HAPPEN

Our vision is that fuel cell cars can provide efficient and clean transportation and at the same time can produce clean and efficient electricity, heat and water. This vision can change the world dramatically. But will it happen? Of course we cannot be sure, but there are some developments and reasons why we think it will.

FUEL CELL CARS WILL COME

The fuel cell car is only at the beginning of its development. There are many demonstration- and introduction projects ongoing. Countries like South Korea, Japan, Germany, the US have significant research-, demonstration- and introduction programs for fuel cell cars, together with hydrogen-production and hydrogen-fueling stations. All large car manufacturers in the world are developing the fuel cell car and some of them have announced to bring first series to the market.

The learning curves of hydrogen conversion and fuel-cell technology generate confidence in a steady increase in efficiencies, life time and reduction of cost (34,36). Some of the car manufacturers have already performed experiments with the fuel cell car to produce power at homes.

The development in the energy sector are also impressive and towards renewable energy generation. Wind and solar show double-digit growth in the past decades. Hydrogen could be produced by electrolysis ‘for free’ already today, at moments when there is an excess of renewable electricity produced by wind, solar and hydro. Countries like Germany, Denmark show this. Natural gas is abundantly available as a feedstock for hydrogen production with a low carbon-dioxide emission. And in future biogas can take that role.

IT IS OUR CAR!

So the fuel cell car will come. But do we actually want to use our car to produce electricity, heat and water? Why not, it does not depend on what companies, governments or organizations want us to buy, do or believe. No – the car is ours, or at least we can decide what to do with it. The fuel cell car will not only give us the freedom to go where we want to go, but it will give us also the freedom of energy and water. We can produce energy and water where and when we need it.

With our fuel cell cars we can even produce electricity for others. Therefore, when we park our fuel cell cars we do not have to pay for parking but we get paid for parking. Isn't that a nice future?

REFERENCES

1. https://media.ford.com/content/fordmedia/fna/us/en/news/2013/08/05/model-t-facts.html
2. Engine specifications from official website: http://www.ford.com/cars/focus/specifications/engine/
3. Kenneth Holmberg, P. A. (2011). Global energy consumption due to friction in passenger cars. Elsevier. http://www.sciencedirect.com/science/article/pii/S0301679X11003501
4. US Department of Energy http://www.fueleconomy.gov/feg/atv.shtml
5. California http://www.consumerenergycenter.org/transportation/consumer_tips/vehicle_energy_losses.html
6. Report from the commission to European Parliament and the council (2010). Monitoring the CO2 emissions from new passenger cars in the EU: Data for the year 2008.
7. Zervas, E. (2010). Analysis of the CO2 emissions and of the other characteristics of the European market of new passenger cars. 1. Analysis of general data and analysis per country. Energy Policy.
8. Georgios Fontaras, V. F. (2013). Development and review of Euro 5 passenger car emission factors based on experimental results over various driving cycles . Science of the total environment.
9. Jing Dong, C. L. (2013). Charging infrastructure planning for promoting battery electric vehicles: An activity-based approach using multiday travel data. In Transportation Research Part C: Emerging Technologies (pp. 44-55). http://www.sciencedirect.com/science/article/pii/S0968090X13002283
10. Data from official website of Nissan. http://www.nissanusa.com/electric-cars/leaf/charging-range/#/leaf-electric-car/faq/list/charging
11. The World Bank database (Bank) is linked to United Nations sources (2013) http://data.worldbank.org/

12. OICA, the International Organization of Motor Vehicle Manufacturers (2013) http://www.oica.net/category/production-statistics/
13. OECD, International Transport Forum, Transport Outlook 2012; Seamless Transport for Greener Growth, Paris 2012 http://www.internationaltransportforum.org/Pub/pdf/12Outlook.pdf
14. Ward's auto world, 2007 light vehicle engines http://www.wardsauto.com
15. US EIA data power plants http://www.eia.gov/cfapps/ipdbproject/IEDIndex3.cfm?tid=2&pid=2&aid=7
16. BP Statistical Review of World Energy (2013) http://www.bp.com/content/dam/bp/pdf/statistical-review/statistical_review_of_world_energy_2013.pdf
17. GWEC Global Wind Energy Council http://www.gwec.net/wp-content/uploads/2012/06/Global-Cumulative-Installed-Wind-Capacity-1996-20122.jpg
18. IEA ETSAP (Energy Technology Systems Analysis Programme), Gas-Fired Power, Technology Brief E02, April 2010 www.etsap.org
19. IEA ETSAP (Energy Technology Systems Analysis Programme), Coal-Fired Power, Technology Brief E01, April 2010 www.etsap.org
20. China electricity system efficiency data http://www.iea.org/statistics/topics/energyefficiency/
21. USA electricity system efficiency data http://www.eia.gov/electricity/annual/html/epa_08_01.html
22. US DOE (http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/fct_h2_fuelcell_factsheet.pdf)
23. EG&G Technical Services, Inc. (2004) Fuel cell hand book, seventh edition, US DOE
24. US DOE Hydrogen Analysis Resource Centre, http://hydrogen.pnl.gov/cocoon/morf/hydrogen
25. Ari Virtanen and Yeon-Mi Lee, Electric Vehicles South Korea, Finpro, Seoul, 2010
26. US DOE http://www.hydrogen.energy.gov/fuel_cells.html

27. Mehrdad Ehsani,Yimin Gao,Ali Emadi, (2010) Modern Electric, Hybrid Electric, and Fuel Cell Vehicles: Fundamentals, Theory and Design, second edition, CRC Press
28. http://www.hyundai.co.uk/about-us/environment/hydrogen-fuel-cell
29. Fatwa F. Abdi, et.al., Efficient solar water splitting by enhanced charge separation in a bismuth vanadate-silicon tandem photoelectrode, Nature Communications 4, Article number: 2195 (2013)
30. US DOE http://www1.eere.energy.gov/hydrogenandfuelcells/storage/current_technology.html
31. US DRIVE, http://www.hydrogen.energy.gov/pdfs/review12/st000_stetson_2012_o.pdf
32. http://shrinkthatfootprint.com/average-household-electricity-consumption
33. Margriet van Schijndel-de Nooij et. al. (2011) 'Definition of necessary vehicle and infrastructure systems for Automated Driving' SMART 2010/0064, Study report to the EC
34. US DOE http://www1.eere.energy.gov/hydrogenandfuelcells/accomplishments.html
35. IEA Hydrogen Implementing Agreement http://ieahia.org/pdfs/StrategicPlan2009-2015.pdf http://ieahia.org/
36. McKinsey&Company (2010) "The role of Battery Electric Vehicles, Plug-in Hybrids and Fuel Cell Electric Vehicles", report for the European Power Train Coalition

SUMMARY

Fuel cell cars: efficient and clean transportation AND clean and efficient production of electricity, heat and water.

Fuel cell cars can provide more efficient and cleaner transportation. However, we use our cars for transportation only 5% of the time. So when parked, the fuel cell in the car can produce electricity from hydrogen. Cleaner and more efficiently than the current electricity system – with useful 'waste' products heat and fresh water. The produced electricity, heat and fresh water can be fed into the respective grids or be used directly in our house, office or the school of our kids. The required hydrogen can be produced from gas (natural gas, biogas) or electricity (hydro, wind, solar, etc.). In the end these fuel cell cars can replace all power plants worldwide. As a result, the 'car as power plant' can create an integrated, efficient, reliable, flexible, clean, smart and personalized transport-, energy- and water system. A real paradigm change: our car as power plant.

ABOUT THE AUTHORS

Ad van Wijk is sustainable energy entrepreneur and Professor Future Energy Systems at TU Delft the Netherlands. Van Wijk started his career as scientific researcher in sustainable energy at Utrecht University

In 1984, van Wijk founded the company Ecofys, which eventually grew into Econcern. Econcern developed many new sustainable energy products, services and projects. Examples include the 120 MW offshore wind farm Princess Amalia in the North Sea, several multi-MW solar farms in Spain and a bio-methanol plant in the Netherlands, which is the largest second generation biomass plant in the world. Van Wijk achieved many important prizes for excellent entrepreneurship. Amongst others he was Dutch entrepreneur of the year in 2007 and Dutch top-executive in 2008. At TU Delft van Wijk will focus on the energy systems of the future such as the car as power plant. Especially he will do research and at the same time will realize ''the Green Village''. www.thegreenvillage.org where these future energy systems will be implemented, tested and researched in 'Future labs'

Van Wijk has published a very readable book about the energy system 'How to boil an egg' ISBN: 978-1-60750-989-9. And a book about the Green Village 'Welcome to the Green Village' ISBN: 978-1-61499-283-7 (print) or ISBN 978-1-61499-284-4 (online)

Follow Ad van Wijk at twitter @advanwijk or via his website www.profadvanwijk.com

Leendert Verhoef is sustainable energy innovator and currently Science and Innovation manager at The Green Village. He started his career with a Ph.D. degree in solar energy from Utrecht University and worked from 1990 to 1998 in R&D management in industry and government. In 1998 he founded a consulting company, which grew into New-Energy-Works. His main interest are technological innovation and large scale introduction of disruptive sustainable technologies. He has held numerous workshop and conference presentations and published books and papers on these topics.

Examples are SunCities: world's largest suburb fully developed to optimize solar energy (ISBN 978-90-75365-96-2), and 'Energy from the desert', a plan to supply the worlds' electric power from deserts covered with GW's of solar panels (ISBN 978-184407-363-4).

At The Green Village, Verhoef will focus on technological innovations in the car as power plant and other Future Labs, and stimulating and harnessing disruptive joint innovation between industry and academia and creating spin-off activities.

Follow Leendert Verhoef at twitter @LeendertVerhoef
or at www.presolve.wordpress.com.