Dr.-Ing. Félix Urbain

AN INTRODUCTION TO ALTERNATIVE AND SUSTAINABLE FUELS FOR THE TRANSPORT OF TOMORROW

Clean Fuels

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SCRIPT
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Clean Fuels

Dr.-Ing. Félix Urbain

AWAY FROM DIESEL AND PETROL -
What are the options in transportation for a more sustainable future of our earth?

Contents

“Anything against nature will not abide for any length of time.“

Charles Darwin

Chapter 1:

Away from fossil fuels

Why do we need alternatives to oil, gas and coal in the future?

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- Chapter 1.1 Fossil fuels -

Fossil fuels are energy sources from which fossil fuel energy can be obtained. The best-known representatives of fossil fuels are, as shown in Figure 1.1, natural gas, peat, petroleum, lignite, and coal. The term fossil is derived from the Latin word *fossa*, which means ditch or digging in Latin. This is easy to understand because to obtain energy from fossil fuels, people have to dig deeply into the earth. In fact, fossil fuels are nothing more than the decomposition products of dead organic life forms, such as plants, animals and marine plankton, which were deposited as biomass on the bottom of wetlands and oceans millions of years ago, in geological prehistory. Over time, more and more organic materials have been deposited, which has led to huge layers of organic material mixtures piling up, with thicknesses of up to 10 kilometres (see Figure 1.2).

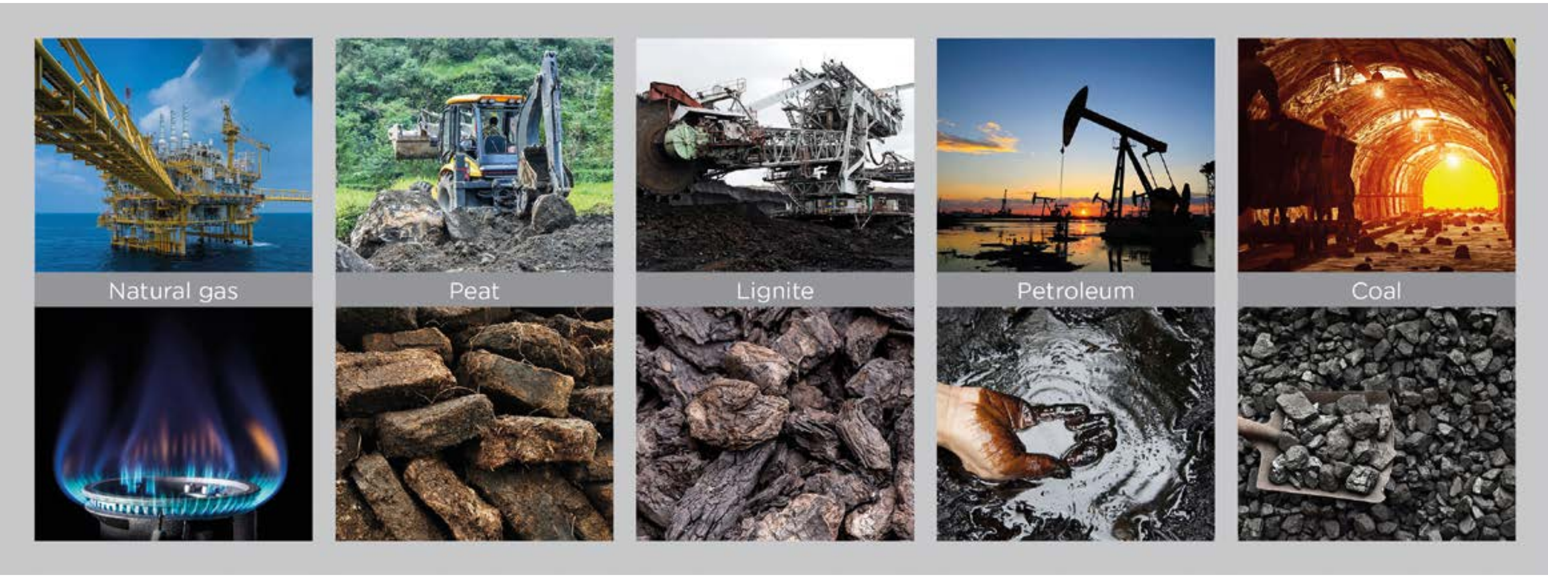

Figure 1.1: Fossil fuels (below) and their extraction (above)

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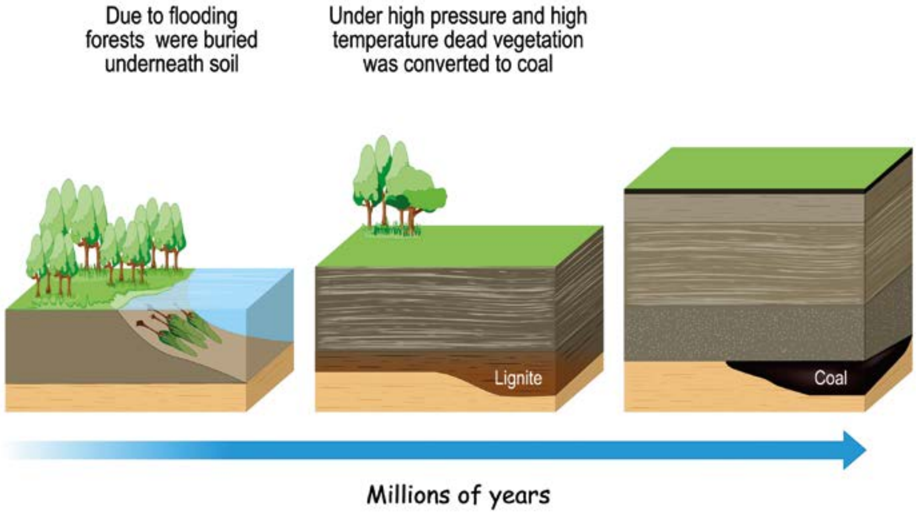

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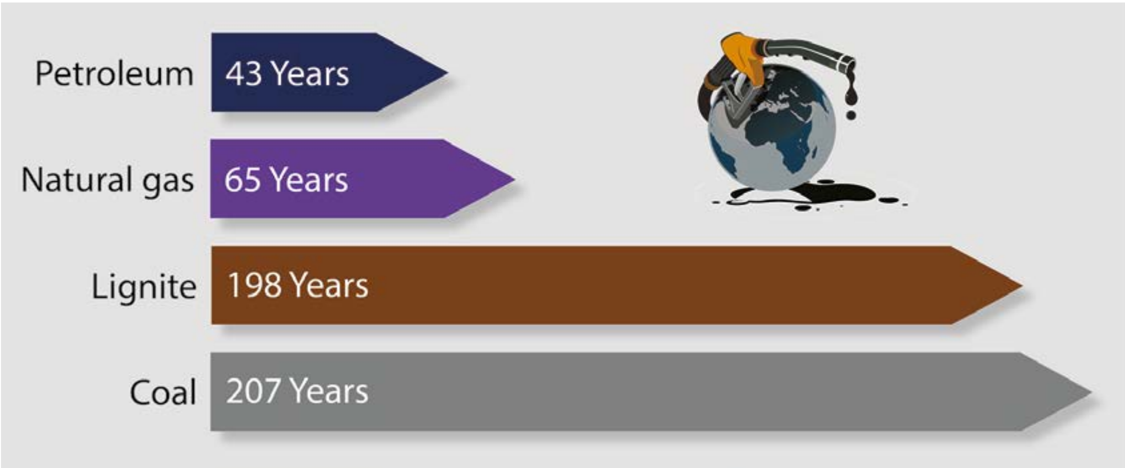
Figure 1.2: Formation of fossil fuels

As these layers had been exposed to ever increasing pressures and temperatures, due to their growth and weight, chemical reactions occurred within the material mixtures. These extreme subterranean conditions ultimately led to the transformation of the buried organic materials into the fossil fuels known to us today, as depicted in Figure 1.1.

- Chapter 1.2 Energy problems of fossil fuels -

Chapter 1.2.1 Sustainability

Nowadays, fossil fuels are formed by photosynthesis in various places on earth. However, these development processes are extremely slow in relation to the current global rate of consumption, for instance for the production of petrol, diesel or electricity. Fossil fuel energy provided by nature is therefore only available to a limited extent and, as shown in Figure 1.3, will not be suficient to meet the global energy demand in the future. For example, researchers predict that if people will not change their current consumption habits, petroleum reserves will be completely depleted in about 43 years.



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However, this is true not only for the consumption of fossil fuels, but also for other resources that are available only to a limited extent. This imbalance between the available energy provided by our earth and the energy that will be required in the future, clearly reflects our current energy problem:

Energy problem 1 - Sustainability:

Mankind is consuming the world's natural oil, gas and coal reserves at breakneck speed and is in the process of completely depleting the fossil fuels formed over millions of years within only a few centuries.

Fossil fuels are not considered as renewable or regenerative energies. As opposed to fossil fuels, renewable energy includes any energy that is taken from energetic processes that are continuously renewed and are not limited in its availability; this includes, for example, solar, wind and water energy. We will take a closer look at these unlimited energy sources in Chapter 2.

Chapter 1.2.2 Environmental pollution

From a purely energetic point of view, it is astonishing how fossil fuels could assume such a dominant role on the global energy scene. In fact, the use of fossil fuels to generate energy, for example by burning it in car engines, is a cumbersome and highly inefficient method, during which more energy is consumed than gained. The efficiency of internal combustion engines is well below 50 percent. In addition to the low energy yield of fossil fuels, its effects on our environment are a major problem today. When fossil fuels and / or their associated gases are burned, in presence of oxygen, energy is released in the form of heat and oxides, which inevitably includes CO_2 - the main cause of global warming.

Other released gases that are harmful to the environment when burning fossil fuels, are sulfur dioxide and nitrogen oxides. Both cause acid rain and thus contribute to severe forest damages. In case the fossil fuels are not completely burned, pollutants such as carbon monoxide, hydrocarbons and soot particles are also left behind. The resulting dust is toxic and damages our health. Hence, environmental pollution can be formulated as a second global energy problem:

Energy problem 2 - Environmental pollution:

The environment is regularly polluted when fossil fuels are converted into another form of energy. Above all, this include greenhouse gas emissions, but also intrusive interventions in landscapes and ecosystems to obtain fossil fuels.

Chapter 1.2.3 Unequal distribution and consumption of energy reserves

We still use fossil fuels extensively, such as oil, natural gas and coal: According to scientific data, these fuels cover a large part of the energy needs in Europe (around 50 percent). Our energy system must therefore be restructured in terms of sustainable and future-oriented development.

The restructuring must target energy savings, more efficient energy generation and use, as well as a transition to emission-free energy sources. In fact, we are living in a world in which the energy demand is very unevenly distributed:

The energy requirement of an average Central European is around ten times that of a person living in Africa. Moreover, about 60 percent of the people living in Africa don't even have electricity. These numbers illustrate how unevenly the available energies are distributed on earth. Hence, our third global energy problem is defined as:

Energy problem 3 - Unequal distribution and consumption:

20 percent of the world's population uses 80 percent of all energy resources.

“If you think the economy is more important than the environment,
try holding your breath while counting your money.“

Dr. Guy McPherson

CHAPTER 2:

Alternative fuels for a more sustainable transportation

What comes after diesel and petrol?

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- Chapter 2.1: The potential of alternative energy -

Chapter 2.1.1: What is alternative energy?

Energy is life. Although this sounds like an advertising slogan, it is the most fundamental of all physical laws: A system cannot work without energy input. The law of conservation of energy states that humans are able to convert energy into various forms of energy without changing the total energy of the system over time. We humans take for granted to be able to consume energy in the form of electricity, heat and fuel, just as we are used to from clean drinking water, food or medical care. Fossil fuels still are the main drivers of the energy industry, especially for the automotive and transportation sector. However, a sustainable future urges for alternative and sustainable energy, because currently widely used raw materials such as coal, uranium, oil and gas are limited resources and will soon be depleted.

Researchers and developers around the world are therefore working on the implementation of innovative processes for generating energy that does not rely on fossil fuels. Alternative energy uses both finite and inexhaustible sources of energy as raw materials.

Chapter 2.1.2: Various possibilities for alternative energy generation

There are many natural energy sources, such as solar energy, wind energy, hydropower, biomass and geothermal energy, that we can make optimal use of to generate sustainable energy. These alternative energy sources are shown graphically in Figure 2.1. In addition, the figure shows how much energy is annually available per source compared to global energy consumption (2020 and 2050). The figure for current and future energy consumption is based on the exhaustible (fossil and nuclear) energy sources still available today: natural gas, crude oil, coal and uranium. In the following chapter we will take a closer look at alternative energy sources.

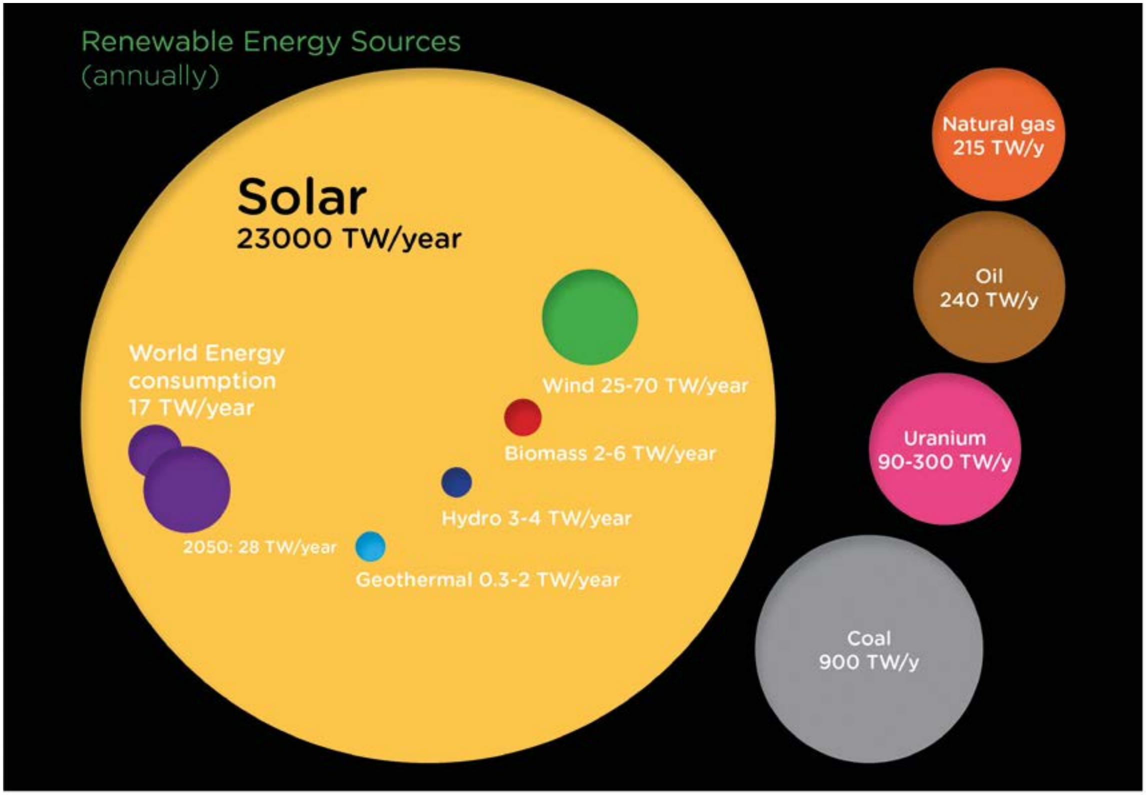

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Figure 2.1: Available energy sources compared with global energy consumption (expressed in terawatts per year [TW / year])

- Chapter 2.2: Alternative energy sources -

Chapter 2.2.1: Solar energy

The sun is by far the most important source of energy on our planet. Without the sun, no life on earth would be possible. It is responsible for the photosynthesis and the climate, while supplying us humans with oxygen and food through the plants. The sun's heat drives ocean currents and winds, which are essential for a stable climate. As an interesting fact, the energy of the sun, which is absorbed by the earth's surface, would be sufficient to cover the world's energy demand by more than ten thousand times (see Figure 2.1). In other words, this means that the sun delivers enough energy in just three hours to cover the annual energy needs of the entire world - unbelievable!

In addition, this enormous source of energy is available to us free of charge. You could say: "The sun doesn't send a bill." Today you can find solar panel systems on building roof surfaces, for example on apartment buildings and industrial plants (Figure 2.2), as well as on large fields.

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Figure 2.2: Solar panels

Chapter 2.2.2: Wind enery

The most widely used alternative energy source for the production of electricity is, however, not the sun, but wind energy. Almost half of the world's alternative energy is generated using wind power. In large wind farms (Figure 2.3), the kinetic energy of rotors, driven by the wind, is converted into torque and converted into electrical energy, i.e. electricity in electrodynamic generators. Wind turbines use rotor blades for this purpose, which, like an airplane wing, work according to the buoyancy principle.

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Figure 2.3: Wind energy farm

Chapter 2.2.3: Hydropower

Hydropower plants use the flow of water to generate electricity via turbines in generators. The most common representatives of this type are water reservoirs (Figure 2.4). They accumulate a large amount of water in large storage reservoirs or dams in order to direct it through turbines. Here, the pure flow force of the water is used ; meaning the potential energy of the water, which is created by the difference in altitude. The power of water is reliable, which makes it well suited as a storage medium and can be accessed within a very short time if necessary.

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Figure 2.4: Water reservoir

Chapter 2.2.4: Biomass

One of the most flexible alternative methods of generating energy is the consumption of biomass. Biomass includes all organic substances that generate energy through fermentation or combustion processes, respectively. You can choose between different procedures:

1) Methane gas is obtained from plant and animal waste. Methane gas, in turn, can be converted into electricity and heat by gas turbines. The electricity generated in this way is fed into the grid. The methane gas is temporarily stored in large tanks (Figure 2.5).
2) Methane gas can also be fed directly into the natural gas network or used as fuel for gas-powered vehicles (see Chapter 3).
3) Thermal power plants burn solid materials, for example wood waste, to generate heat. Through a combined heat and power system, electrical energy is generated at the same time, while the waste heat is used for local and district heating.

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Figure 2.5: Methane gas storage

- Chapter 2.3: Fuels from alternative energy sources -

The primary goal of alternative energy generation is currently to generate clean electricity to counteract the decreasing amount of fossil fuels. Research and industry around the world are therefore looking for methods to use this electricity from renewable energies for environmentally friendly alternative forms of energy. On the one hand, fuels can be produced, such as hydrogen and bio-fuel, on the other hand, clean electricity should be stored efficiently, e.g. in batteries.

Chapter 2.3.1: Hydrogen

In fact, hydrogen (H_2) has been on the research agenda for a long time. “Water”, as predicted by the French visionary Jules Verne almost 150 years ago, could become “the coal of the future”, if it would be possible to obtain one of its energy-rich elementary particles, namely hydrogen. Already then, numerous scientists were investigating hydrogen and its possible fields of application.
Hydrogen can be found in the first main group of the periodic table and is considered the most reactive element of all. When it reacts with oxygen atoms, it releases enormous amounts of energy. For this reason, hydrogen is ideal for powering vehicles and machines. We will see exactly how this works in Chapter 3.
Although it is the lightest of all elements, hydrogen is the most abundant chemical substance, constituting roughly 75 percent of the mass of the entire universe. Moreover, it is found in all living organisms known today. However, there is one major problem: Hydrogen rarely exists alone and occurs almost exclusively in bound state, e.g. as a component of water (H_2O) or of larger organic compounds. In order to make it usable as an energy carrier, hydrogen must first be isolated using energy-intensive chemical processes. In the case of H_2O, it thus has to be separated from the oxygen atom, and one also speaks of the so-called “water splitting“ reaction.

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Depending on the used H_2 generation process, hydrogen is classified into **gray**, **blue** or **green** hydrogen.

Although the end product is the same in each process, the latter differ considerably in their production method - and thus also in their carbon footprint:

Gray hydrogen is obtained from fossil fuels, primarily through the steam reforming process: In the presence of heat, natural fossil gas reacts with water vapor and releases (carbon monoxide, CO) and hydrogen. The latter can then be used for further applications. However, this process also creates CO_2, which is why gray hydrogen is not classified as climate-neutral.

Blue hydrogen is initially obtained in the same way as gray hydrogen. Thus, this process also emits CO_2. However, in this case hydrogen is not gray, and becomes blue, i.e. more climate-friendly, because the resulting CO_2 is captured directly after the production process before reaching the atmosphere. This CO_2 can then, for example, be stored underground or further processed as a raw material. Technically one speaks of "CO_2 capture and storage" (CCS or CO_2 sequestration).

Green hydrogen is the end product of an electrolysis process that is carried out entirely with renewable energies. Electrolysis is an electro-chemical process in which water (H_2O) is split into hydrogen (H_2) and oxygen (O_2) with the help of electrical energy (electricity). If this electricity comes from renewable energy sources, the electrolysis works without any direct emissions of CO_2 or other greenhouse gases. For example, green hydrogen can be produced directly using electricity generated from solar energy.

Hydrogen can only contribute to climate protection targets if its production is CO_2-neutral. Currently, blue hydrogen is a controversial topic, because CO_2 storage in soils is still not considered as a mature technology, raising doubts regarding its practical feasibility. This is because, it cannot be guaranteed that climate-damaging greenhouse gases will not escape into the atmosphere in the course of the process. In addition, only around 90 percent of the CO_2 can be captured in the process, meaning that 10 percent escape and inevitably enter the atmosphere. The production is therefore not completely emission-neutral.

From an ecological point of view, green hydrogen is therefore the only practical alternative, at least in the long term. The current associated problem: The quantities of emission-free electricity required for production of green H_2 are enormous. According to the International Energy Agency (IEA), 20 to 40 percent of the input energy is lost during current state-of-the-art electrolysis processes. In addition, there are losses in further processing during compression (up to 15 percent) or liquefaction (up to 25 percent). As a result, a large part of the energy is already lost - around 80 percent - before hydrogen can even be used as an energy carrier.

Moreover, the renewable production of green hydrogen from water is also very expensive. The costs of production are around three times (with electricity from wind energy) to up to ten times (with electricity from solar energy) as much as producing hydrogen from fossil fuels. This is exactly what defines the strategic dilemma of today's hydrogen policy.
All over the world, meticulous research is therefore being carried out on new and renewable concepts in order to be able to produce green hydrogen much more cheaply to make it practical for a more ubiquitous use.

Chapter 2.3.2: Bio-fuel


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Bio-fuels include bio-diesel, bio-ethanol, bio-methane and other synthetic fuels currently being developed. All of them meet the needs of the automotive and transportation industry, because they are very similar to diesel and petrol in many parameters and can be used in conventional internal combustion engines with relatively simple adaptation measures.

Apart from bio-methane, which is chemically identical to natural gas, bio-fuels are liquid fuels and therefore easy to store, while they can be distributed via the existing network of petrol stations.

Bio-fuels help to protect the climate, because when they are burned to produce energy, they only release the CO_2 that was already bound in the plants they consisted of. Hence, their CO_2 balance is largely neutral. Although energy is used to produce the biofuel, which usually comes from fossil sources, large amounts of CO_2 can be saved compared to burning diesel and petrol. In this way, bio-fuels make a decisive contribution to climate protection.

Chapter 2.3.3: The battery as an effective energy storage medium

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Batteries, mostly using lithium-ion batteries, are the preferred storage medium to store energy generated by photovoltaic, wind power and hybrid systems. Also in the transport sector, battery technology is playing an increasingly important role. Every battery basically works in the same way: They convert chemically stored energy into electrically usable energy. Inside a battery, metals react with a conducting liquid (electrolyte) and emit negatively charged particles: the electrons. Ultimately, an electrical voltage is created between a positive and negative electrode, which defines the energy that can be stored.

Today's batteries can be applied on a broad basis because of its ever decreasing costs and they have become the most popular solution for storing renewable energy. However, today's batteries still pose challenges regarding their production because they contain materials that are highly harmful to the environment. Most batteries used in electric vehicles contain metals that are toxic and harm the environment, such as cobalt and nickel. Recycling turns out to be even more difficult. In addition, batteries have a short lifespan and little storage capacity compared to the required manufacturing efforts. Minimizing these issues is one of the main challenges that researchers and engineers all over the world are currently facing.

“Water will be the coal of the future. Tomorrow’s energy will be water which has been decomposed by electricity, and that its elements (hydrogen and oxygen) will provide the earth with an indefinite supply of energy.“

Jules Verne (Novel: The Mysterious Island, 1870)

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Chapter 3:

Environmentally friendly drive technologies

Where will the drives of the future be compared to conventional drives?

- Chapter 3.1: Diesel and petrol - the *status quo* -

Diesel and petrol, which have been in constant use for over 100 years, set the benchmark by which any future fuel must be compared to. Today's diesel and petrol that are offered at filling stations, have already gone through a long development process. Continuous basic research and industrial development over the years, have led to today's available fuels. Both, diesel and petrol, are high-quality and high-tech products, consisting of a complex chemical mixture of various hydrocarbons, aromatics, additives and other substances. For example, today's diesel fuel contains around 500 ingredients, including over 200 different hydrocarbons. Each of these ingredients has a specific role in how the fuel works.

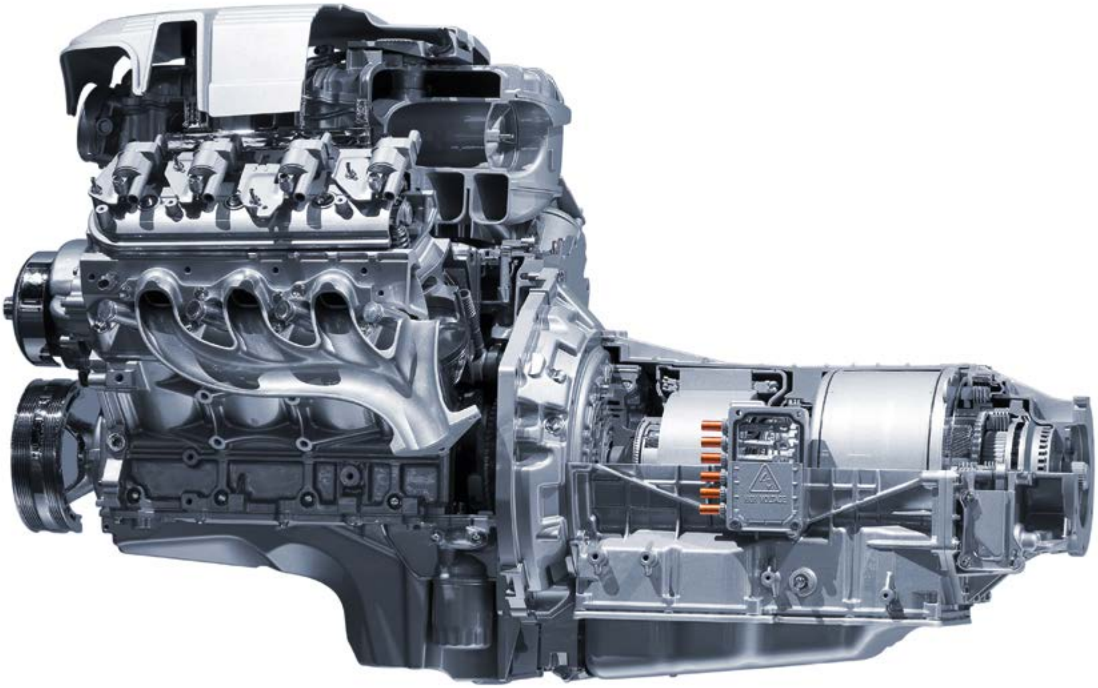
However, the large amount of ingredients also entails disadvantages, as it makes it very difficult to optimize the efficiency of the combustion process. Certain ingredients, such as aromatics are simply undesirable, because they only increase pollutant emissions. This is why fuel manufacturers are striving to reduce or even eliminate these as much as possible through better manufacturing processes.

- Chapter 3.2: Novel and sustainable drive technologies -

In the following, we analyse to the most promising novel drive technologies that can contribute to a more sustainable transportation. We will get to know the working principles, but also the advantages and disadvantages of these future driving approaches.

Chapter 3.2.1: Hybrid drive

A hybrid drive is the combination of an electric drive with a diesel or petrol drive.



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Working principle: In diesel- or petrol-electric hybrid vehicles, the advantages of the electric and the internal combustion engine are combined in such a way that the overall drive system works as efficiently as possible. Excess mechanical energy from the internal combustion engine is converted into electrical energy and stored in a battery. The latter, in turn, emits this electrical energy when required in order to drive the electric drive. When the battery power drops, the electric drive automatically works as a generator and recharges the battery while driving.

If the battery in a hybrid vehicle can be charged via the power grid, it is called a plug-in hybrid. Such hybrids have a much more powerful electric drive and a larger battery than normal hybrids. It can be driven purely electrically up to over 100 km/h and electric ranges between 50 - 70 km can be achieved. Plug-in hybrids are therefore particularly promising for journeys within the electric range and wherever the vehicle can be charged at the destination or at home.

Advantages: When driving in cities or metropolitan areas, a hybrid drive uses up to 25 percent less fuel than an internal combustion engine.
In contrast to a purely electric car, drivers are also less dependent on existing charging stations.

Disadvantages: Hybrid cars are several thousand euros more expensive than conventional vehicles of the same model. The lower fuel consumption will currently not be able to compensate for this additional expenditure.
Hybrid drives are often heavier than normal diesel or petrol drives - which can even lead to increased fuel consumption, especially on longer motorway journeys.

Chapter 3.2.2: Battery-electric drive

A battery-electric drive is quiet, locally emission-free and, thanks to its high-torque drive, it offers driving comfort and driving pleasure.

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Figure 3.1: Battery for an all-electric drive

With electric ranges of between 200 and 450 kilometers (or more), electric cars nowadays cover significantly longer distances than they did a few years ago. With an extended infrastructure of fast charging technology and good planning, even much longer distances become possible. Tesla, with its network of superchargers in Europe and around the world, is a prime example of this.

Working principle: The heart of an electric drive is the battery (Figure 3.1). Further components are the electric motor, the power electronics and the cooling systems and temperature regulation.

In an electric motor, the electrical energy of the battery is converted into mechanical energy, by leveraging the phenomenon of magnetism. As we know, poles with the same charge repel and poles with different charges attract each other. Furthermore, it is possible to make a non-magnetically charged material magnetic by passing an electric current. The polarity can also be influenced, depending on the direction in which the current flows. In a simple electric motor there is a fixed magnetic part (stator) and a moving part (rotor), which, with the help of its coil structure, is made magnetic by the current coming from the battery (Figure 3.2). If two positive poles are facing each other due to the electrical charge, then they repel each other and the moving part of the electric motor rotates. The direction of current changes automatically with every half turn. This ensures that the machine is permanently in motion and thus ensures that the vehicle can move along. The electric current required for this process is stored in the battery of the electric car and can be made available on demand.

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Figure 3.2: Electric motor

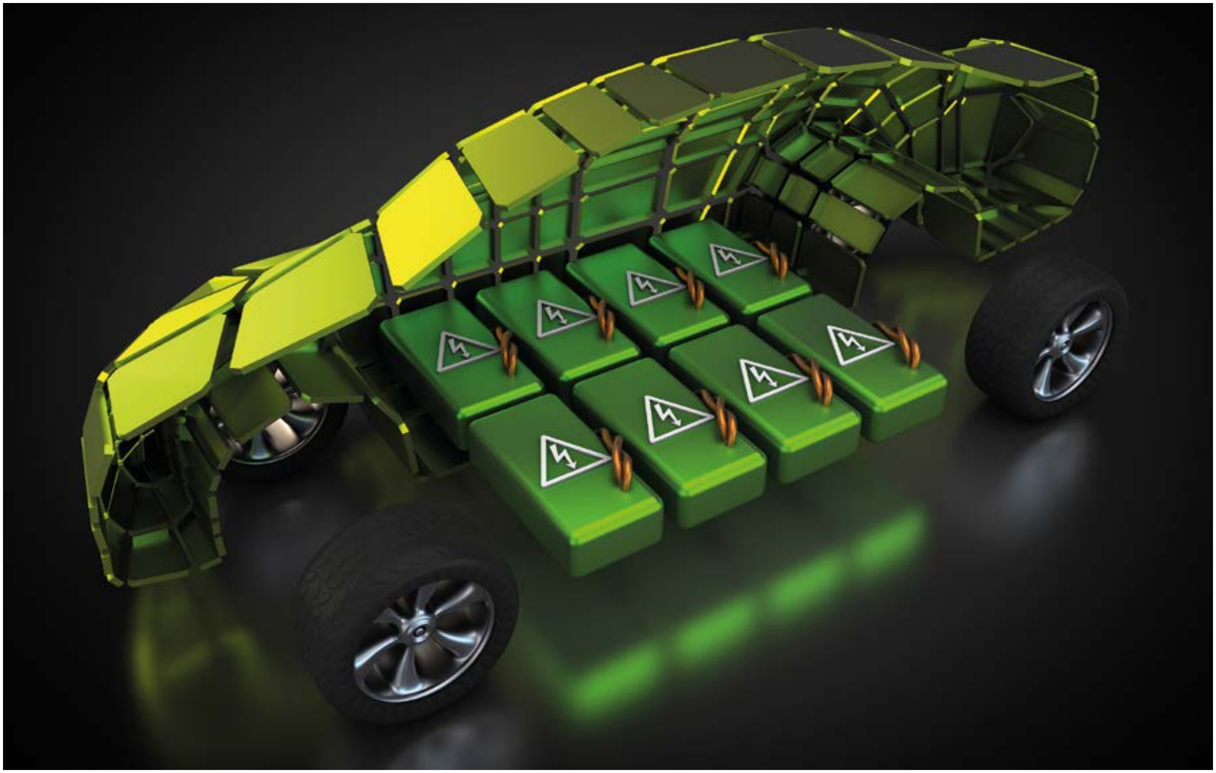

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Figure 3.3: Electric car interior design

The components in electric vehicles are arranged according to the so-called “skateboard” architecture design. This shape was ultimately the most efficient and thus the most convincing for the automotive industry. The mostly flat battery is arranged between the axles in the underbody (Figure 3.3), with the electric motor and power electronics being positioned on the front and / or rear axles. The car body is put over this “skateboard“, so to speak. This architecture makes even better use of space than vehicles with internal combustion engines.

Advantages: Simpler structure: An internal combustion engine is much more complex than a comparable electric drive. While a typical car today consists of around 1,500 individual parts, a comparable electric drive consists of fewer than 1,000 individual parts. The less complex an engine is, the less susceptible it is to failure and the more cost-effective it is to maintain.

Rapid acceleration: An electric drive can use its full torque shortly after starting. An internal combustion engine usually requires a certain speed in order to achieve the maximum torque.

Less noise: The electric drive has the advantage that it is significantly quieter than noisy internal combustion engines.

Disadvantages: Low energy density: Perhaps the biggest disadvantage of the electric drive is the low energy density of the battery. The battery storage systems in cars cannot compete with the energy density of diesel or petrol, respectively, and certainly not with that of hydrogen. Conventional lithium-ion batteries can store around 70 to 75 times less energy per kilogram than diesel or petrol, and even up to 210 times less than hydrogen. This is the reason why vehicles need many and very large batteries to enable a driving range that comes close to that of an internal combustion engine. Consequently, the batteries used in cars, or other vehicle types, are extremely heavy (e.g. 750kg in the Tesla Model S), which unravels the advantage of the lighter electric drive.

Small infrastructure: The infrastructure for charging is being continuously expanded. Nevertheless, it would still not be possible today to supply all existing cars with electricity without using the electricity grid to full capacity.

Long charging: Since the charging process for an electric car takes significantly longer than refueling with 50 liters of diesel or petrol, significantly more charging stations would be required than there are fossil fuel-based filling stations today. Fully electric vehicles currently need several hours for a full charge.

Heating up negatively affects the range: In winter times electric drives face serious challenges because the engine does not heat up the vehicle's interior enough and therefore has to be heated with extra electricity from the integrated battery. Heating therefore reduces the range of electric vehicles.

High costs: Although battery prices have more than halved since 2013, the production of state-of-the-art liquid lithium-ion batteries is still relatively expensive.

Chapter 3.2.3: Fuel cell electric drive

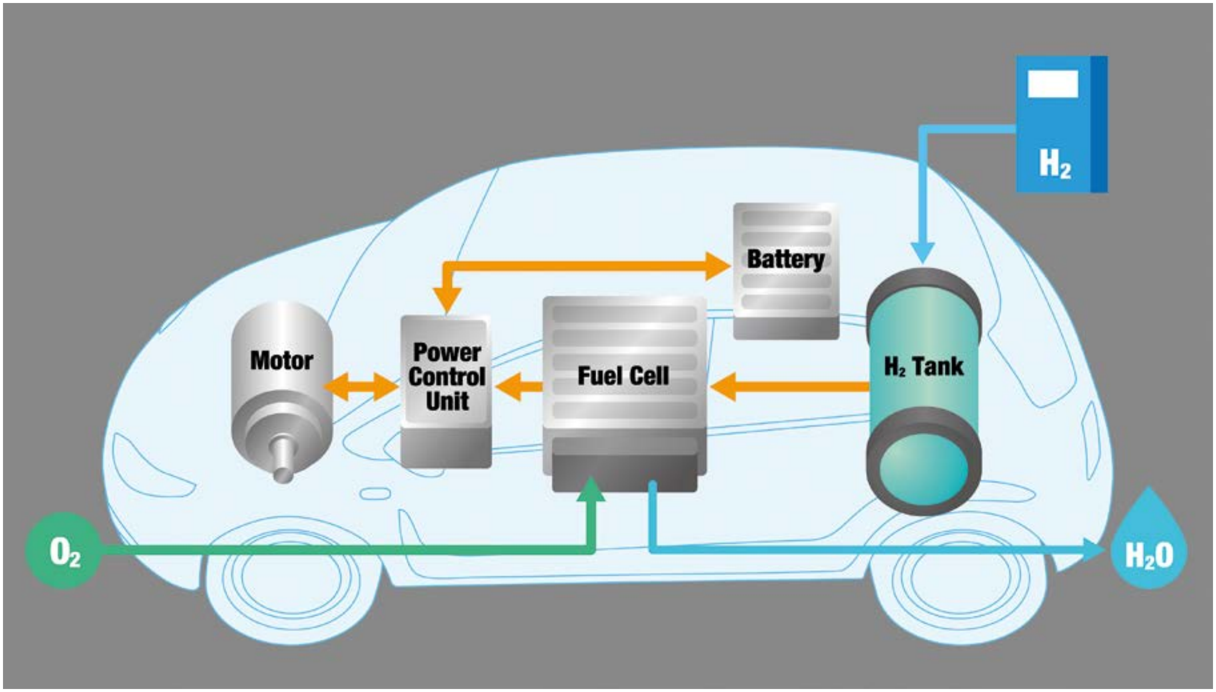

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Figure 3.4: Schematic structure of a fuel cell electric drive

Fuel cell vehicles with hydrogen are perceived as a clean and efficient alternative to internal combustion engines (structure in Figure 3.4). In fact, replacing diesel and petrol with fuel cell cars makes perfect sense, when the energy density of the used fuel is considered. As shown in the following table, hydrogen has the highest mass related energy density .

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Technology	Physical state	Energy density in [MJ/kg]	Energy density in [MJ/L]
Petrol	liquid	40-42	35-36
Diesel	liquid	43,0	19-32
Li-Ion- Battery	-	0,65	0,7-1,8
Hydrogen	gas (700bar)	120,0	7,6
Hydrogen	liquid (-253°C)	13,2	8,5

In terms of energy, hydrogen can compete with diesel and petrol. To put it into context: 1 kg of hydrogen can store around three times as much energy as 1 kg of diesel or petrol (and, as we have already seen, around 210 times as much as a battery). However, hydrogen is the lightest chemical element of all, meaning that gaseous hydrogen has an extremely low mass ; one would need roughly the volume of a zeppelin for storing 1 kg of hydrogen. In order to enable the storage of sufficiently high amounts of hydrogen, e.g. in a car or bus, the gas is therefore compressed to a very high pressure and kept safely in a limited volume. Nowadays, pressurized gas cylinders and tanks exist for this purpose, which are typically suitable for pressures in the range of 700 to 800 bar (Figure 3.5). The used pressurized gas cylinders are made of expensive, optimized

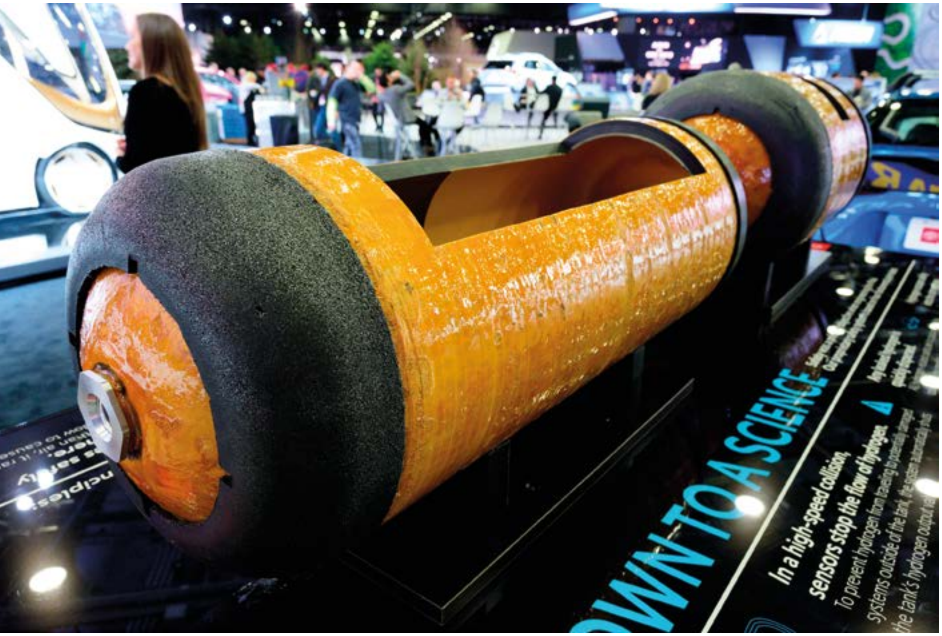

Figure 3.5: Hydrogen pressure tanks

materials (which do not become brittle due to the hydrogen) and have special closures, to avoid losses through gas diffusion.

Working principle: Hydrogen-driven vehicles, or more correctly, fuel cell-driven vehicles, are essentially electric vehicles. The difference to normal battery-electric drives is that fuel cell electric vehicles have a fuel cell and a hydrogen tank that generate the electricity for the drive while driving.
In the fuell cell, electricity is generated from hydrogen. This is done by reversing the electrolysis process (see Chapter 2.3.1). Hydrogen reacts with oxygen from the air to form water vapor, as well as heat and electrical energy. The latter is used to drive the electric motor (Figure 3.6).

Figure 3.6: Fuel cell electric drive

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So-called PEM (Polymer Electrolyte Membrane) fuel cells are used in the vehicles (Figure 3.7). This membrane makes it possible to separate the hydrogen and the atmospheric oxygen at the anode and cathode, respectively. The membrane is only permeable to hydrogen ions. At the anode, the hydrogen molecules separate into ions and electrons. The hydrogen ions migrate through the PEM to the cathode and combine with the oxygen in the air to form water. However, because the PEM represents an impenetrable barrier for them, the hydrogen electrons have to take the detour via a line from the anode to the cathode: the resulting electrical current flow charges the battery or powers the vehicle's electric motor.

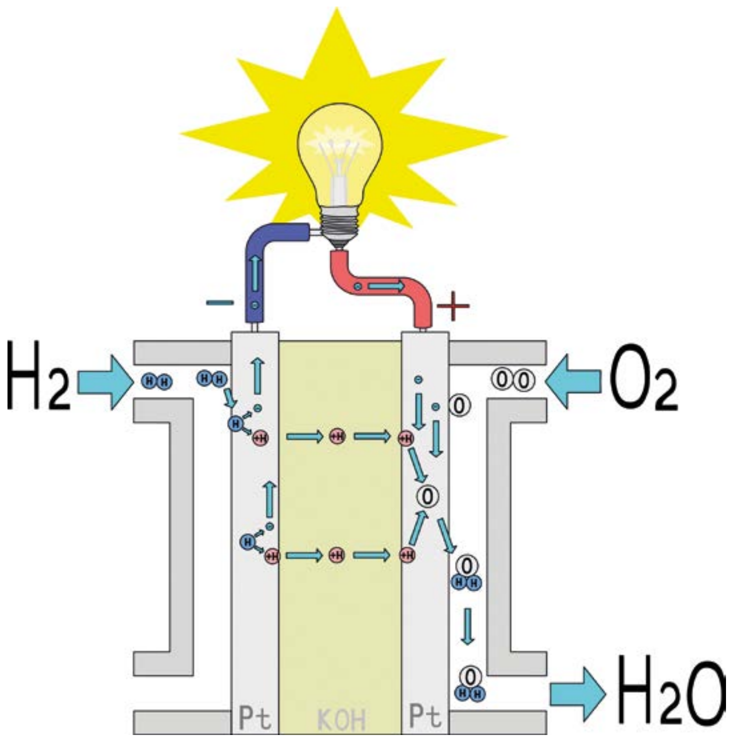

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Figure 3.7: Working principle of a fuel cell

Advantages: Quiet driving experience: Hydrogen-driven vehicles are powered purely electrically, which makes the driving experience similar to that of an electric vehicle.

Short charging time: The hydrogen tank of a fuel cell electric drive can be filled in less than 5 minutes. This means that vehicle availability and flexibility for customers are on par with a conventional diesel or petrol vehicle.

Long range: Hydrogen-driven vehicles have a longer range. A full hydrogen tank enables driving up to about 500 kilometers. In contrast to battery drives, the range of hydrogen vehicles is independent of the outside temperature, so it does not deteriorate in cold weather.

Safety: An uncontrolled reaction between hydrogen and oxygen (oxyhydrogen reaction or Knallgas) in the operation of a fuel cell car is virtually impossible. The hydrogen is stored in the vehicle in gaseous form in thick-walled tanks that are specially manufactured and subject to high safety standards. Numerous crash tests have confirmed the safety of this construction set-up. The hydrogen tanks were neither damaged in a collision, nor did hydrogen leak.

Disadvantages: One of the biggest shortcoming of fuel cell electric drives at the moment is the poor infrastructure for refueling hydrogen. Hydrogen can be filled up only at special fuel pumps, which in the future will most likely be found at regular filling stations. However, there are currently very few hydrogen filling stations in the world. At the end of 2019 there were around 80 refueling points in Germany, 134 throughout Europe (43 more planned) and around 40 in the USA.

Expensive purchase: The few models with fuel cell electric drives already available on the market cost around 70,000 euros for a mid-range or upper mid-range vehicle. This makes them almost twice as expensive as comparable all-electric drives or hybrid vehicles.

One kilogram of hydrogen currently costs 9.50 euros in Germany and around 14 dollars in the USA. A fuel cell-powered car can travel around 100 kilometers with one kilogram of hydrogen. This means that the cost per kilometer of a fuel cell electric car is currently almost twice as high as that of a battery-electric vehicle. If the demand for hydrogen increases, it is expected that the price per kilogram will drop to around 5 euros by 2030.

Chapter 3.2.4: Bio-fuel based drive technologies

Liquefied petroleum gas: Liquefied petroleum gas (LPG) is a mixture of propane and butane that is liquefied under pressure. It is produced in oil and natural gas production and in oil refineries.
Its chemical composition is related to gasoline and can - after conversion - be used in normal combustion engines. LPG is gaseous at atmospheric pressure, and changes to a liquid state at a maximum pressure of 10 bar, which makes it more convenient to store.

Advantages: The filling station network in Europe is well developed and LPG is much cheaper than petrol (a liter currently costs 0.65 euros on average in Germany). Economic advantages arise above all for frequent drivers and for vehicles with high fuel consumption.

Environmental friendliness: The liquid gas is much more environmentally friendly than petrol. The CO_2 emissions are reduced by around 15 percent, the emissions of nitrogen oxides by as much as 80 percent.

Disadvantages: LPG can store less energy per volume than petrol (approx. 25 percent less), which means that consumption when operating with LPG increases by up to 25-30 percent depending on the engine and driving style.

Some underground car parks still prohibit gas vehicles from entering.

Diesel vehicles cannot be converted.


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Natural gas: Compressed natural gas (CNG) consists of around 85 percent methane and up to 10 percent nitrogen and CO_2. The remaining 5 percent are made up of higher hydrocarbons such as ethane, propane and butane. The natural gas is carried in one or more cylinder-shaped tanks under the passenger compartment or in the vehicle.

Advantages: The properties of the fuel itself lead to clean combustion and therefore to a significantly lower environmental impact, compared to diesel or petrol. Most vehicles also have a petrol tank. The engine automatically switches to petrol when the natural gas tank is empty.

Since natural gas is lighter than air, it would simply evaporate in the worst-case scenario. However, this is impossible in today's modern natural gas tanks, which meet the highest safety standards and would withstand about twice the actual refueling pressure.

Disadvantages: Converting to CNG is expensive and costs lie between 4,000 and 5,000 euros, depending on the model and engine.

The filling station network is not as developed as that for LPG. For example, there are just around 1,000 natural gas filling stations in Germany.

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“It is not only for what we don’t do
that we are held responsible.“

Jean Baptiste Molière

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Chapter 4:

Sustainable mobility of tomorrow - an outlook

What will be the transport trends of the future?

- Chapter 4.1: Future trends -

Chapter 4.1.1: Car sharing

Sustainable mobility for a healthy environment will only be possible in the future with alternative fuels and drives. However, if we only refer to the flow of traffic within congested cities, pollution-reducing measures cannot solve the whole problem. Nowadays, up to 40 percent of all inner-city traffic is caused by searching for parking. Current projects and studies show that urban mobility improves significantly when several people share a car. A direct consequence is that the search for parking opportunities is significantly less time-consuming and fewer parking sites are used. The name of the associated concept is car sharing; there are essentially two types of car sharing:

1) Stationary car sharing: The shared car must be returned to its fixed parking site at the end of the rental period.

2) Freefloater: The shared car can be parked in a larger but clearly defined area.

The number of car sharing users is increasing substantially: While there were almost 700,000 car sharing users in Europe at the end of 2011, it is estimated that by 2020 there will be around 15 million users.

This trend is indeed having a positive effect on the crowded streets and parking sites in cities: one car sharing car can replace up to 20 private vehicles. The car sharing trend is being spurred on by the possibilities of digitization: online platform users can quickly and easily determine the availability and location of the vehicles via an App and book them directly and usually also open them via the App.

Chapter 4.1.2: Autonomous driving: leave the work to the vehicle

Autonomous driving is no longer a vision of the future, but the clear target in many research and development centers around the world. The way to 100% autonomous driving leads over 5 levels:

	Level 1	Level 2	Level 3	Level 4	Level 5
Driver	Driver performs permanent longitudinal **or** lateral control	Driver **must monitor** the driving task & driving environment **permanently**	Driver **doesn't need to monitor** the driving task & must always be able to take over	Driver is **not required** during defined use case	
Automation	System performs the other driving task	System performs longitudinal **and** lateral control in a defined use case	System takes full control in a defined case. **Recognizes its performance limits** & requests driver to take over with **sufficient time margin** e.g. autopilot	System performs driving task automatically **in a defined use case**	System takes over the complete driving task **during the entire journey**. No driver required e.g. robotaxi
	Driver assistent	**Partial automation**	**Conditional automation**	**High automation**	**Full automation**

The autonomous driving concept is being perceived as highly promising with the following concomitant advantages:

- Better air quality in cities: Autonomous vehicles drive independently from one destination to another e.g., to pick up people and bring them to their respective desired destination. This scenario could not only reduce the number of vehicles on the streets, but also reduce the number of parking sites required. The sites that are freed up could then be used to build more green spaces, which would help improve air quality in cities too.

- Avoiding traffic jams: By digitally networking vehicles, traffic signs and traffic lights, drivers could be intelligently steered so that a more efficient flow of traffic is achieved, with considerably fewer waiting and congestion times.

Nevertheless, the change to autonomous driving will most likely take a very long time. At the moment, there are still many questions to be answered, such as how autonomous and "normal" driver-controlled vehicles could coexist in traffic? Could this problem be solved by equipping traffic signs with sensors, for example? Will we even need an additional lane in the future, during a period of transition from partially autonomous to fully autonomous vehicles? The future will tell us in which direction these questions and their solutions will develop.

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Chapter 4.1.3: Car-to-X communication: When everything communicates with everything and everyone

Car-to-X communication is the key to autonomous driving. Digitally networked vehicles can connect with each other (car-to-car) and with objects in their close environment and communicate with each other (car-to-X), for example, via mobile devices or wireless networks (car-to-mobile).

This sensor-controlled and thus more coordinated traffic flow optimizes the driving style, as all vehicles brake or accelerate at the same time and thus act more vigilantly. Some vehicle models can already interact with other vehicles or objects in their environment. For example, they warn the driver of other road users and sudden obstacles such as traffic jams or frozen sections of the road so that they can react safely in time. This could thus prevent many more accidents. Car-to-X technology could also contribute to a more efficient and less dense city traffic.

In China, car-to-x communication is already part of everyday life. In the east Chinese city of Wuxi there are almost 2 million communicating vehicles on the road, and cars, buses, traffic lights and signs interact with each other. The driver is notified as soon as he or she is driving too fast, and an early warning system provides information about upcoming obstacles.

Chapter 4.1.4: Autonomous electric shuttle buses

The combination of electric mobility and autonomous driving in electric shuttle buses is considered a solution for local transport that can be implemented very quickly. In Europe alone there are now 10 public test tracks for autonomous electric shuttle buses. It can be foreseen that the systems will become more and more intelligent, safer and thus more independent. The routes are currently relatively short and do not have any major hurdles. Nevertheless, the pilot projects are conducted with average speeds of 15 km / h, thus providing a clear picture of how electric shuttle services could work in the near future.

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Chapter 4.1.5: Passenger drones

Chauffeuring in flying passenger drone taxis is a very promising concept in view of increasingly congested city centers and highways. In fact, using the airspace, is a logical consequence of today's urban traffic problems. Drone taxis are scheduled to start trial operations as early as 2020, in Dubai, Los Angeles, Dallas and Singapore. Commercial use is planned for 2023.

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- Chapter 4.2: Conclusion -

The transportation industry is well positioned to tackle the climate challenges of the future. The indusrty will:

- use fossil fuels more efficiently in the short and medium term,
- use more alternative fuels and drives including renewable energy sources in the medium and long term,
- promote the renewable hydrogen economy and electric mobility in the long term.

However, drives and fuels are only one facet of sustainable and environmentally friendly mobility. It encompasses a wide range of innovative concepts that make the transport sector ever more intelligent, effective, safer and more comfortable. The key factor for success is innovative strength in all areas of transportation - both in terms of technology and in conveying an overall impression of the perfect vehicle. The modern vehicle of tomorrow needs a suitable infrastructure.

Only with a holistic approach we can achieve sustainable mobility that includes all means - the fuel cell electric drive, the combustion engine and the battery-electric drive.

“The best way to predict the future is to create it.“

Abraham Lincoln (16th President of the United States)

Appendix

Glossary

Acid rain:

Precipitation that has a lower pH value than about 5.5 due to the action of various chemical substances. Acid rain can wash out toxic minerals and heavy metal ions from rocks and soil and is a major cause of forest damage. The main cause of acid rain is air pollution.

Anode:

Positively charged electrode (positive pole) in an electrolytic cell.

Aromatics:

Class of substances in organic chemistry. Their name is derived from the aromatic odour of the first discovered compounds of this substance class.

Carbon black:

Black, powdery solid consisting of 80% to 99.5% carbon, depending on quality and use. Both, industrial products and undesirable, harmful by-products of combustion processes are referred to as carbon black (soot particles).

Carbon monoxide:

Chemical compound of carbon and oxygen with the empirical formula CO. Carbon monoxide is a colourless, odourless, tasteless and toxic gas.

Cathode:

Negatively charged electrode (minus pole) in an electrolytic cell.

Climate neutrality:

Activities are climate neutral (or CO_2 neutral) if they do not cause greenhouse gas emissions, i.e. if they do not pollute the climate.

Ecosystem:

Habitat and the organisms living in it together form an ecosystem. There are aquatic ecosystems (oceans, rivers, estuaries, lakes, coasts, etc.), terrestrial ecosystems (forest, park, desert, etc.) and artificial ecosystems (city, port, wells, etc.).

Electrical voltage:

Can be defined as the «strength» of a voltage source; it is the cause of the electric current that carries the electric charge. It is also known as «energy per charge».

Electrode:
Electron conductor that interacts with a counter electrode (anode - cathode) with a medium (e.g. electrolyte) located between the two electrodes.

Electrodynamics:
The study of electricity, which deals with moving electrical charges and with electrical and magnetic fields that change over time.

Electrolyte:
Minerals that carry electrical charges when dissolved in a liquid, such as water. These electrolytes in water are e.g. sodium, potassium, or salt.

Energy density:
Distribution of energy over a certain volume or unit of mass. It is most commonly used as volumetric energy density, a measure of the energy per volume of a substance (SI unit: Joules per litre [J/L]), and as gravimetric energy density, a measure of the energy per mass of a substance (SI unit: Joules per kilogram [J/kg]).

Generator:
Electrical machine that converts kinetic energy into electrical energy. The generator is the counterpart of an electric motor, which converts electrical energy into kinetic energy.

Greenhouse gases:
Gases in the earth's atmosphere that produce the so-called greenhouse effect. Most greenhouse gases can have a natural, but also an anthropogenic (human-made) origin. The best-known greenhouse gases are carbon dioxide (CO_2), methane and nitrous oxide.

Hydrocarbon:
Chemical compound of carbon and hydrogen with the molecular formula CH. Hydrocarbons are very versatile and there are many compounds of this class in organic chemistry.

Internal combustion engine:
Engine that generates energy by burning a fossil fuel (mixed with air) (e.g. petrol, diesel engine).

Ions: *Electrically charged particles that are formed from a neutral (metal) atom or molecule by the attachment or transfer of electrons.*

Lithium:

Chemical element with the symbol Li. Lithium is the lightest metal and the solid element with the lowest density. For battery applications, lithium also stands out because it has the highest readiness for electron transfer of all metals. This characteristic is also known as the electrochemical potential. Compared to traditional batteries, lithium-ion batteries therefore offer the highest energy storage capacity with the lowest weight/volume ratio.

Membrane:

Thin structure with different properties. Membranes can be manufactured in such a way that, for example, only certain substances or ions can pass through, while others cannot. Such membranes are called selectively permeable membranes.

Nitrogen oxides:

Collective term for various gaseous compounds that are made up of the atoms nitrogen (N) and oxygen (O). Nitrogen oxides are the precursor substances of fine dust and smog.

Organic materials:

Substances that are either formed by living beings in metabolism, or which are produced industrially. They always contain the element carbon, and almost all of them also contain hydrogen.

Periodic table:

Table containing all 118 chemical elements that exist on earth. The periodic table consists of eight main groups (I to VIII), whereby all elements within a main group have similar properties. The number of the main group indicates the number of electrons on the outermost shell (the so-called valence electrons, except for helium with two electrons on the first shell).

Photosynthesis:

Biogeochemical process in which plants, algae and bacteria use solar energy and water and carbon dioxide (CO_2) to form organic substances.

Polymer:

Chemical substance consisting of macromolecules.

Recycling:

Material recycling of batteries to recover the elements they contain, such as lead, cadmium or zinc.

State of aggregation:

The different states of a substance are called states of aggregation. There are the three classical states of matter solid, liquid and gaseous, as well as in physics other non-classical states such as plasma. Aggregate states can transform into each other when temperature or pressure changes.

Sulphur dioxide:

Colourless, mucous membrane irritating, pungent smelling and sour tasting, poisonous gas.

Supercharger:

Charging stations of the Tesla company, which were built for the quick charging of vehicles of their own brand.

Torque:

Physical quantity that indicates how strong a force acts on a rotatably mounted body. Unit: one Newton meter (1 Nm).

Watt:

The unit of measurement for power used in the International System of Units (SI). One Watt corresponds to the power in which the energy of one joule is converted within one second (energy conversion per time period). One terawatt is one trillion watts (10^{12} W).

The author

Dr. Félix Urbain (born 1986 in Luxembourg) studied materials science and economics at the Rheinisch-Westfälische Technische Hochschule Aachen (RWTH). He completed his doctorate in 2016 on the subject of «Hydrogen from Sunlight» at Forschungszentrum Jülich. After successful research positions in Germany and Spain, with numerous research awards (e.g. Forschungspreis Wasserstoff NRW) and 40 scientific publications with more than 600 citations, the Luxembourger decided to change to the management consultancy for EU-funded projects in 2019. In this position, Dr. Urbain supports emerging companies in the development and market introduction of innovative ideas and products aimed at solving today's energy problems. With his knowledge and experience in the field of renewable energies, Félix has already helped many environmentally friendly inventions to achieve a breakthrough.

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