ZERO EMISSION CHALLENGE

E-Mobility

Fundamentals

ENGLISH EDITION | LEARNING MATERIAL

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1 Introduction to the Topic

The growth of electric cars continues. For China, Europe and the USA, a share of more than 50 percent electric cars is forecast by 2030.

In particular, comprehensive public and private charging infrastructure is an important step towards a successful mobility transition. Higher energy efficiency and the use of renewable energy are prerequisites for achieving climate targets, and the transition to purely electric drives supports these goals.

Electric vehicles use only about one third of the energy of a vehicle with an internal combustion engine, produce no local exhaust emissions and are quieter. When powered by electricity from renewable sources, purely electric vehicles have a significantly better CO_2 balance than petrol or diesel vehicles.

For trucks, buses and long-distance transport, the final direction has not yet been decided. Recent studies nevertheless indicate that a transition to renewable energy can also be successful for heavy commercial vehicles, especially in local and freight transport. The EU has introduced increasingly strict CO_2 emission targets for new vehicles, with particularly ambitious targets for cars, vans and heavy-duty vehicles.

1.1 About Electromobility

Safety concerns relating to electric vehicles usually focus on:

(a) Low driving noise: especially at low speeds, the low noise level can be a problem for other road users.
(b) Rapid acceleration: electric motors provide high acceleration, which may become a problem in particular driving situations.
(c) Fire behaviour: particular attention must be paid to the battery as an energy storage device.

Statistical data show that electric vehicles are affected by vehicle fires significantly less often than vehicles with internal combustion engines. At low speeds, electric vehicles must be accompanied by an artificial driving sound.

Key Point 1: In principle, an electric car does not represent a greater safety risk than a vehicle with an internal combustion engine.

1.2 Power, Energy and Efficiency

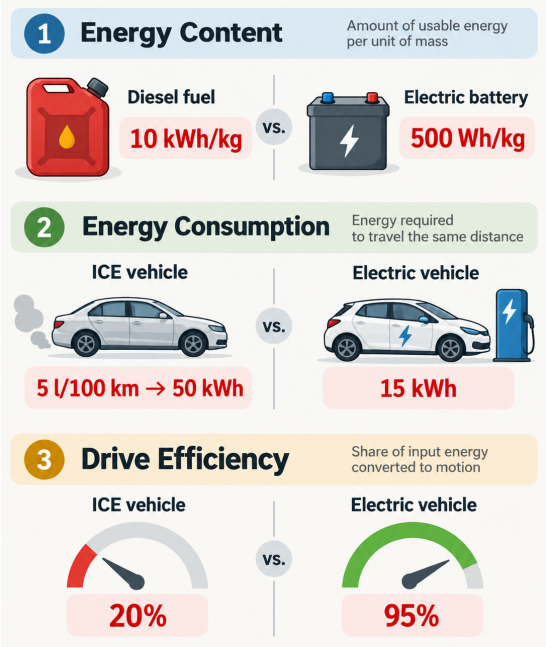


Figure 1: Comparison of Energy Content, Energy Consumption and Drive Efficiency

Electromobility includes not only battery electric vehicles, but also all types of hybrid vehicles. Fuel-cell vehicles also belong to this group. Modern passenger cars with electric drive components currently operate with high-voltage systems up to 900 V, with an upward trend. The peak currents decrease at the same power level – although even here the 500 A limit has already been exceeded.

The energy storage system is currently still the most challenging component of electrically powered mobility. The possible energy content compared with hydrocarbon fuels alone shows that very high efficiency is required in all components in order to compensate for this disadvantage.

A simple energy-related consideration also supports the recovery of kinetic energy during braking:

If a vehicle is driven from home to work in the morning and is back in the carport at home in the evening, it has travelled the same route downhill and uphill during the day.

At present, an efficiency of about 50 percent is achieved when braking electrically and recovering the vehicle's kinetic energy.

This process is called recuperation!

Key Point 2: Recuperation means energy recovery (battery charging) during the deceleration of electric vehicles.

1.3 Reasons for Electromobility

The number of vehicles worldwide is increasing strongly with the world population, and the share of the greenhouse gas CO_2 produced by internal combustion engines is significant. The environmental effects can no longer be denied. Increased CO_2 concentration in the atmosphere leads to a substantial rise in average temperature with corresponding effects on the environment.

The EU sets fleet-wide CO_2 emission targets for new passenger cars.

Key Point 3: CO_2 emissions correlate with fuel consumption. 95 g CO_2 corresponds approximately to a fuel consumption of 4 l/100 km!

Exceeding the specified CO_2 limits could lead to high penalty payments for vehicle manufacturers. Falling below the 95 g CO_2/km target was only possible if a significant number of purely electric vehicles were sold within the manufacturer's fleet, since these were calculated with 0 g CO_2/km.

The 95 g CO_2/km value is an average across the vehicle fleet. Depending on the manufacturer, an individual target applies based on the vehicles in the fleet.

1.3.1 Electric Bicycles, Pedelecs and S-Pedelecs

Basically, three variants are distinguished:
(a) Pedelec: the pedelec (Pedal Electric Cycle) is one of the most widely used electric bicycles. The motor supports the rider's pedalling. Without pedalling, there is no motor power! The drive operates up to a speed of 25 km/h and may have a maximum power of 250 W.
(b) S-Pedelec:... the S-pedelec supports the rider up to a speed of 45 km/h, and the motor may have a maximum power of 4 kW. S-pedelecs therefore belong to the category of light motor vehicles. To ride an S-pedelec, you need a driving licence and a registration plate.
(c) E-Bike: here, the motor can propel the e-bike even without pedalling – in other words, without any active pedalling by the rider. Speed is usually controlled by a throttle or accelerator. E-bikes are available for 20/25/45 km/h; in most cases, a driving licence and registration plate are required.

The drives are available as front-, rear- or mid-mounted motors.

1.3.2 Electric Motorcycles

Electric motorcycles include both mopeds and significantly more powerful motorcycles. Their acceleration can be very high, while their range is currently still relatively limited. One example is the KTM Freeride E-XC.

A major focus is the low noise level, since motorcycles of this type are often ridden and practised in open terrain. The high torque available at low rotational speeds is also particularly useful for demanding riding manoeuvres and tricks.



Figure 2: The KTM Freeride E-XC

1.3.3 Marine Applications

There is currently also a strong trend towards electromobility in the marine sector. One reason for this development is that boats with internal combustion engines are prohibited on some inland lakes. By switching sports boats to electric drives, these restrictions can currently be avoided without any corresponding speed limitation.

Depending on the required power, either special components from the marine sector are used or proven components from the automotive industry are adopted.

It can therefore be assumed that there will be a significant shift towards electric drives on our lakes over the coming years.

2 Legal Principles

European occupational safety framework:
... occupational safety and health requirements in the European Union are based on common minimum principles. Employers must assess risks, take appropriate protective measures and provide suitable information and training. National legislation may contain additional requirements.

Directive 2009/104/EC – Use of Work Equipment:
... defines minimum safety and health requirements for the use of work equipment by workers. Work equipment must be suitable for the intended task and must be used without endangering the safety or health of workers.

IEC 60364 – Low-voltage electrical installations:
... provides fundamental principles and safety requirements for low-voltage electrical installations. National implementations and additional requirements may apply.

EN 50110-1 – Operation of Electrical Installations:
... applies to operating and working on, with or near electrical installations. The basic safety principles include the following five safety rules:

1. Disconnect completely
2. Secure against reconnection
3. Verify absence of operating voltage
4. Carry out earthing and short-circuiting
5. Provide protection against adjacent live parts

Live working:
... work on or near live electrical parts requires special precautions, appropriate qualifications and compliance with the applicable national regulations.

High-voltage systems:
In electrically propelled road vehicles, high voltage is defined as a working voltage of more than 60 V DC up to 1,500 V DC, or more than 30 V AC (rms) up to 1,000 V AC (rms). These limits correspond to voltage class B electrical circuits used in international vehicle safety standards.

Key Point 4: Voltages and currents in high-voltage vehicle systems can be life-threatening. Work on such systems requires appropriate safety measures, suitable qualifications and compliance with the applicable standards and national regulations. Whenever possible, work should be carried out in a de-energised state.

ISO 6469-3:2021 – Electrically propelled road vehicles – Safety specifications – Part 3: Electrical safety:
... specifies electrical safety requirements for voltage-class-B circuits of electric propulsion systems and conductively connected auxiliary systems. It addresses protection against electric shock and thermal incidents. Requirements for manufacturing, maintenance and repair personnel may additionally be defined by national regulations.

UN Regulation No. 100 – Electric power train vehicles:
... specifies safety requirements for electric power trains, rechargeable energy storage systems and protection against electric shock in electrically powered road vehicles.

3 Electrical Engineering Fundamentals

3.1 Electric Current

Electric current is the directed movement of charge carriers. Charge carriers are elementary particles that are either negatively charged (electrons) or positively charged (ions).

For a current to flow in one direction, a corresponding potential difference must exist. This potential difference is called electrical voltage.

Key Point 5: The unit of electric current is A (ampere); the symbol for current is I.

If no voltage is applied, the charge carriers move freely and randomly within the material, depending on temperature. Current can flow only when a voltage Ubat is present and the circuit is closed. This creates a current Ibat from the energy source (battery) through the load RL and back to the energy source.

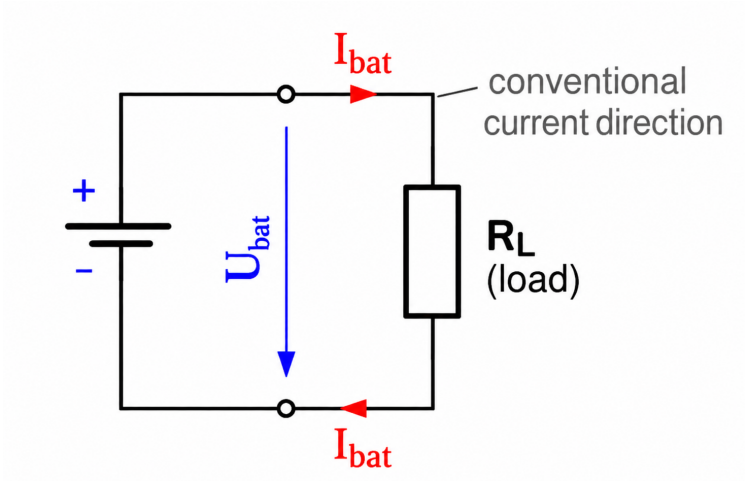


Figure 3: Simple electric circuit

Basically, two current directions are distinguished:
Physical current direction: ... the electrons move from the negative terminal of the energy source through the load to the positive terminal.
Conventional current direction: ... conventional current direction was defined arbitrarily at the beginning of electrical research and is exactly opposite to the actual direction of electron flow.

In this script, conventional current direction is used.

Key Point 6: Whenever current flows, a magnetic field is produced and, due to losses, the conductor material heats up.

3.2 Electric Voltage

Electrical voltage is created by charge separation. Positive and negative elementary particles are separated using energy. This creates a potential difference. The potential difference between two differently charged points is called voltage.

Key Point 7: The unit of electrical voltage is V (volt); the symbol for voltage is U.

At the positive terminal there is a shortage of electrons, while at the negative terminal there is an excess of electrons. Electrical voltage is a measure of the driving force for electric current. The greater the voltage, the greater the driving force.

Key Point 8: Whenever voltage is present, an electric field exists. With direct voltage, no corresponding losses are expected. With alternating voltage, capacitive losses can occur.

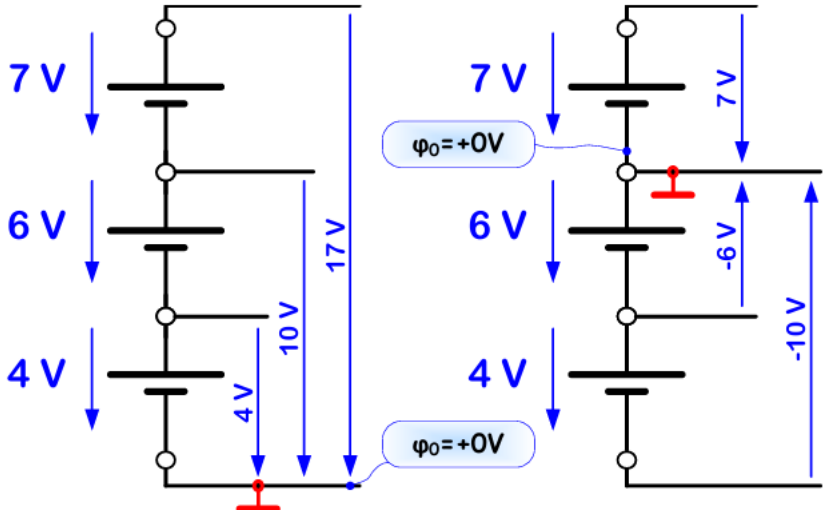


Figure 4: Arrangement of voltage sources and voltages relative to a reference point.

Normally, voltages are specified relative to a reference point such as GND (ground), chassis ground or 0 V.

In addition to indicating voltages using arrows and numerical values, potential points φ (phi) are often used. The manufacturer of a device specifies the values that should occur at various points in the circuit during normal operation. By measuring and checking these points, faults can be located.

One point in the circuit is assigned the potential $\varphi_0 = 0$ V. This potential is also called ground.

3.3 Alternating Voltage versus Direct Voltage

Direct voltage is an electrical voltage with a constant direction, whereas alternating voltage changes periodically with a certain frequency.

Key Point 9: A direct current can flow only when a direct voltage is present. With alternating voltage, alternating current is produced.

Typically, alternating voltage and alternating current vary sinusoidally with a fixed frequency f. In household installations, we use 230 V / 400 V AC at 50 Hz. The corresponding period is T = 20 ms.

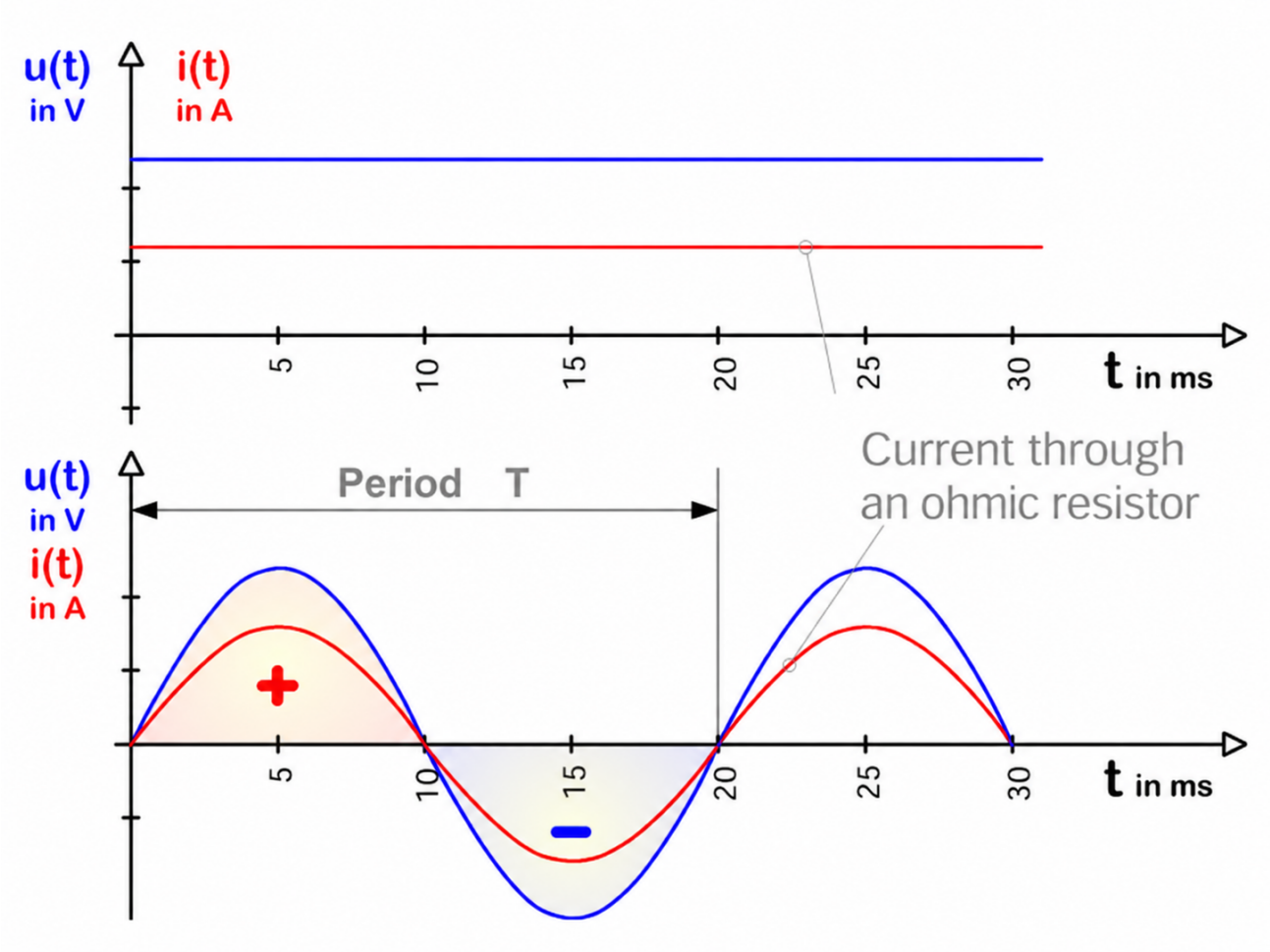


Figure 5: Direct voltage (DC) and alternating voltage (AC) with the corresponding current over time.

Why do we use both direct current and alternating current?

To transmit energy or power as economically as possible over long distances, the voltage should be high and the current low.

As a rule of thumb:

An economically reasonable transmission voltage is approximately 1000 V (= 1 kV) per kilometre.

With a 380 kV high-voltage transmission line, distances of about 380 km can therefore be covered.

Direct current is generated electrochemically by batteries and by photovoltaic systems. Historically, the disadvantage was that DC voltage was difficult to transform to higher and then back to lower voltage levels.

Alternating voltage, on the other hand, can be transformed to higher or lower voltage levels with relatively low losses.

Alternating current is generated by generators, which is also where the frequency of the alternating current originates. Using transformers, alternating voltage can easily be transformed to high voltage levels. This makes it possible to transmit energy over large distances with relatively low losses.

Today, there are also efficient technologies for high-voltage direct current transmission (HVDC). This allows DC energy to be transmitted over long distances with high efficiency.

3.4 Electrical Resistance R

When electric current flows through a conductor, the charge carriers repeatedly collide with imperfections in the crystal lattice. The main causes of these imperfections are impurities and thermally induced lattice vibrations.

These effects make it more difficult for the current to flow. This property of the conductor material is called electrical resistance.

The symbol for electrical resistance is R and its unit is ohm (Ω).

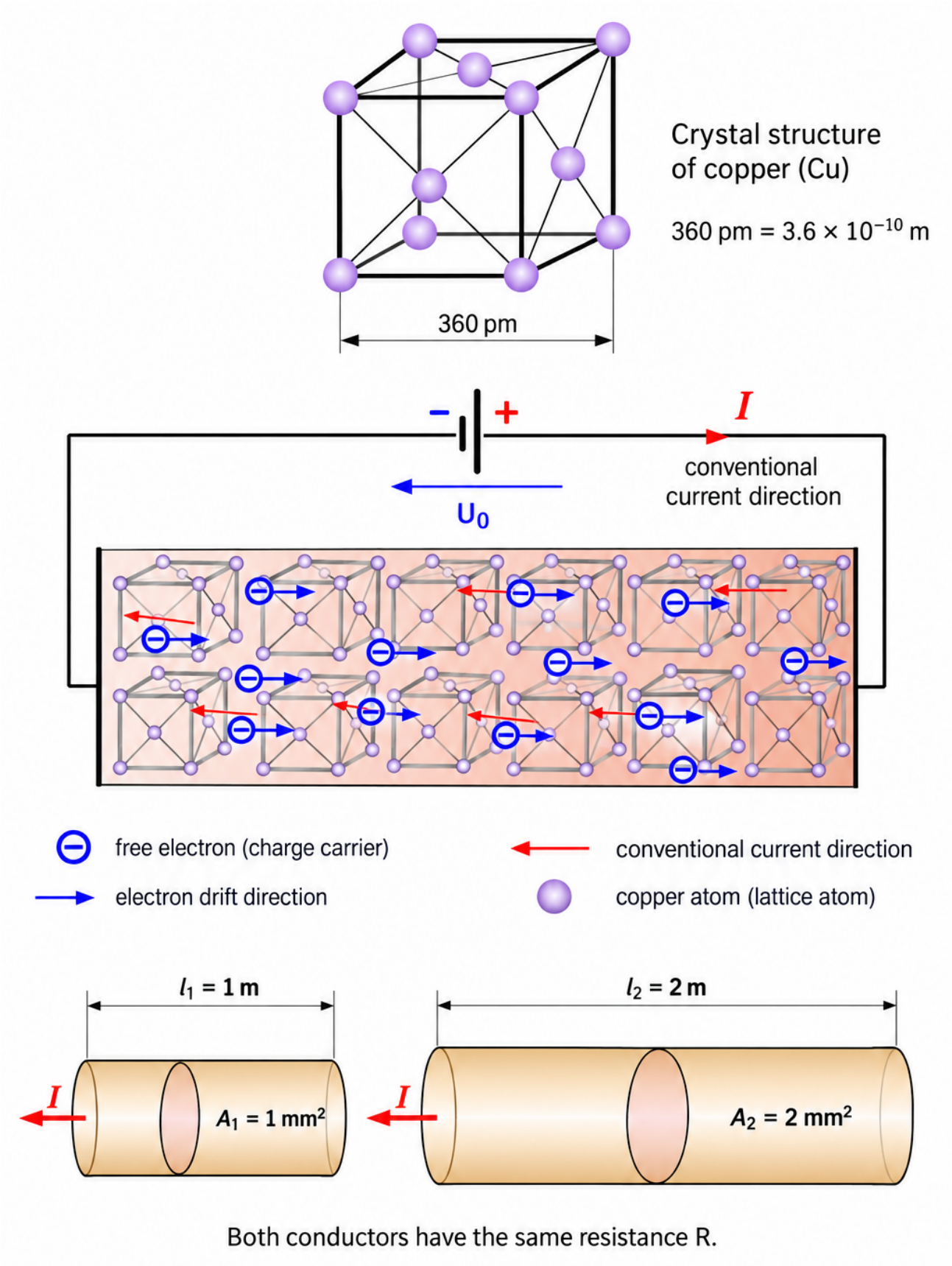


Figure 6: Crystal structure of copper (Cu). Charge carriers collide with the lattice atoms. The figure also shows the influence of conductor length and cross-sectional area. Both conductors shown have the same resistance R.

3.4.1 Conductor Resistance

The term conductor includes wires used to carry current, as well as conductor tracks on a printed circuit board.

The resistance depends on:

conductor length l

conductor cross-sectional area A

conductor material

temperature

Copper (Cu) and aluminium (Al) are the most important conductor materials.

With the specific resistivity ϱ, the conductor resistance R in ohms is:

$$R = \frac{\rho \cdot l}{A} = \frac{l}{\gamma \cdot A}$$

ϱ ... specific resistivity in $\Omega \cdot mm^2/m$

γ ... specific conductivity in $m/\Omega \cdot mm^2$

l ... conductor length in m

A ... conductor cross-sectional area in mm^2

The longer the distance the electrons have to travel through the conductor, the more often they collide with atoms of the metal lattice.

Key Point 10: The resistance R increases proportionally with conductor length. As the conductor cross-sectional area increases, the resistance decreases because there are fewer collisions with atoms.

Specific resistivity ϱ and conductivity γ

The density of atoms and the number of free electrons are important for the resistance behaviour of a material. This is expressed by the specific resistivity ϱ.

A conductor with a low specific resistivity ρ has a high conductivity γ, because it conducts electric current well.

Two main groups can be distinguished:
(a) Good conductors: ... copper and aluminium. These materials are used for cables and wires in order to transport electric current with as little resistance and as few losses as possible. **Copper**: γ =56 m/Ω · mm2 or S · m/mm^2 **Aluminium**: γ =35m/Ω · mm2 or S · m/mm^2
Poor conductors: ... ceramics and plastics. These materials are used to reduce the risks associated with electric current, for example as insulation around electrical cables.

3.5 Ohm's Law

Georg Simon Ohm recognised in 1826 that the current in an electric circuit depends on both the driving electrical force and the resistance opposing it.

Ohm's law can therefore be written as:

$$U = R \cdot I$$

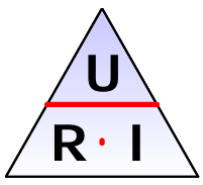
U ...voltage across the resistor in volts

I current through the resistor in amperes

R ..... electrical resistance in ohms

This describes the linear relationship between current and voltage. The current is proportional to the voltage.

By rearranging the equation, the three forms that are most important in practice are obtained:



$$I = \frac{U}{R}, \quad R = \frac{U}{I}, \quad U = R \cdot I$$

Figure 7: Ohm's law shown graphically.

By covering the quantity you are looking for in the formula triangle, the required equation remains visible.

3.6 Energy and Work

3.6.1 Mechanical Work W_{mech} and Energy E_{kin}, E_{pot}

When a body is raised through a height h in a gravitational field, mechanical work must be performed. It does not matter whether the body is lifted directly or along another path.

The symbol for work is W.

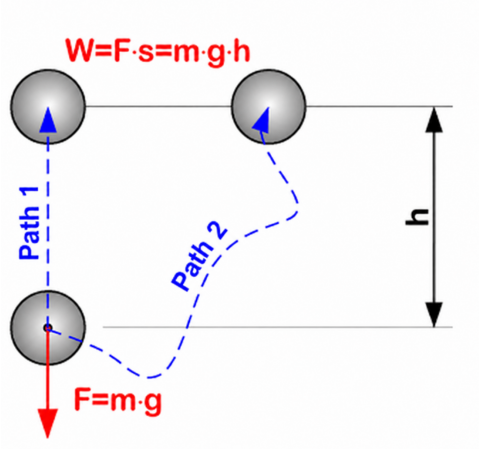


Figure 8: Mechanical work W when lifting a body.

Key Point 11: If a body returns to its original position along a closed path, the total work is W = 0, provided losses are neglected.

The work performed when lifting the body (W > 0) can be recovered as energy when lowering the body (W < 0).

Key Point 12: The terms work and energy are fundamentally **identical**. Work is used to bring a body into a certain state, for example to a certain height or speed. **Energy is stored work.**

A body at a height h possesses a certain form of energy, called **potential** energy. If the body falls through the height h, its potential energy is converted into **kinetic** energy.

The kinetic energy E_{kin} in Nm or joules is:

$$E_{kin} = \frac{m \cdot v^2}{2}$$

m ... mass of the body in kilograms

v ... velocity in m/s

The potential energy in Nm or joules is:

$$E_{pot} = m \cdot g \cdot h$$

m ... mass of the body in kilograms

g ... gravitational acceleration in m/s^2

h ... height difference in metres

3.6.2 Electrical Energy E_{el} in Watt-Seconds

When an electric charge carrier, such as an electron with charge Q, is moved in an electric field, the electric force acting on the charge carrier performs work.

The electrical energy E_{el} in Ws (watt-seconds) is:

$$E_{el} = U \cdot I \cdot t = P \cdot t$$

U ... Voltage in volts

I ... current in amperes

t ... time in seconds

P ... power in watts

In energy supply, electrical work is usually specified in kilowatt-hours (kWh).

$$1\ kWh = 3.6 \cdot 10^6\ Ws = 3.6 \cdot 10^6\ J$$

Electricity suppliers measure the electrical energy supplied in kilowatt-hours using an electricity meter and charge consumers according to the applicable tariffs.

3.6.3 Forms of Energy and Conservation of Energy

In addition to mechanical energy, such as potential and kinetic energy, and electrical energy, there are many other forms of energy, for example thermal energy and chemical energy.

Key Point 13: During energy conversion, the fundamental principle of conservation of energy always applies. The total amount of energy remains constant during every energy conversion. Energy can neither be created nor destroyed.

The everyday term energy generation can therefore, in a physical sense, only mean the conversion of one form of energy into another.

One advantage of SI units is that the units of different forms of energy are directly comparable:

1watt-second (electrical) = 1 newton-metre (mechanical) = 1 joule (chemical)

$$1\ Ws = 1\ Nm = 1\ J$$

In mechanics, the unit **joule** is also used for energy in order to avoid confusion with torque.

3.7 Different Concepts of Power

3.7.1 Mechanical Power

Power from a mechanical point of view:

When lifting a body with a mass m through a height h, mechanical work must be performed.

If this work W is related to the time t required for lifting, we obtain the mechanical power needed to lift the body within that time.

The symbol for power is P (from the English word power).

The mechanical power P in watts is:

$$P = \frac{Work}{Time} = \frac{W}{t}$$

W	...	mechanical work in J (joules)
t	...	time in seconds

Key Point 14: If the same work W is to be performed in half the time t, twice the power P is required!

3.7.2 Electrical Power

An electrical power of P = 1 W (watt) is delivered when a voltage of U = 1 V (volt) is present and a current of I = 1 A (ampere) flows.

The electrical power P in watts can be expressed as:

$$P = \frac{W}{t} = \frac{U \cdot I \cdot \cancel{t}}{\cancel{t}} = U \cdot I$$

W	...	electrical work in Ws (watt-seconds)
U	...	voltage in volts
I	...	current in amperes
t	...	time in seconds

The power formula also applies to alternating electrical quantities. In this case, it describes the instantaneous power delivered by the voltage source to the load.

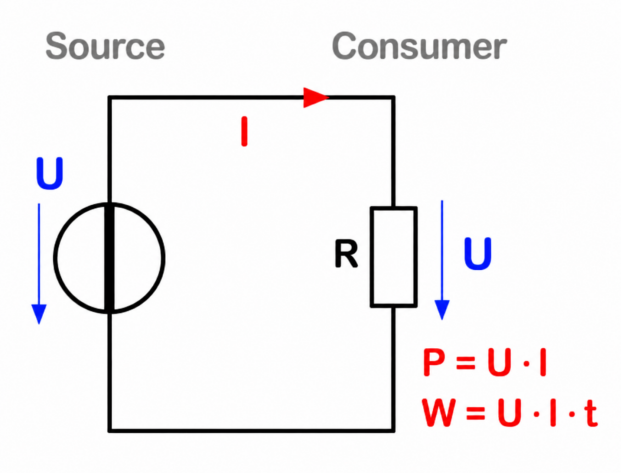


Figure 9: Power at an ohmic resistor.

$$P = U \cdot I = I^2 \cdot R = \frac{U^2}{R}$$

[1] By applying Ohm's law, the power formula can be expressed in three different ways:

3.8 Power Losses and Efficiency η (Eta)

During energy conversion, unwanted forms of energy are produced in addition to the desired form. The conversion of one form of energy into another is therefore associated with losses.

Examples of different power losses are:

(a) Heat caused by friction: ... in bearings (motor, generator) and mechanically moving parts, such as the drivetrain.

(b) Heat caused by electronics: ... current-related heating in motor windings, losses in the energy storage system and motor control, as well as losses during battery charging.

(c) Vehicle and road characteristics: ... rolling resistance of the tyres, aerodynamic drag and road conditions.

A distinction is made between supplied power and delivered power.

The power loss can be calculated as:

$$P_{loss} = P_{in} - P_{out}$$

According to the principle of conservation of energy (energy cannot be lost), the input power must always equal the sum of the output power and the power losses.

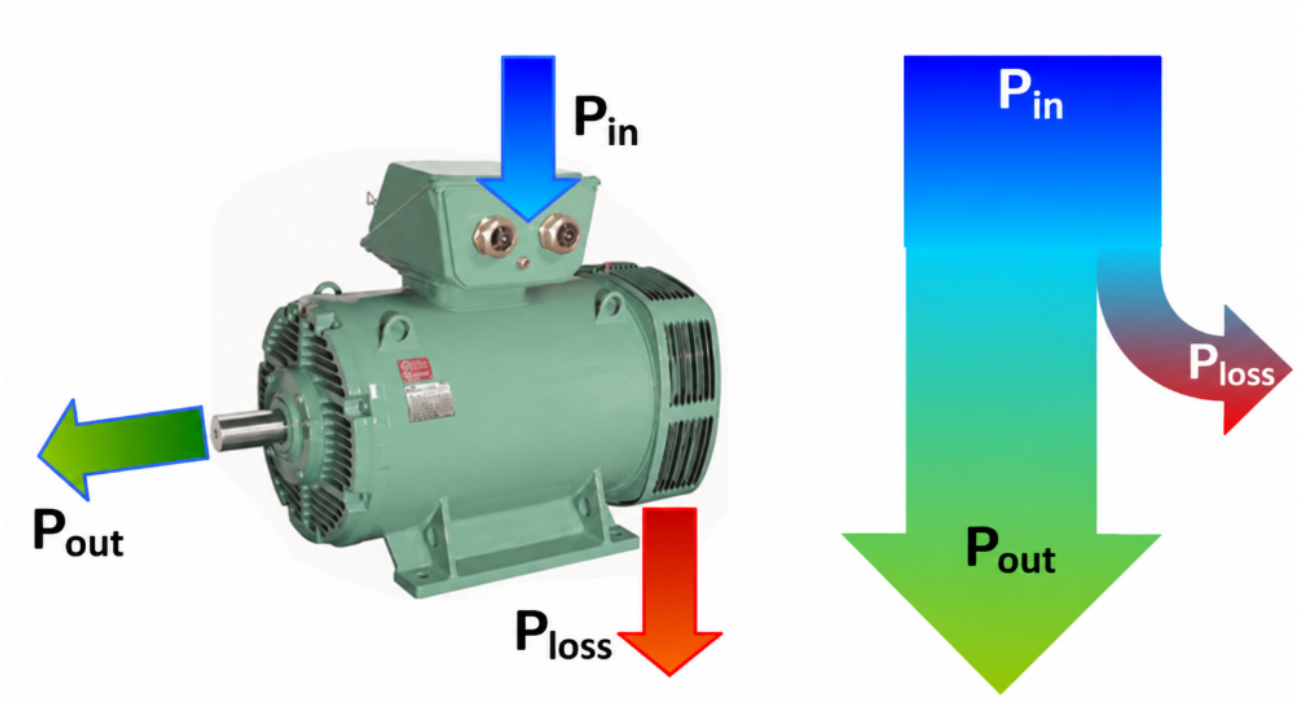


Figure 10: Supplied and delivered power and the power flow in a motor (Sankey diagram).

Key Point 15: For motors, the power stated in the data sheet is always the mechanical power delivered at the shaft. In other cases, the supplied power is normally specified.

By comparing the delivered power with the supplied power, the efficiency η (eta) can be calculated.:

The dimensionless efficiency η is defined as:

$$\eta = \frac{P_{out}}{P_{in}}$$

P_{out} ... output power in watt

P_{in} ... input power in watt

..

According to the principle of conservation of energy: $\eta < 1$ This means that the output power cannot exceed the input power. Efficiency is often expressed as a percentage. In this case, η represents the percentage of supplied power that is usefully converted.

For a system with losses:

$\eta < 100\%$

Overall efficiency of several energy conversion stages

If energy must be converted from one form into another several times, the individual efficiencies must be taken into account.

For two individual efficiencies η_1 and η_2:

$$\eta_1 = \frac{P_{out1}}{P_{in1}}, \qquad \eta_2 = \frac{P_{out2}}{P_{in2}}$$

overall efficiency η_{total}:

$$\eta_{total} = \frac{P_{out2}}{P_{in1}} = \eta_1 \cdot \eta_2$$

In general, the overall efficiency of a multi-stage energy conversion process is η_{total}:

$$\eta_{total} = \eta_1 \cdot \eta_2 \cdot \eta_3 \cdot \ldots$$

Example 1: Overall efficiency of an electric vehicle:

The overall efficiency of a multi-stage energy conversion process is to be calculated.

The charger operates with an efficiency of η_{chrg} = 92%, and energy is stored in the battery with an efficiency of η_{bat} = 90%.

Finally, this energy is converted into mechanical drive power by a motor with an efficiency of η_{mot} = 85%.

What is the overall efficiency of the energy conversion process?

The overall efficiency η_{total} can be calculated using the individual efficiencies:

$$\eta_{total} = \eta_{chrg} \cdot \eta_{bat} \cdot \eta_{mot}$$
$$\eta_{total} = 0.92 \cdot 0.90 \cdot 0.85$$
$$\eta_{total} = 70.3\ \%$$

Key Point 16: Every additional energy conversion or storage process in the energy chain of an electric vehicle reduces the overall efficiency of electric propulsion.

4 Drive Concepts in Mobility

4.1 Vehicle with Internal Combustion Engine Only

At the beginning of motorised mobility, it was not clear which drive energy source would become dominant. At that time, the internal combustion engine (ICE) delivered better results than the electric motor and therefore became the dominant technology for almost 100 years.

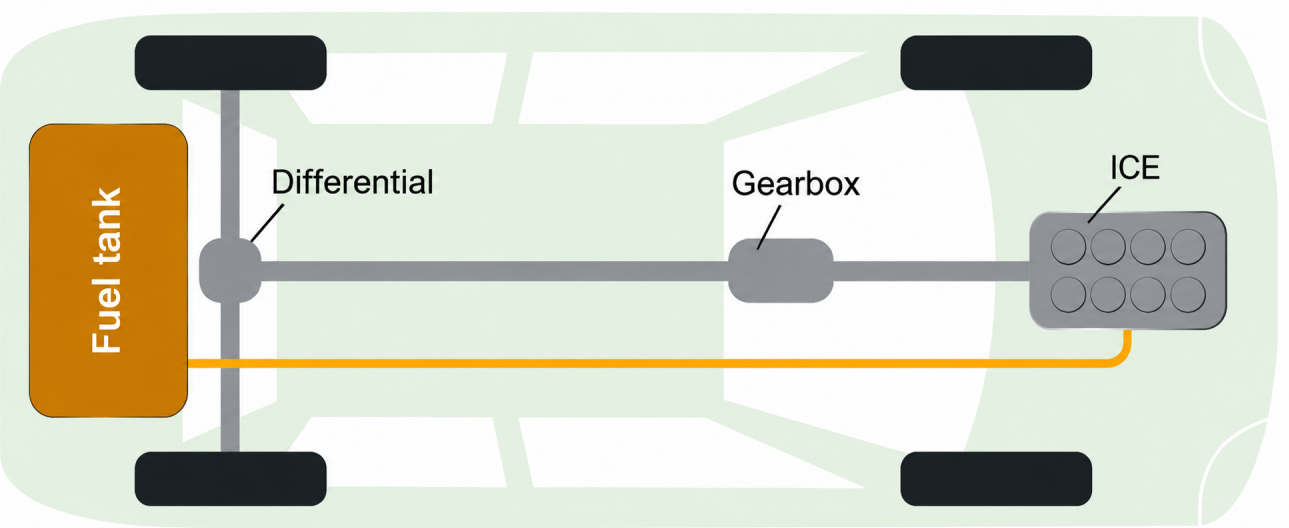


Figure 11: Vehicle with a conventional internal combustion engine.

The current advantages of the internal combustion engine are mainly its well-known and continuously developed technology. There is sufficient infrastructure for operating and maintaining these vehicles. However, the large number of moving parts results in relatively high maintenance and repair costs.

The disadvantages of the internal combustion engine are:
(a) Efficiency: ... up to 40% at the optimum operating point, but closer to 20% at partial load. The remaining energy is converted into heat.
(b) Pollution: ... increasing mobility has caused serious air pollution in densely populated areas.
(c) Complexity: ... the technical effort required to meet increasingly strict exhaust emission regulations rises significantly. As a result, development, approval and component costs increase due to the growing complexity.

Another problem is the mechanical distribution of drive power to the wheels. Complex systems such as X-Drive (BMW) or 4Motion (VW) are examples of this.

With electric drives, this task can be implemented more easily.

4.2 Hybrid Vehicles

Hybrid vehicles combine both technologies: internal combustion engines and electric vehicle drives. The development effort is significantly higher, and the complexity is increased by installing several independent drive systems. However,

hybrid drives offer a greater range, which purely electric vehicles may not yet provide sufficiently under certain conditions, such as adverse weather or other external influences.

Looking ahead to the next five to ten years, it can be assumed that hybrid drives will increasingly be replaced by purely electric vehicles or fuel-cell vehicles.

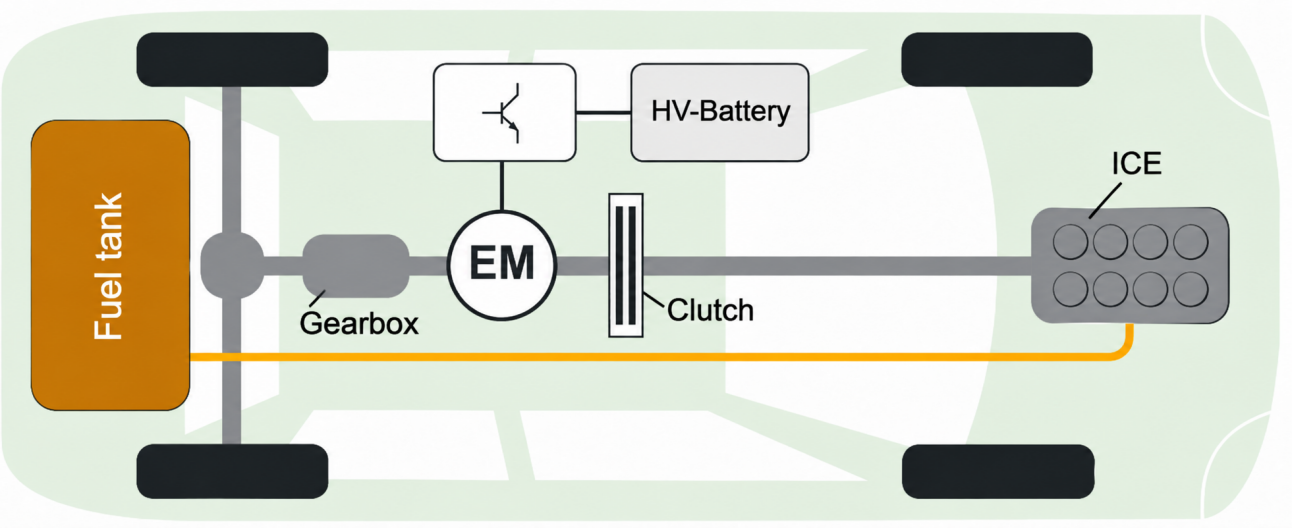


Figure 12: Vehicle with a hybrid drive.

ICE ... Internal Combustion Engine

EM ... Electric Motor

4.2.1 Classification by Electrical Power: Micro-Hybrid

The micro-hybrid represents the lowest level of hybrid vehicles. The vehicle is driven exclusively by a conventional internal combustion engine.

The hybrid function is usually provided by a starter-generator connected to the engine via a belt. The vehicle has a conventional 12 V electrical system.

A battery charging management system allows the starter-generator to support the engine during acceleration and to recharge the battery during braking through regenerative braking.

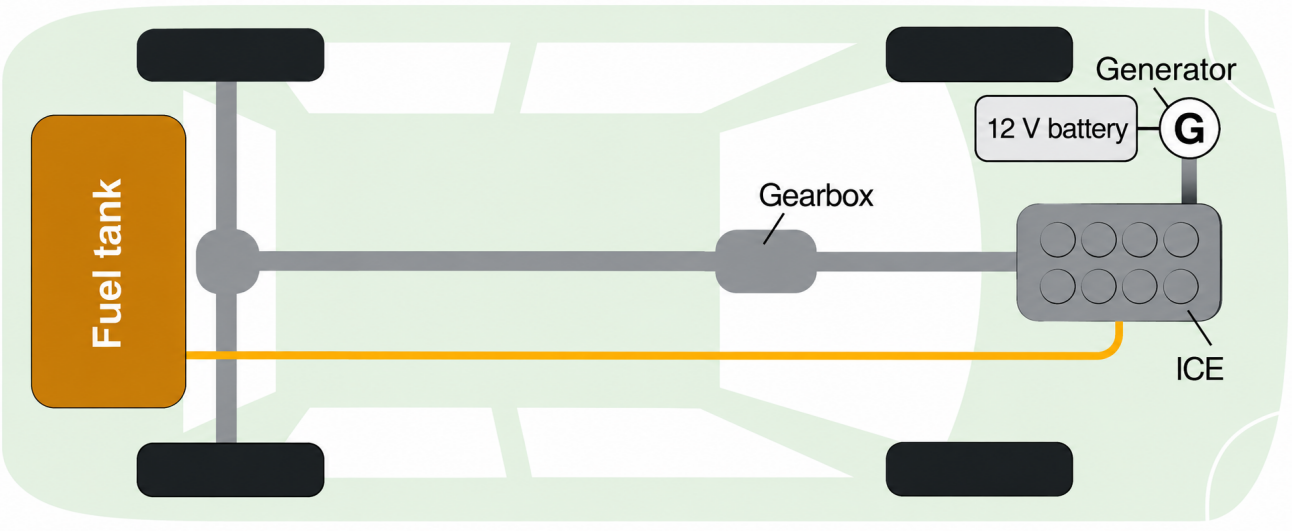


Figure 13: Vehicle with a micro-hybrid drive.

Characteristics of a micro-hybrid drive:
(a) Concept: ... Start-stop system.

(b) Advantage: ... 3–5% fuel savings.
(c) Disadvantage: ... frequent engine starts in urban traffic lead to increased crankshaft wear. Continuous start-stop operation can also be inconvenient for the driver.

4.2.2 Classification by Electrical Power: Mild Hybrid

In a mild hybrid, the starter-generator is mounted on the crankshaft and could, in principle, provide limited propulsion for the vehicle.

However, the electric motor usually supports the internal combustion engine mainly during acceleration.

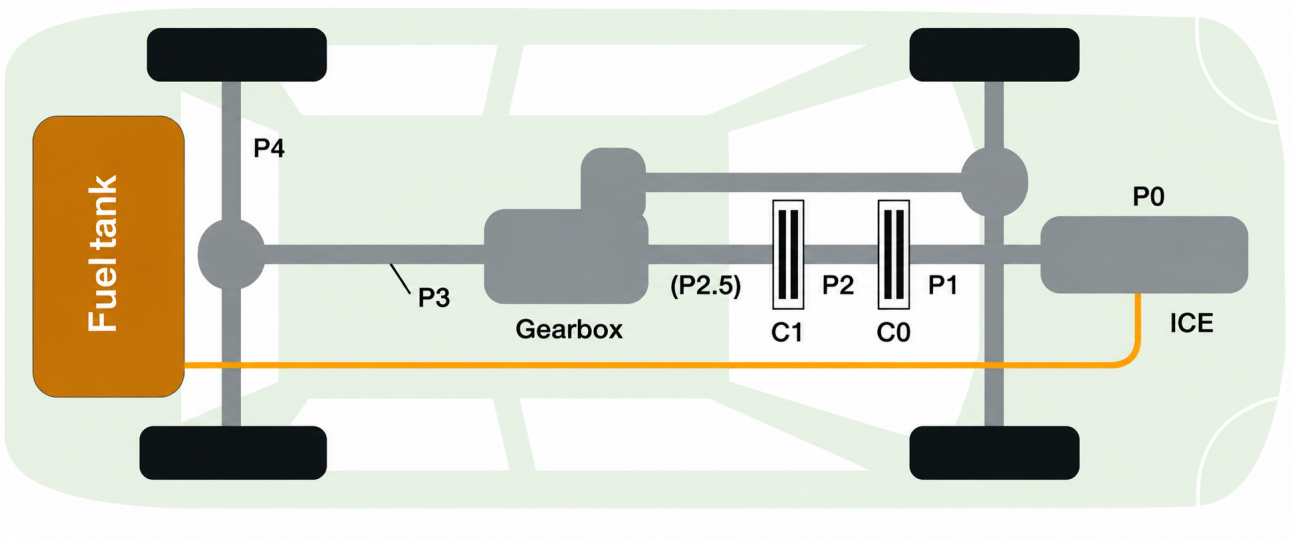


Figure 14: Vehicle with a mild-hybrid drive. C0, C1 ... Clutches.

During braking, part of the braking energy can be recovered and stored in the battery through recuperation.

High-voltage systems are mainly used, typically operating between 100 V DC and 400 V DC. The power of the motor-generator is between 6 and 15 kW per 1,000 kg of vehicle mass.

Key Point 17: By individually controlling electric motors located at the four wheels, different drive control concepts can be implemented (P4)!

Four main variants of the mild-hybrid drive:
P1: ... The electric motor is permanently connected to the internal combustion engine.
P2 . . . The electric motor is connected to the internal combustion engine via a clutch and is located at the gearbox input. If the additional clutch C1 is omitted, this corresponds to the P2.5 configuration.
P3 . . . The electric motor is connected to the internal combustion engine via a clutch and is located at the gearbox output.
P4 . . . The electric motor is located on a separate axle that is not driven by the internal combustion engine. This allows all-wheel drive to be implemented.

The P0 configuration, also shown in Figure 14, corresponds to a micro-hybrid.

Characteristics of a mild-hybrid drive:
(a) Concept: ... Electric motor in different positions.
(b) Fuel savings: ... Approximately 10–15%.
(c) Operation: ... In the P2 to P4 configurations, the vehicle can be driven purely electrically over short distances.
... Electric coasting is possible. This means driving purely electrically at a constant speed and low partial load.

In the P1 configuration, the electric motor is mounted on the crankshaft. It is supplied with energy by a battery and controlled by a motor controller.

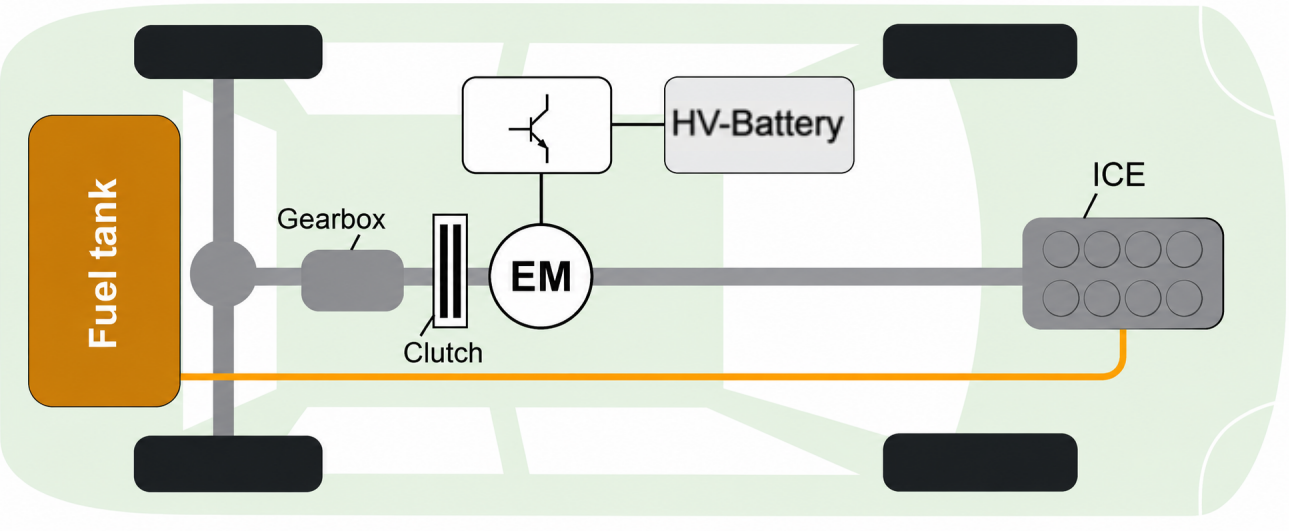


Figure 15: Mild hybrid as a parallel hybrid (P1).

In the P3 configuration, the electric motor can be disconnected from the internal combustion engine by means of a clutch. It is supplied with energy by a battery and controlled by a motor controller.

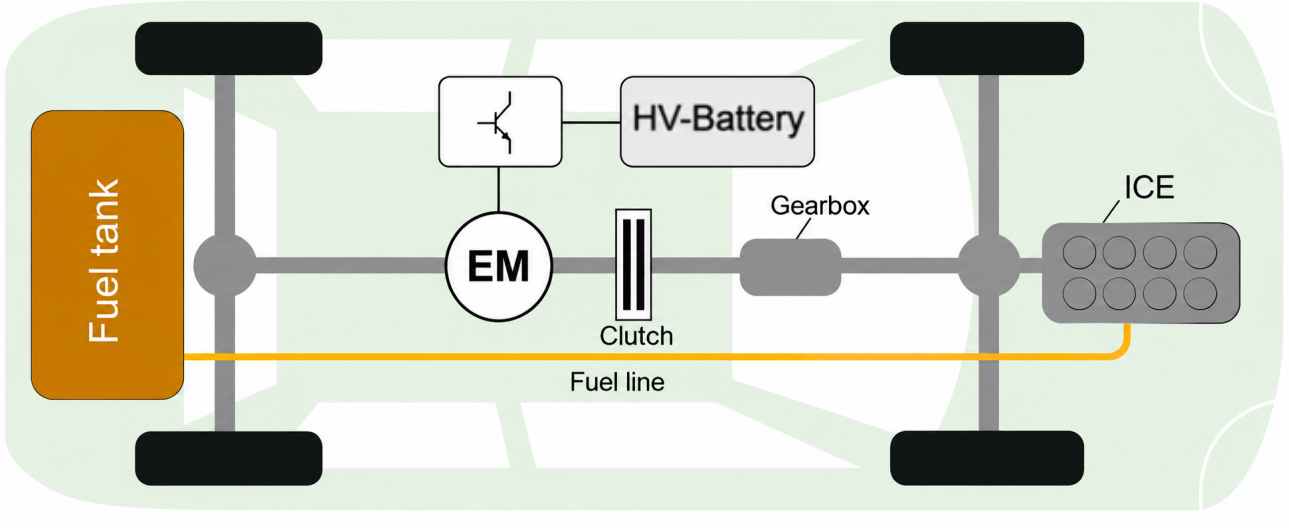


Figure 16: Mild hybrid as a parallel hybrid (P3).

4.2.3 Classification by Electrical Power: Full Hybrid

The electric motor has significantly higher power than in a mild hybrid.

A high-voltage (HV) system is also used, with voltages of up to approximately 800 V.

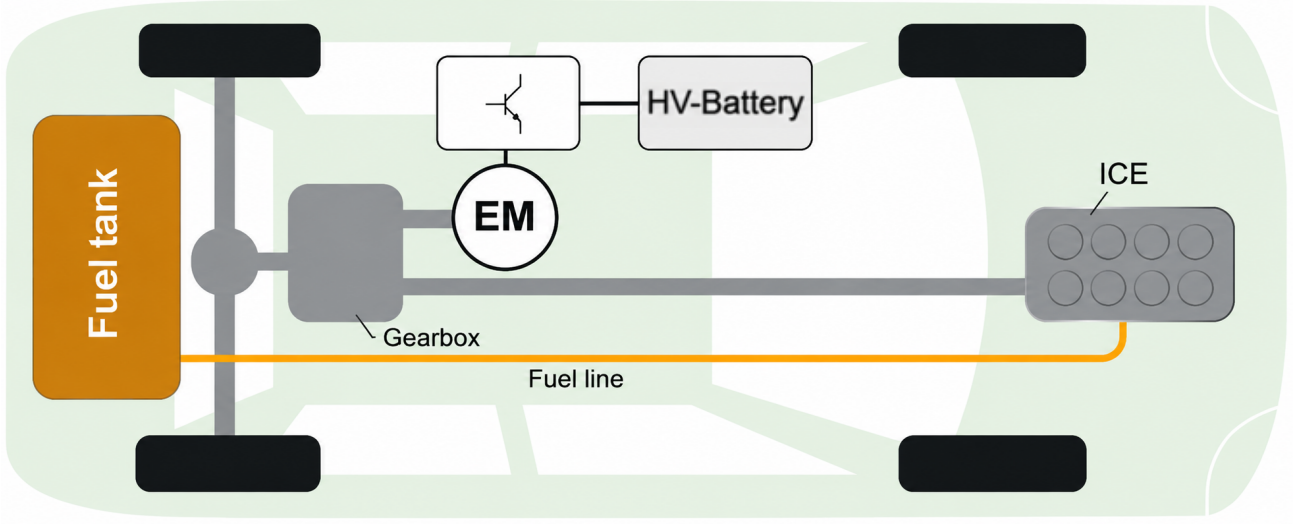


Figure 17: Vehicle with a full-hybrid drive.

Characteristics of a full-hybrid drive:
(a) Concept: ... The vehicle can be driven exclusively by the internal combustion engine, exclusively by the electric motor, or by a combination of both drive systems.
(b) Operation: ... The electric drive can provide a short-term power boost or allow purely electric driving over short distances.
(c) Variant: ... A plug-in hybrid differs from a conventional hybrid in that its battery can also be charged using an external charging station.

4.2.4 Classification by Energy Flow: Parallel Hybrid

In a parallel hybrid, the internal combustion engine drives the wheels directly through a gearbox, as in a conventional vehicle.

The electric drive is connected in parallel and can be activated or deactivated independently of the internal combustion engine.

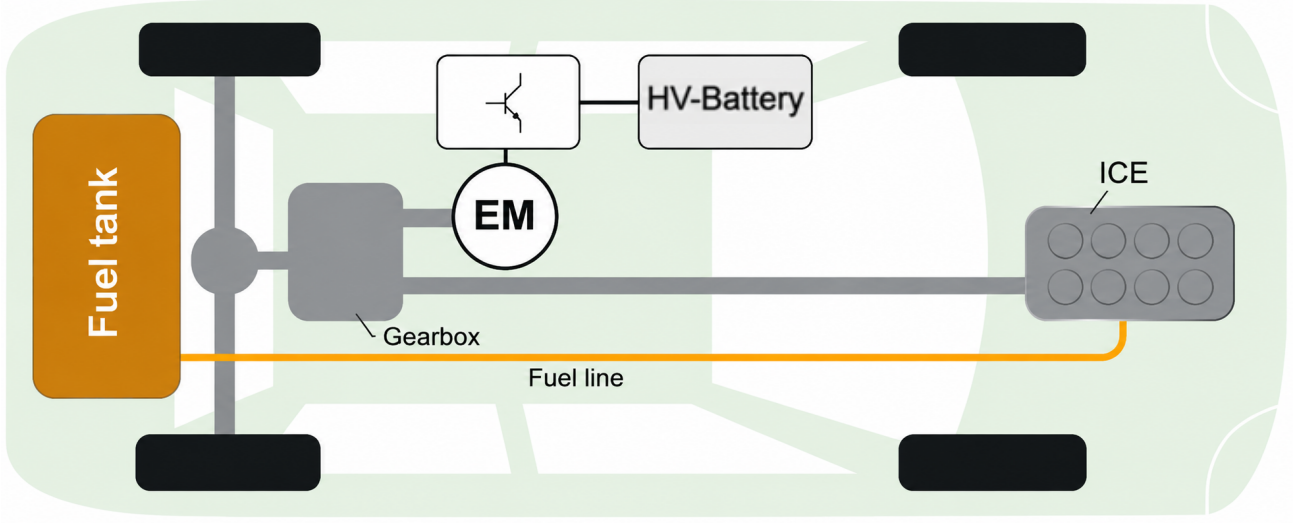


Figure 18: Vehicle with a parallel-hybrid drive.

In principle, both drive units can propel the vehicle independently (full hybrid).

The electric motor is often activated during peak loads, allowing a smaller internal combustion engine to be used.

When the vehicle is braking or travelling downhill, the electric motor operates as a generator and charges the traction battery.

Recuperation also has the advantage of significantly reducing brake disc wear.

Key Point 18: A large proportion of hybrid vehicles currently on the market use the parallel-hybrid concept.

4.2.5 Classification by Energy Flow: Series Hybrid

In a series hybrid, there is no direct connection between the internal combustion engine and the drive wheels.

A generator is coupled to the internal combustion engine and produces the electrical energy required to propel the vehicle.

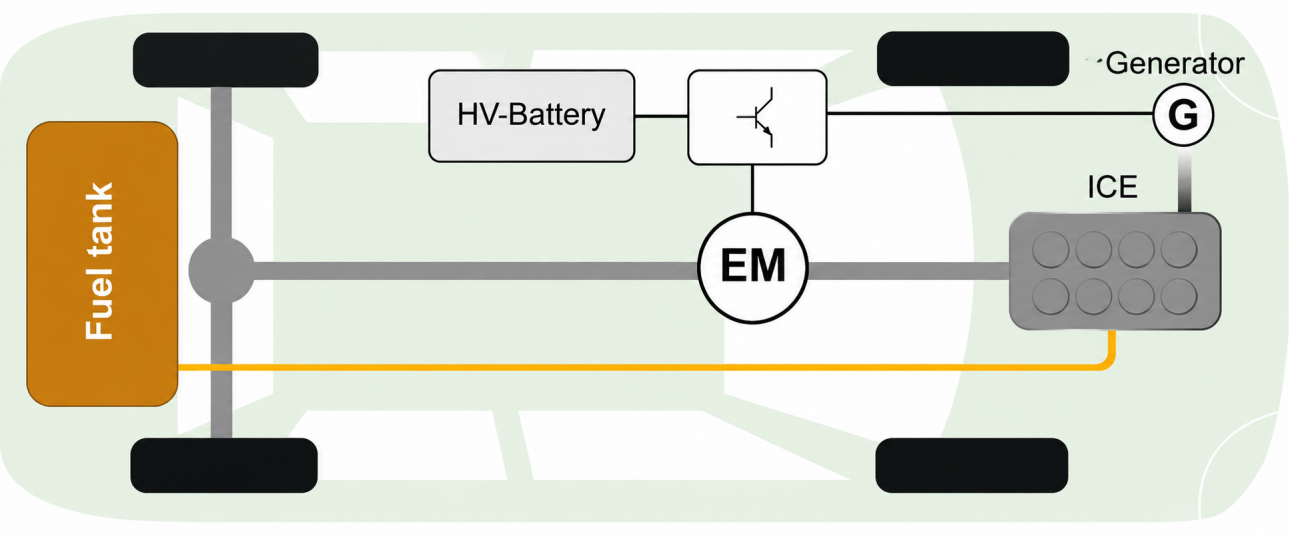


Figure 19: Vehicle with a series-hybrid drive.

Key Point 19: A complex gearbox is not required, and the internal combustion engine can be operated in an engine speed range optimised for fuel consumption!

Due to the lower efficiency of a series hybrid compared with a parallel hybrid, this concept is mainly used in the form of a range extender.

4.2.6 Special Series Hybrid: Range Extender

The vehicle operates as a purely electric vehicle. The drive energy flows exclusively from the battery to the electric motors at the drive wheels.

To increase the vehicle's range, a small internal combustion engine coupled to a generator is installed. This generator charges the high-voltage (HV) battery.

The potential for CO_2 savings is very high, as a large proportion of average journeys are short-distance trips, meaning that the range extender is not activated.

Key Point 20: With a range extender, the charging stops required by purely electric vehicles on long-distance journeys can be avoided completely!

The power of the range extender is usually not sufficient to operate the vehicle at its normal performance limits (maximum speed, torque, etc.) when the battery is empty. Its main purpose is to support battery charging.

4.3 Battery Electric Vehicle

A battery electric vehicle consists of at least one maintenance-free electric motor, a suitable inverter to control the motor and a sufficiently large battery pack.

Due to the high torque and wide speed range of the electric motor, complex gearboxes are not required.

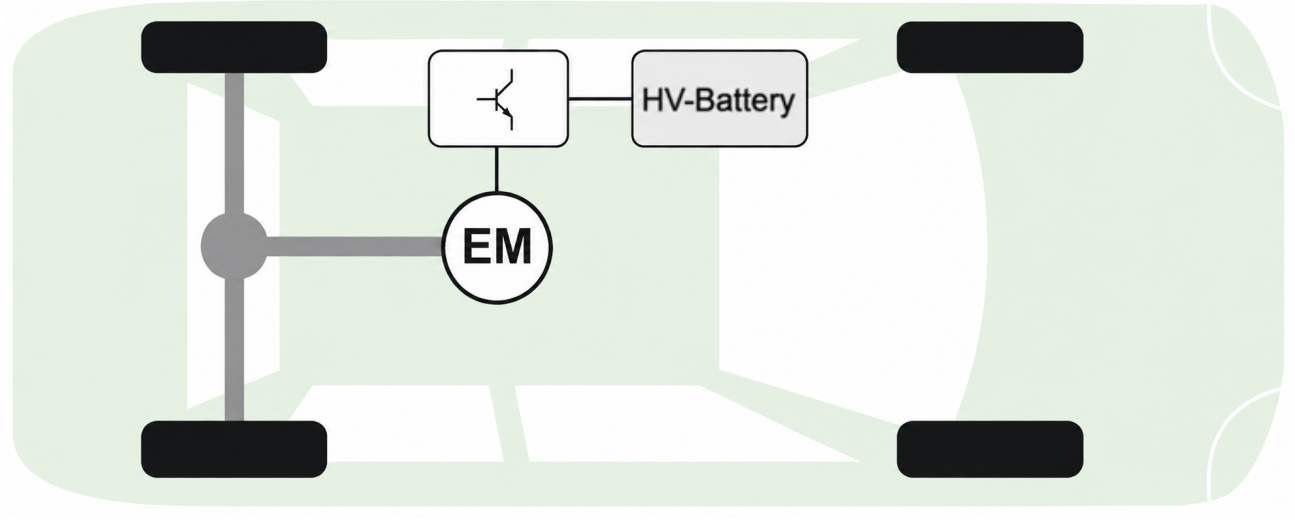


Figure 20: Battery electric vehicle.

Key Point 21: The battery electric vehicle is the vehicle concept with the lowest number of components and the least complexity!

Energy requirements: The vehicle's drive power comes exclusively from the installed battery pack. The battery is recharged through recuperation and external charging stations.

The efficiency is two to four times higher than that of an internal combustion engine and is approximately 80%.

Cost structure: Due to the simpler design, development and manufacturing costs decrease significantly once vehicle manufacturers reach sufficient production volumes.

At present, prices are sometimes kept high to achieve higher profit margins with the new technology. In addition, the initial investments required for the transition to this technology must be recovered by distributing development costs across individual vehicles.

Maintenance: The service and maintenance costs of an electric vehicle are significantly lower than those of a vehicle with an internal combustion engine.

Many essential fluids are no longer required, brake discs wear less due to recuperation, and timing belts and similar components are no longer needed. Complex gearboxes, exhaust gas treatment systems, fuel tanks and filters are also eliminated.

4.4 Fuel Cell Vehicle

A fuel cell vehicle is essentially an electric vehicle whose traction battery is also charged by a fuel cell while driving.

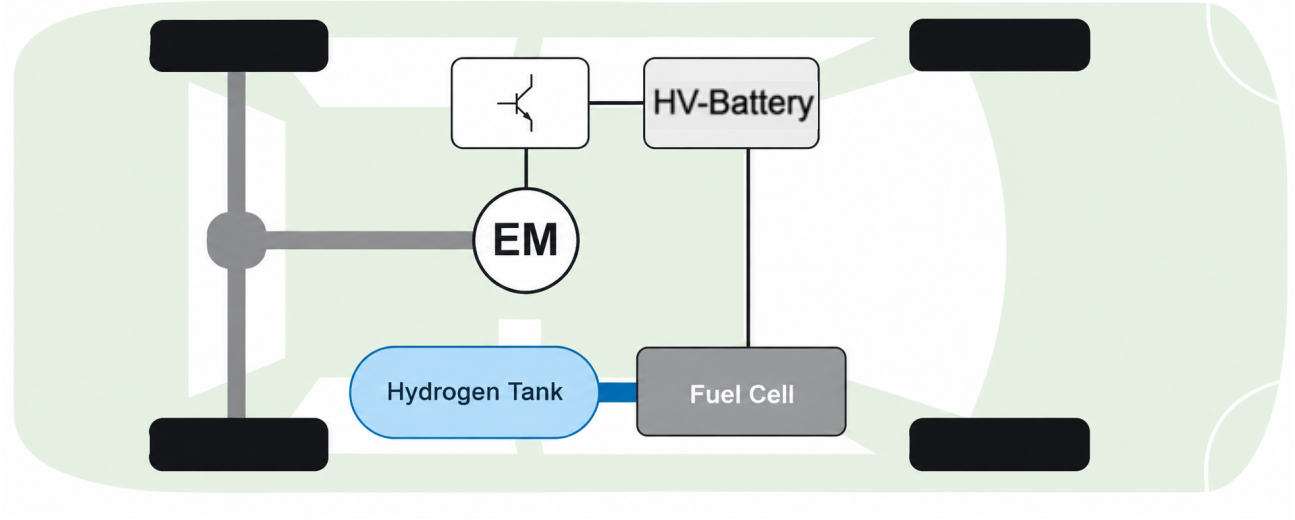


Figure 21: Fuel cell vehicle.

A fuel cell generates the electricity required for propulsion from hydrogen or methanol.

Electricity generation is continuous. Therefore, a hydrogen-powered vehicle also requires a high-voltage (HV) battery to provide additional power during peak torque demands (acceleration) and to recover braking energy through recuperation.

However, the size and weight of this battery are significantly lower than those of a purely battery electric vehicle.

Key Point 22: Projects involving fuel cell technology are increasingly being implemented, particularly in the areas of trucks, agricultural and construction machinery, ships and trains!

Unlike battery electric vehicles, refuelling takes only a few minutes. The achievable range per tank of fuel is comparable to that of conventional diesel or petrol vehicles.

Since the low-voltage electricity networks in our cities can only be expanded to meet the increasing demands of electromobility over a very long period, fuel cell technology has significant potential to replace internal combustion engines.

However, its overall efficiency is considerably lower than that of purely battery electric vehicles.

5 Emissions in the Production and Operation of Electric Vehicles

Electric cars (EVs) produce no exhaust emissions during operation. However, their production, particularly battery manufacturing, causes significant CO_2 emissions, which strongly depend on the energy mix used during manufacturing.

Compared with vehicles with internal combustion engines, electric cars have a significantly better overall carbon footprint, as the lower emissions during operation compensate for the initially higher production emissions over their lifetime.

Using electricity from renewable energy sources significantly reduces the CO_2 footprint, and future technologies could further improve battery production and recycling.

5.1 Emissions in Production

5.1.1 Battery Manufacturing

The majority of emissions during electric vehicle production are caused by the manufacturing of lithium-ion batteries.

This energy-intensive process is strongly influenced by the electricity mix used in the country of production.

5.1.2 Vehicle Production

The production of the remaining vehicle components also causes emissions, but these are less significant compared with battery manufacturing.

5.2 Emissions During Operation

5.2.1 Operation Without Exhaust Emissions

Electric cars do not emit harmful exhaust gases or CO_2 while driving, as they do not have an internal combustion engine.

5.2.2 Electricity Consumption

The environmental impact during operation strongly depends on the electricity source.

Charging with electricity from renewable energy sources (green electricity) significantly reduces overall CO_2 emissions.

5.2.3 Tyre and Brake Wear in Electric Cars

Electric cars produce less brake wear because recuperation reduces the use of mechanical brakes, resulting in less brake dust.

However, tyre wear is often higher than in vehicles with internal combustion engines because the greater vehicle weight and immediately available high torque place additional stress on the tyres.

This increased tyre wear is a growing concern for particulate matter pollution, as it accounts for a significant proportion of so-called non-exhaust emissions.

Reduced Brake Wear Through Recuperation

Electric cars use regenerative braking to recover kinetic energy during deceleration and feed it back into the battery.

As a result, the mechanical brakes are used less frequently and produce less brake dust.

Risk of Brake Pad Glazing

Because the mechanical brakes are used less frequently, the brake pads may age more quickly and become glazed, which can reduce their braking performance.

Rust Formation on Brakes

Less frequent use can also lead to rust formation on the brake discs, resulting in an uneven contact surface.

Higher Vehicle Weight

Electric cars are generally heavier than comparable vehicles with internal combustion engines due to their batteries, which increases tyre wear.

The immediately available high torque of an electric motor places additional stress on the tyres and can accelerate wear, particularly with an aggressive driving style.

Particulate Matter Pollution

Increased tyre wear is a significant source of particulate matter in the environment, as it accounts for a large proportion of total non-exhaust emissions.

5.2.4 Conclusion

While electric cars reduce brake wear through recuperation, increased tyre wear due to their weight and torque presents a challenge for both the environment and the tyres.

5.3 Comparison of the Overall Environmental Impact

5.3.1 Life Cycle Assessment

A complete life cycle assessment shows that electric cars emit significantly fewer greenhouse gases than vehicles with internal combustion engines, especially when electricity from renewable energy sources is used.

Compensation for Production Emissions

The initially higher CO_2 footprint of electric vehicle production is compensated for and outweighed by the lower emissions during operation over the vehicle's lifetime.

5.3.2 Potential for Future Improvements

Improved Battery Technology

Battery manufacturing is a relatively young and developing process with great potential for efficiency improvements and emission reductions.

Renewable Energy

The increased use of renewable energy sources in both vehicle production and battery charging will further improve the environmental performance of electric cars.

Recycling and Reuse

The development and implementation of processes for recycling and reusing battery materials are essential for sustainable electromobility.