The transition of propulsion technologies on the way to carbon-neutral mobility

Guest-lecture at the Department of Electrical Power Engineering
Brno University of Technology

Date:
22.11.2022

Host:
Assoc. Prof. Ing. Petr Baxant

Speaker:
Associate Prof. Dr. Mario Hirz
Institute of Automotive Engineering
Graz University of Technology

The transition in the automotive industry is driven by ...

(1) Legislative boundary conditions targeting to a reduction of emissions

(2) Digitalization & automation

(3) New mobility concepts & business models

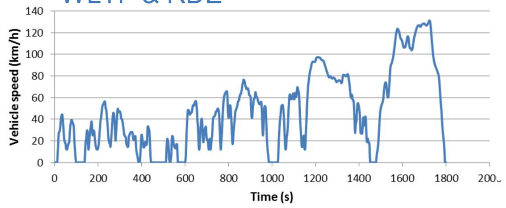
=> In this lecture, the focus is on propulsion technologies on the way to carbon-neutral mobility

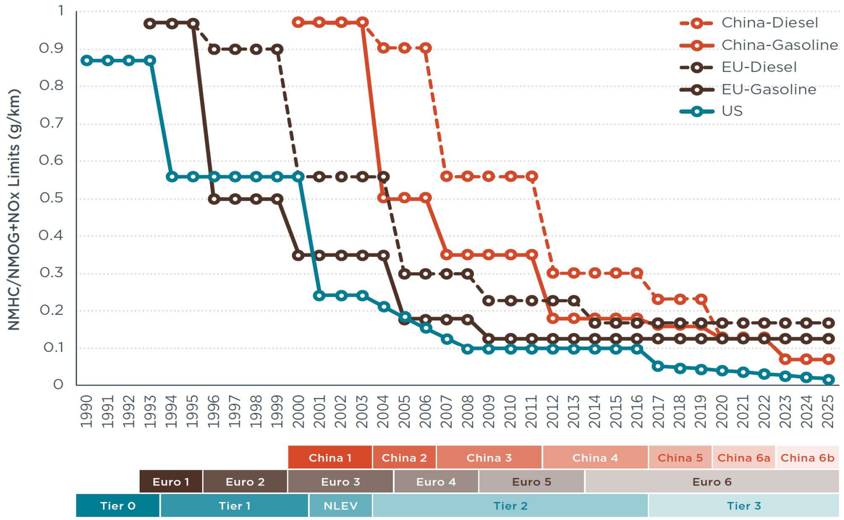
Legislative boundary conditions targeting to a reduction of exhaust emissions

Reduction of harmful exhaust emissions

- Hydro-carbons HC
- Carbon monoxide CO
- Nitro-oxygen NOx
- Particulate emissions

WLTP & RDE





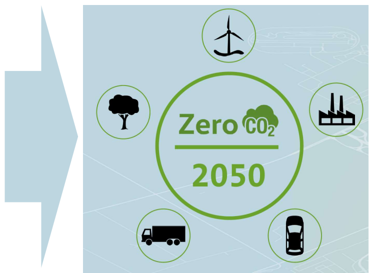
Example: Limitation of NOx-emissions in different markets

Reduction of greenhouse gases
e.g. EU "Green Deal" targets:

CO_2 reduction of

- 50% in 2030
- 100% in 2050

... in all branches.



Proposed technologies:

- "Green" electricity production
- Electrification of mobility (cars, trucks)
- Hydrogen as a fuel (cars, trucks, ships)
- Synthetic fuels (trucks, ships, aviation)
- Carbon capture & storage (industry)

Transport

Legislative boundary conditions targeting to a reduction of exhaust emissions

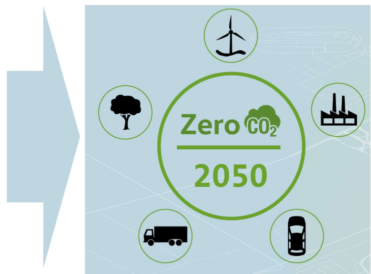
Emitted CO_2 – emissions in the EU since 1990
(1990 = 100%)

Reduction of greenhouse gases
e.g. EU "Green Deal" targets:

CO_2 reduction of

- 50% in 2030
- 100% in 2050

... in all branches.



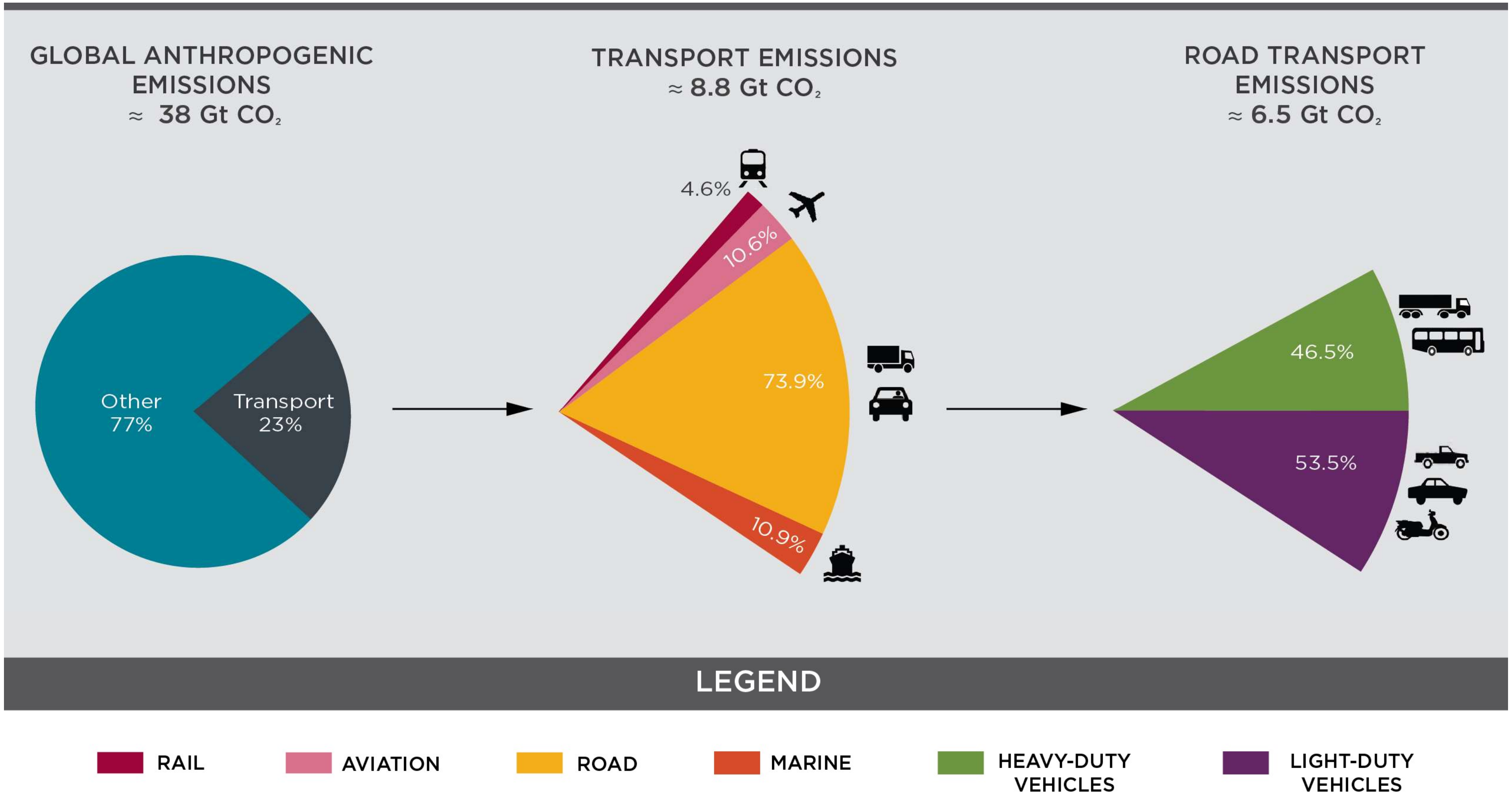
Proposed technologies:

- "Green" electricity production
- Electrification of mobility (cars, trucks)
- Hydrogen as a fuel (cars, trucks, ships)
- Synthetic fuels (trucks, ships, aviation)
- Carbon capture & storage (industry)

Transport

Source: EU, Transport & Environment

Worldwide CO_2-impact of the transportation sector



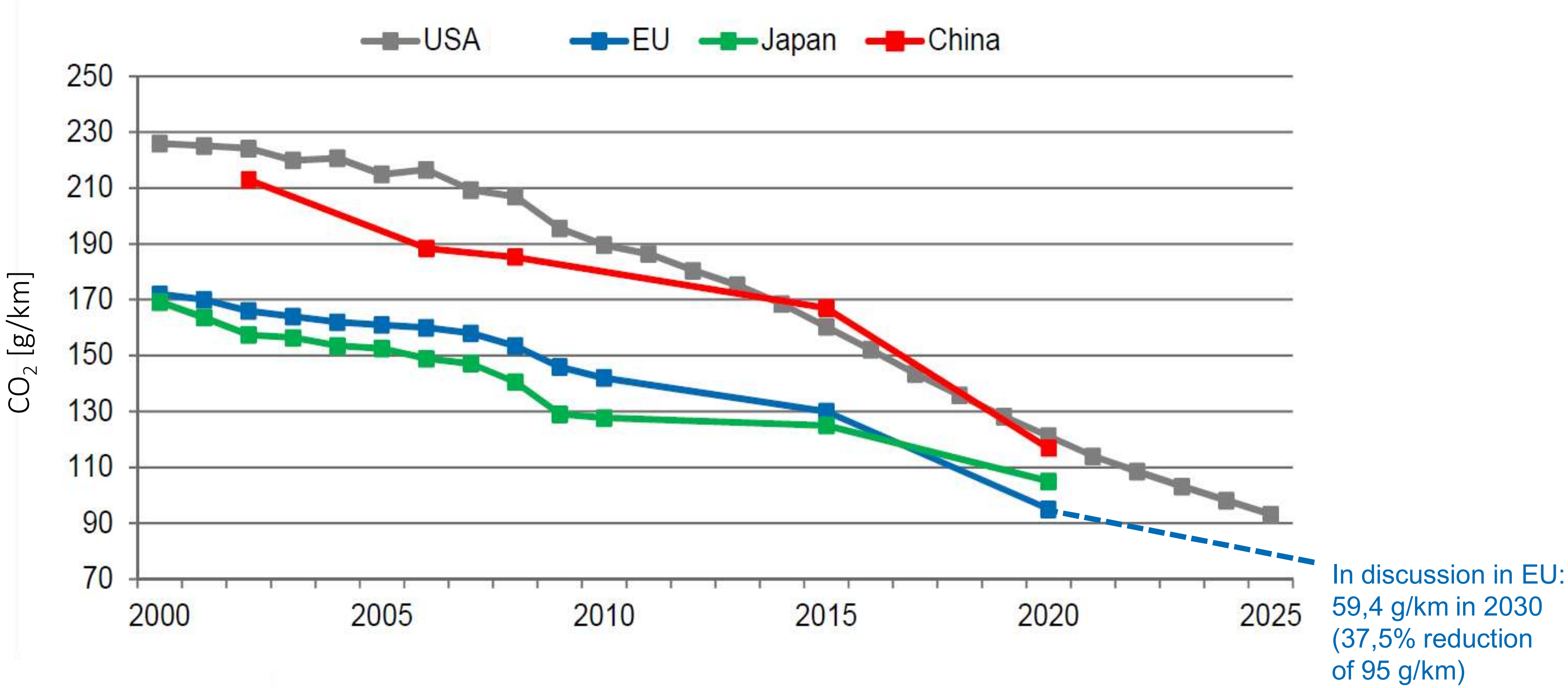
⇒ ca. 17% CO_2 from road transportation

… 8% CO_2 commercial transport

… 9% CO_2 individual mobility

Source: ICCT

Legislative boundary conditions: Trends of CO_2 fleet-emissions of personal cars



95 g/km CO_2 → 4.1 liter per 100km Gasoline
→ 3.6 liter per 100km Diesel fuel

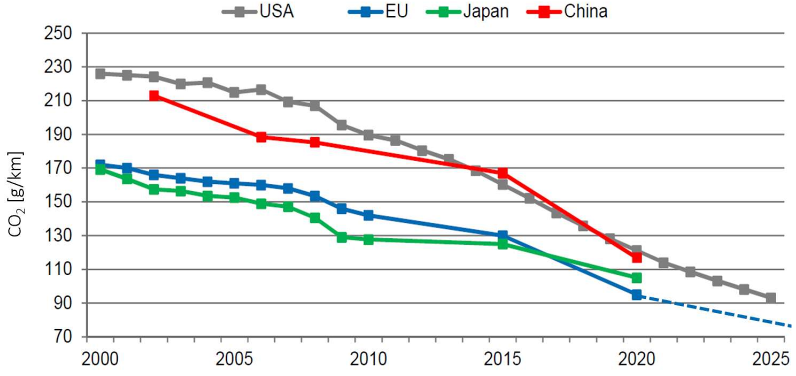
59.4 g/km CO_2 → 2.6 liter per 100km Gasoline
→ 2.3 liter per 100km Diesel fuel

Source: ICCT, EU

Penalty payments in the EU

Penalty payment for car manufacturer that do not reach the CO_2 - target:

- 95 € per Gramm CO_2 target violation per car sold and registered in the EU in a year
- Phasing-in regulations 2021 - 2023, special credits for eco-innovation
- Pooling is allowed (group-wide consideration)
- Reliefs for small manufacturers



Strategies of the automotive industry:

Short term (- 2027):

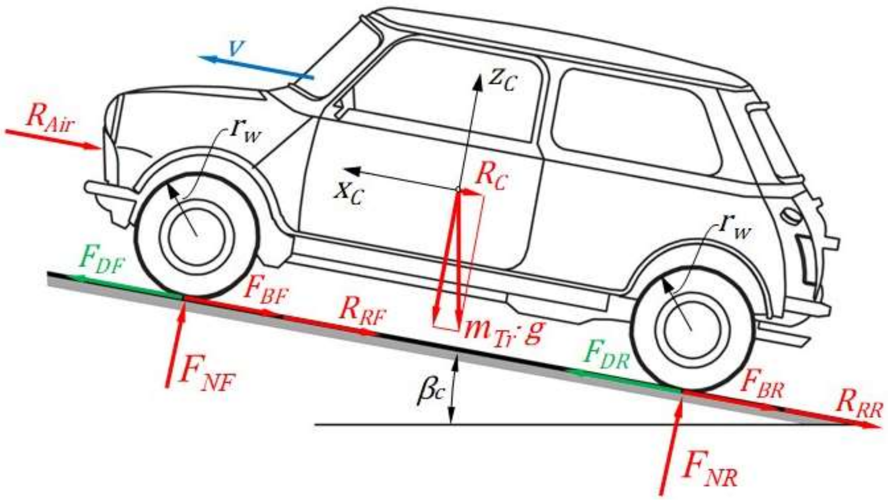
→ Optimization of combustion engines
→ "Smaller" combustion engines
→ Electrification (HEV / PHEV / BEV)

Mid- / long term (2030 +):

→ Electric cars
→ Hydrogen vehicles
→ Synthetic fuel applications

Comparison of propulsion technologies

The physics: driving resistances



Driving resistances: $R_{ges} = F_B + R_R + R_{Air} + R_C + R_{Acc}$

Braking force: $F_B = (F_{BF} + F_{BR})$

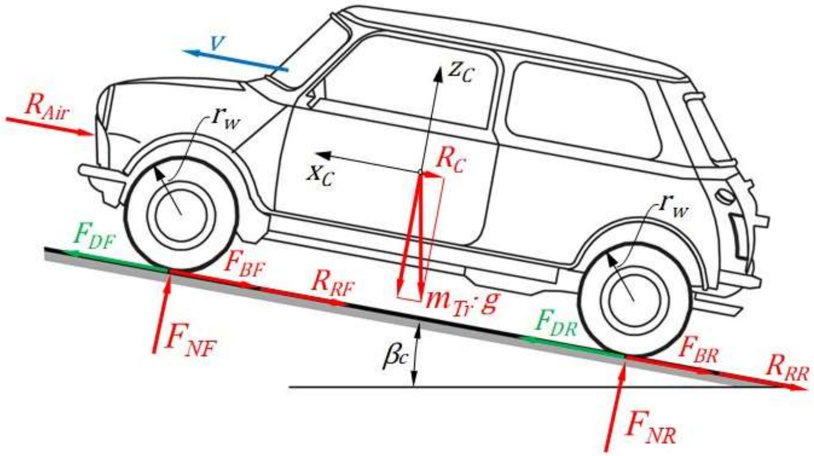
Rolling resistance: $R_R \approx c_R\, m_{To}\, g\, \cos\beta_c\, \mathrm{sign}(v)$

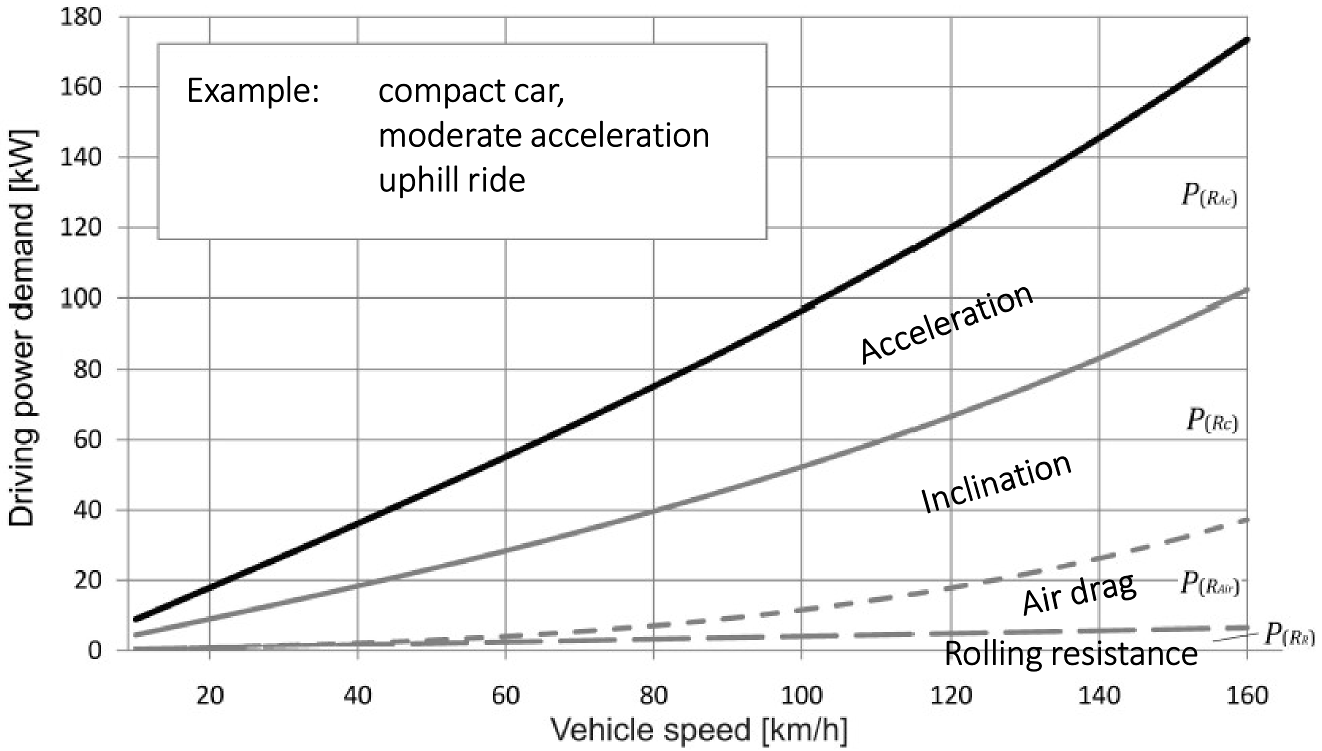
Air drag: $R_{Air} = {}^1/_2\, c_{Air}\, A_F\, \rho_L\, v\, |v|$

Climbing resistance: $R_C = m_{To}\, g\, \sin\beta_c$

Acceleration resistance: $R_{Acc} = m_{To}\, a_{Veh}$ $\quad m_{To} = m_{Tr} + \frac{\sum I_{Red}}{r_W^2}$

The physics: driving resistances





Possibility of energy recovering e.g. by coasting, recuperation

„Lost energy“

Overview of propulsion technologies

Conventional drive systems

+ Established technologies, low costs
+ Quick fuel-filling, large driving distances
+ Potential for further improvements

- Thermodynamically bad efficiency
- Local exhaust emissions
- Direct dependency on crude oil (today)

Electric drive systems

+ Most efficient propulsion technology
+ No local emissions
+ Quiet technology, high driving comfort

- Expensive & complex battery systems
- Short driving distances, long charging times
- Environment-friendliness depends on the technology of electric power generation

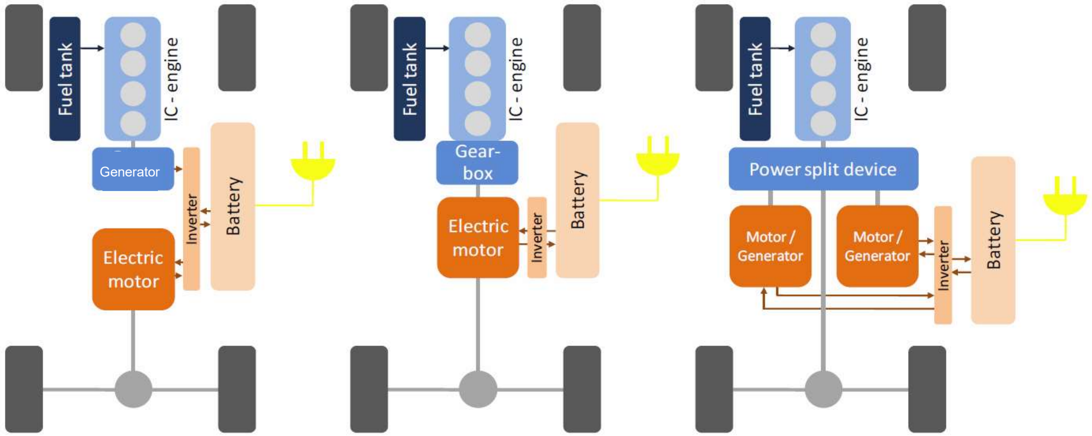
Hybrid drives

+ Combination of conventional and electric drive systems
+ Good efficiency possible
+ No driving range limitation
+ Specific test-procedures defined (for PHEV)

- Complex technology, integrating two propulsion systems
- CO_2 reduction potential is significantly influenced by user pattern / customer behavior

Architectures of hybrid- and battery-electric drive trains

Overview of hybrid drive train configurations



Serial hybrid

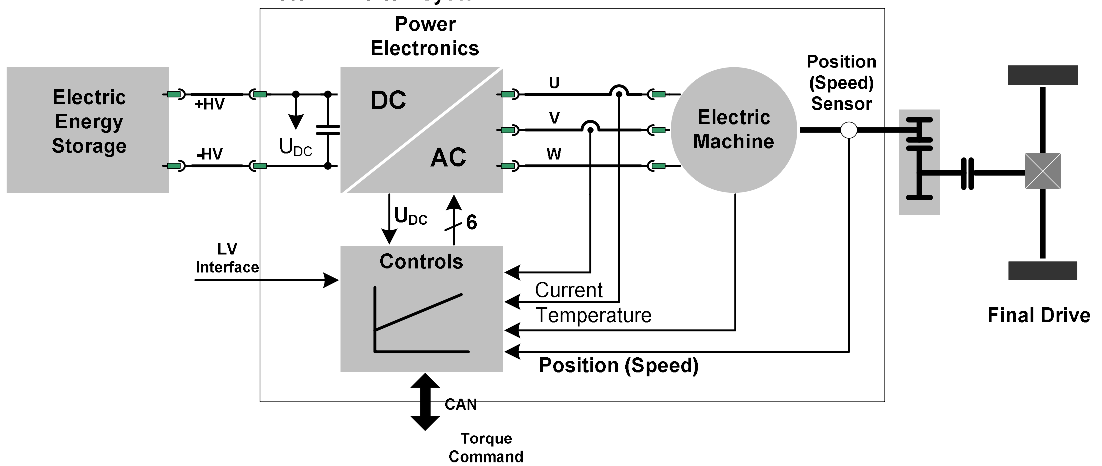
Parallel hybrid
P1, P2, P3, P4

Combined hybrid configuration

- Different combinations of ICE and e-drive possible
- Different levels of hybridization (MHEV, HEV, PHEV)
- CO_2 – reduction potential between 5% and > 50%, depending on the user behavior

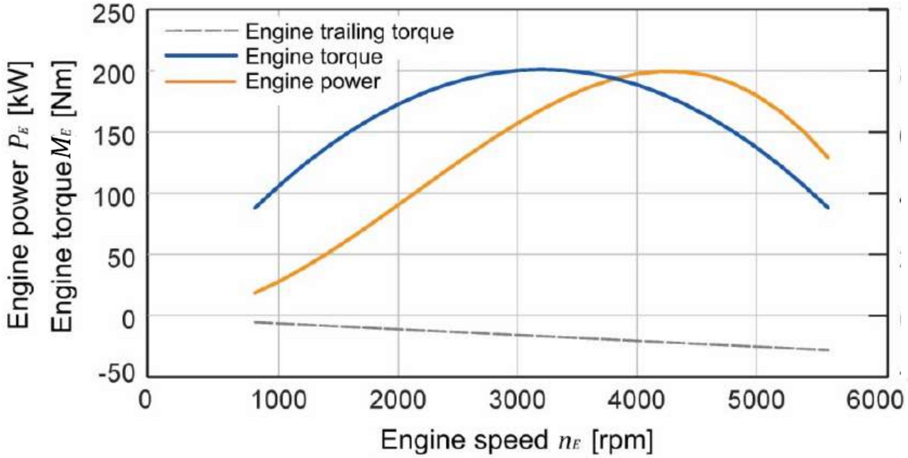
Battery-electric drive trains

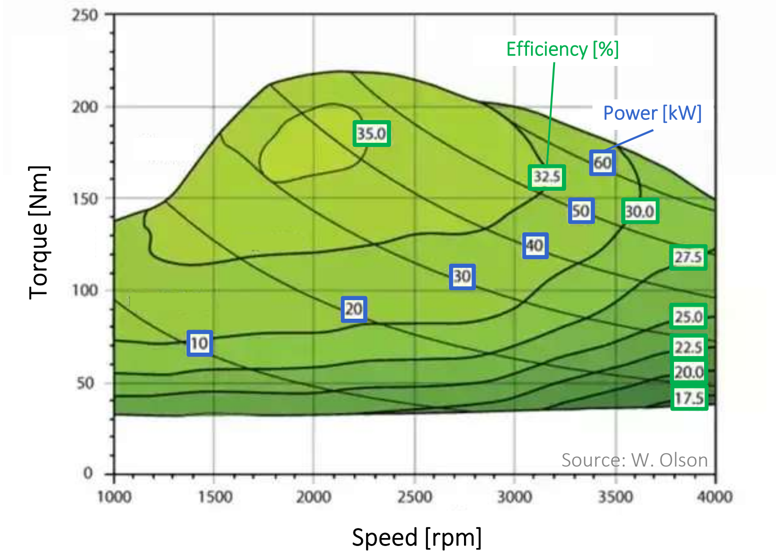
- Simple mechanical powertrain
- … but complex E/E systems
- Key components:
  - Battery
  - Inverter
  - Electric motor



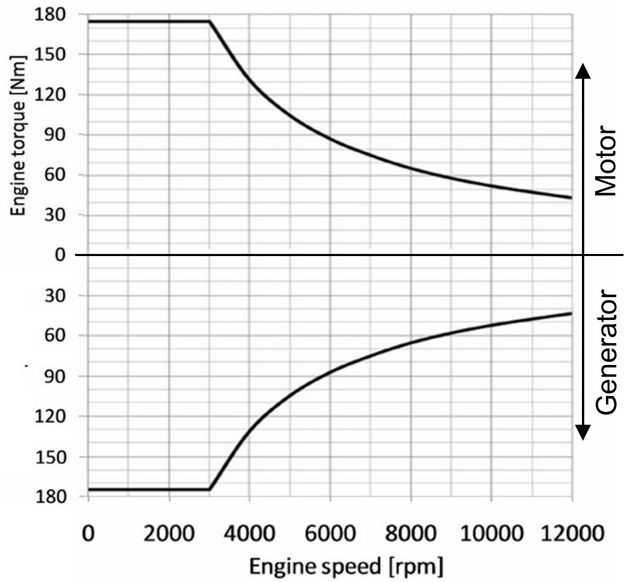
Internal combustion engine vs. electric motor

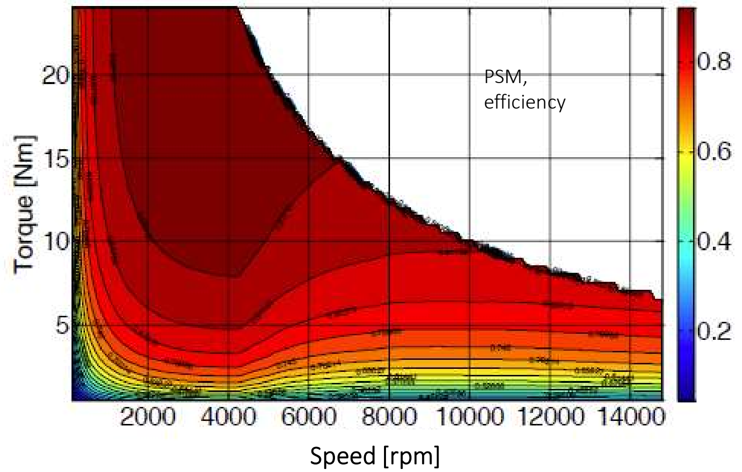
ICE



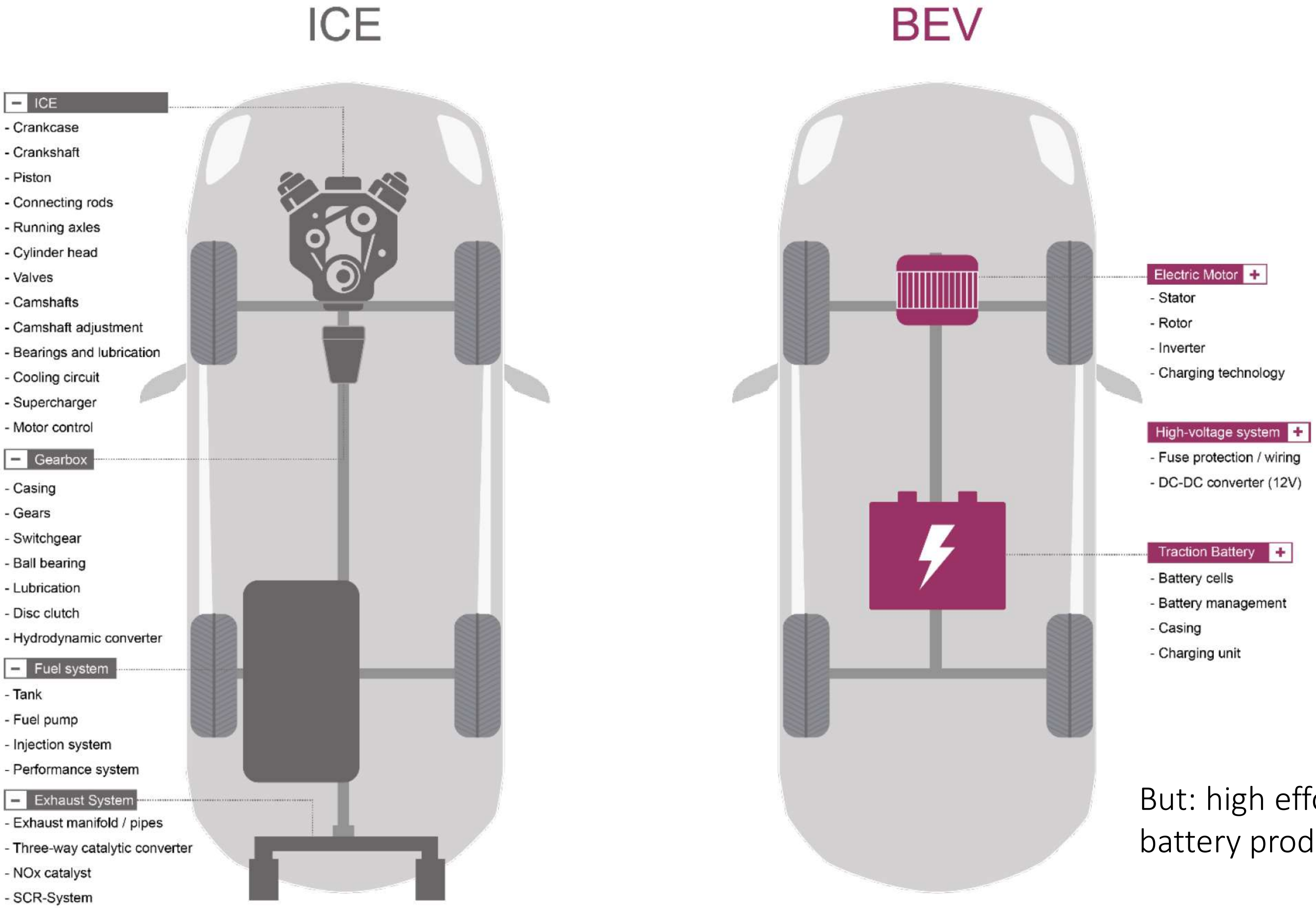


E-Motor





Electric drive trains: reduction of complexity

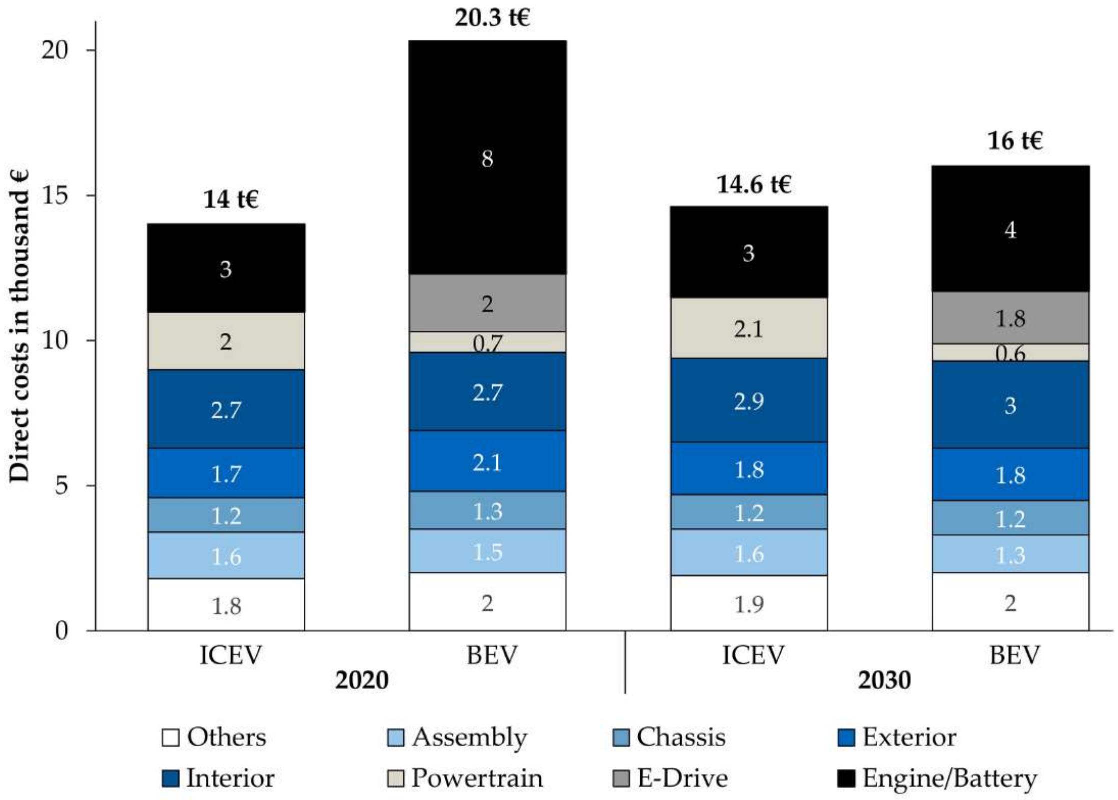


But: high effort for battery production

Source: Semmer

Cost comparison of propulsion technologies

Cost breakdown, compact SUV



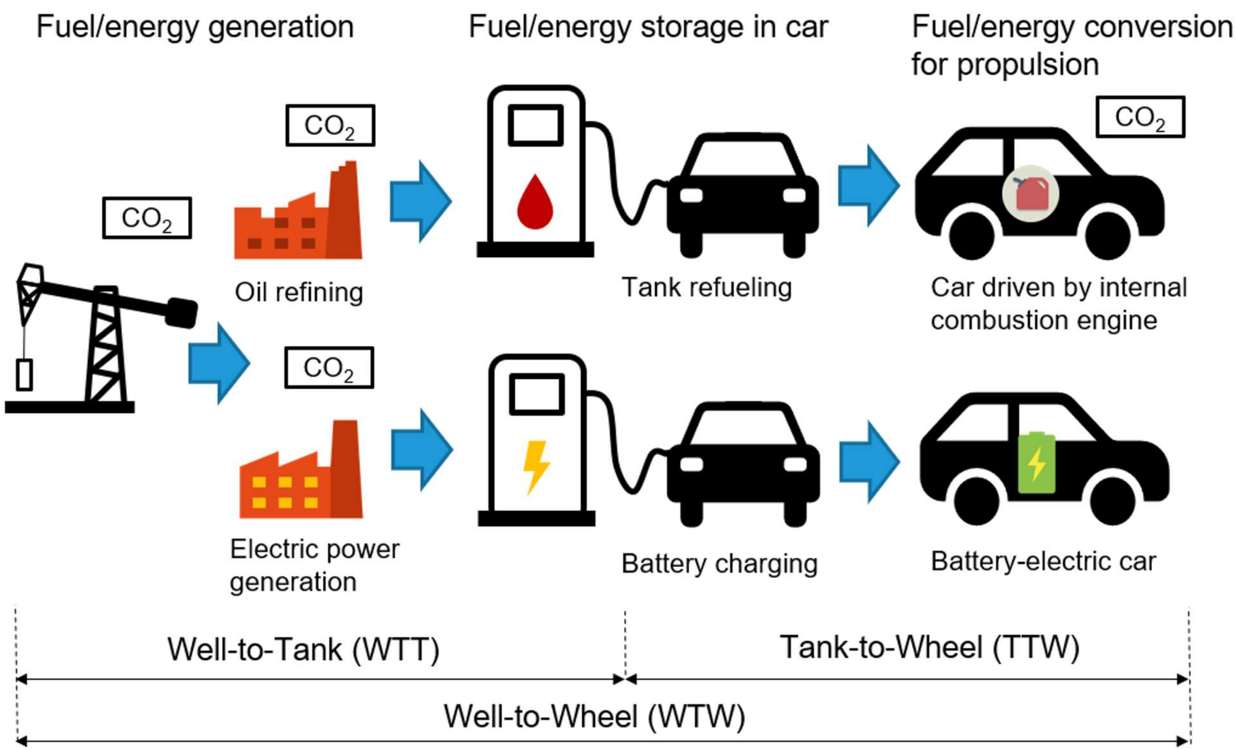
Source: König et.al, TU-Munich

CO_2 – impact of propulsion technologies

Well-to-tank & tank-to-wheel emissions

CO_2 equivalent emissions include:

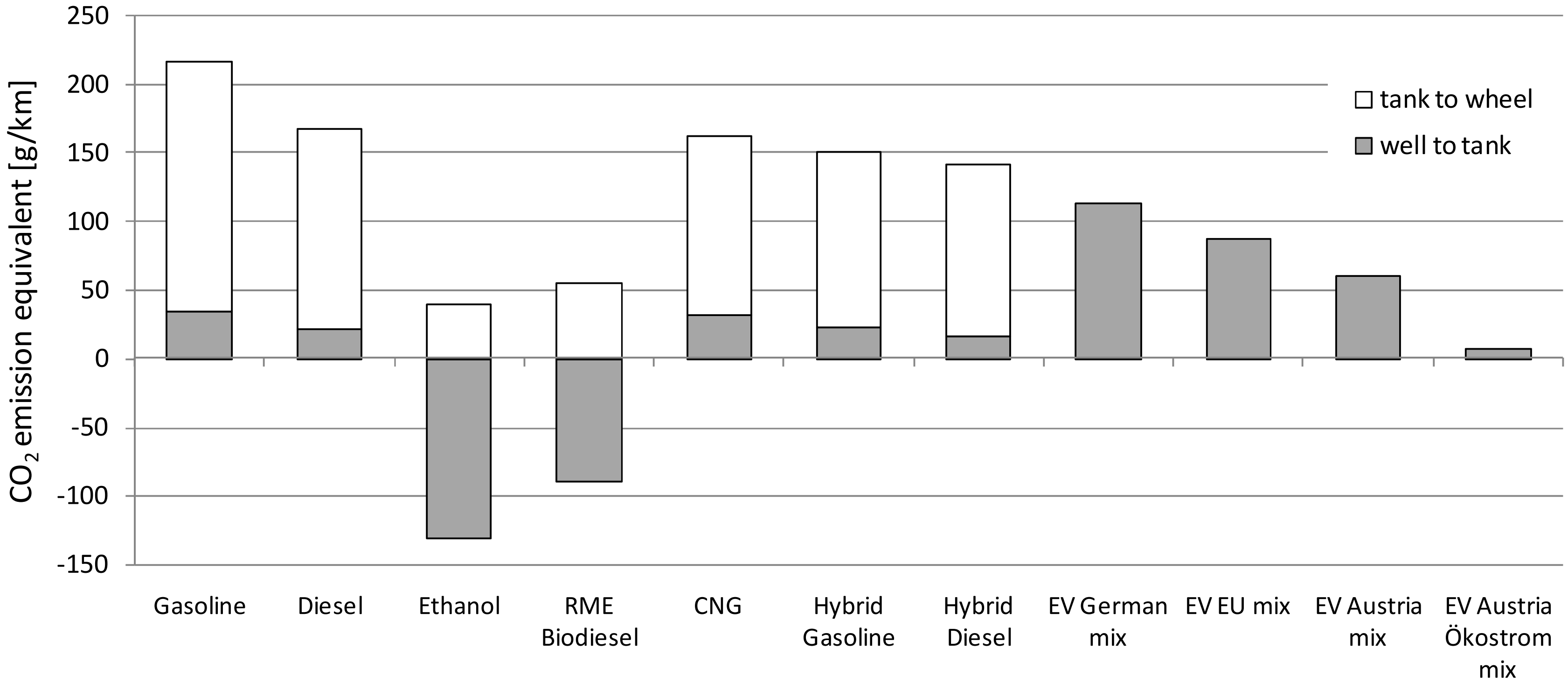
- Production of fuel (electric energy): WTT (well-to-tank emissions) ... not considered in fleet-related CO_2-legislation
- Conversion of energy in the car: TTW (tank-to-wheel emissions) ... => fleet emission targets
- Sum of WTT & TTW: WTW (well-to-wheel emissions)



Well-to-tank & tank-to-wheel emissions

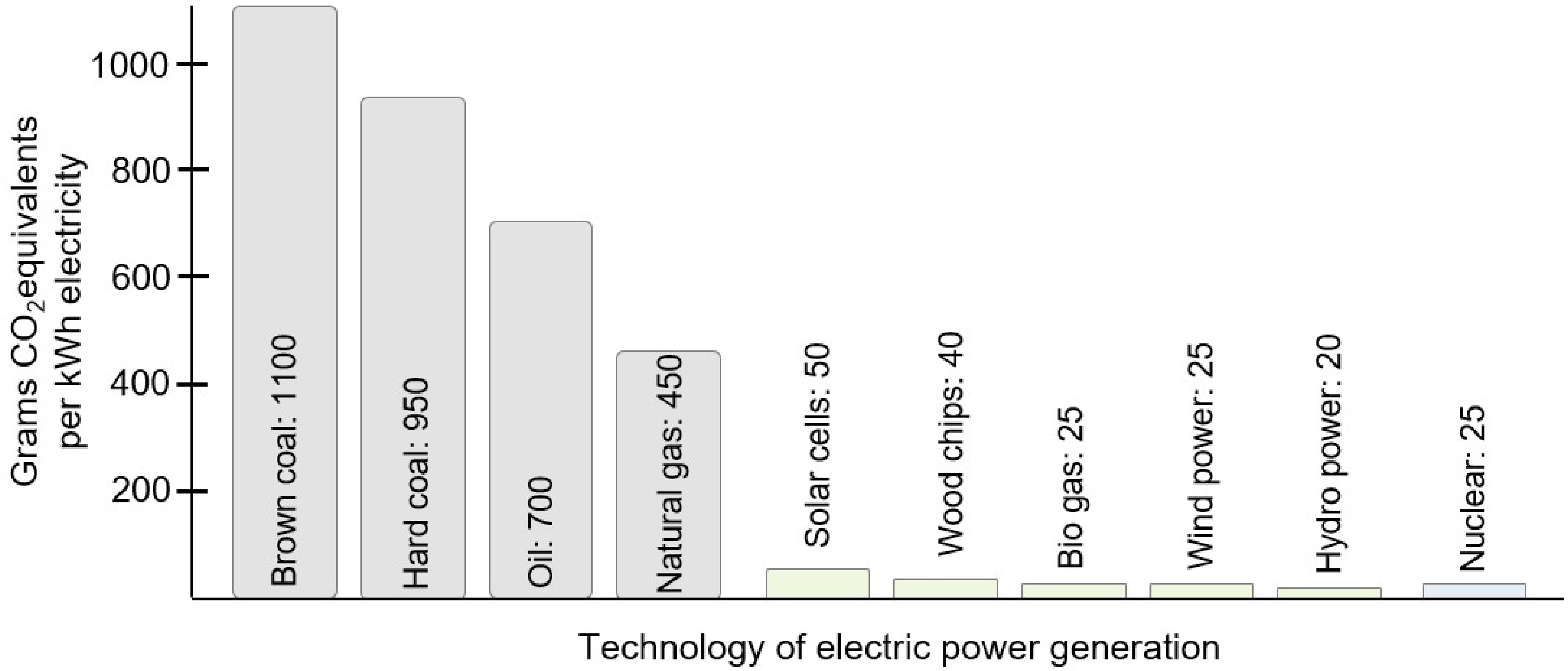
CO_2 equivalent emissions include:

- Production of fuel (electric energy): WTT (well-to-tank emissions) ... not considered in fleet-related CO_2-legislation
- Conversion of energy in the car: TTW (tank-to-wheel emissions) ... => fleet emission targets
- Sum of WTT & TTW: WTW (well-to-wheel emissions)

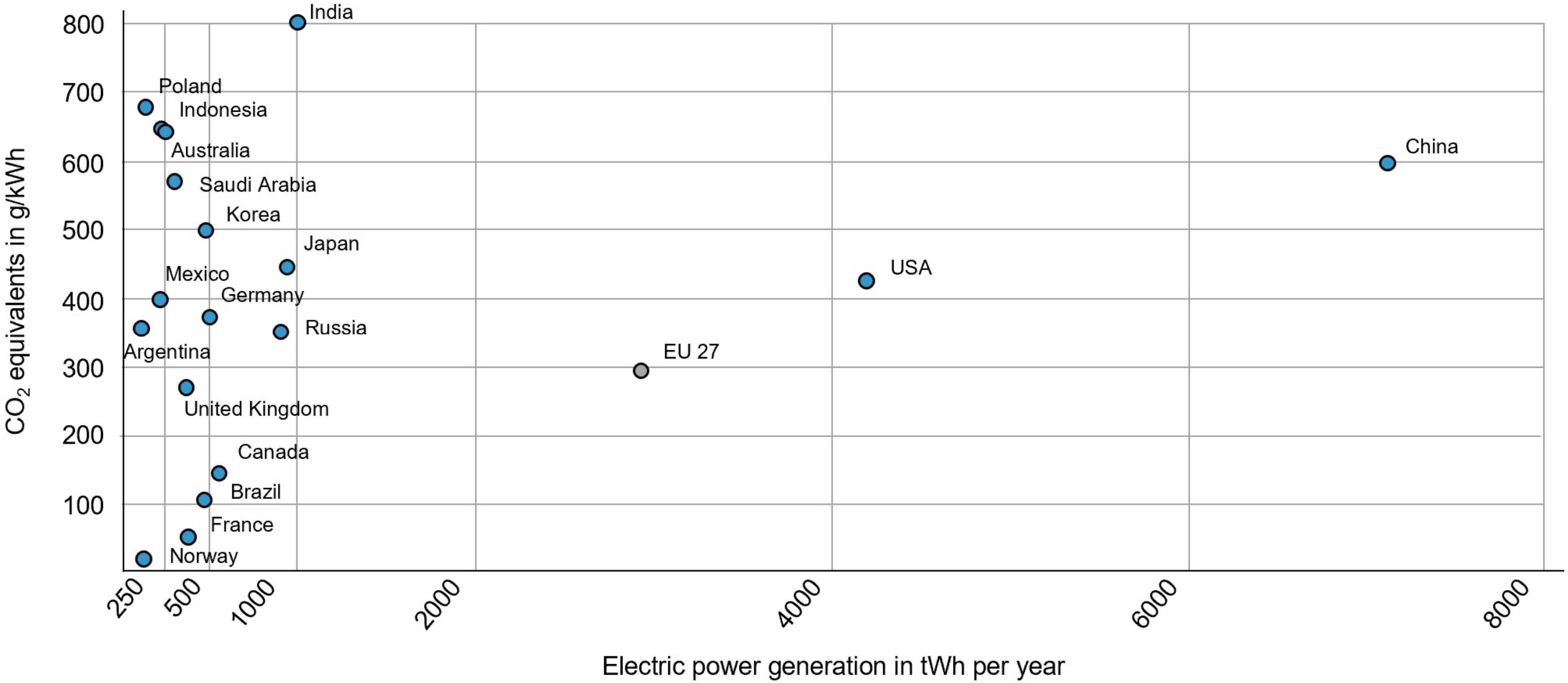


CO_2 equivalent emissions of a midsize car

Key role: electric energy production
Different technologies have different CO_2-impact



Key role: electric energy production
Electricity mix in selected countries / regions



… a link to real-time data: https://www.electricitymap.org/map

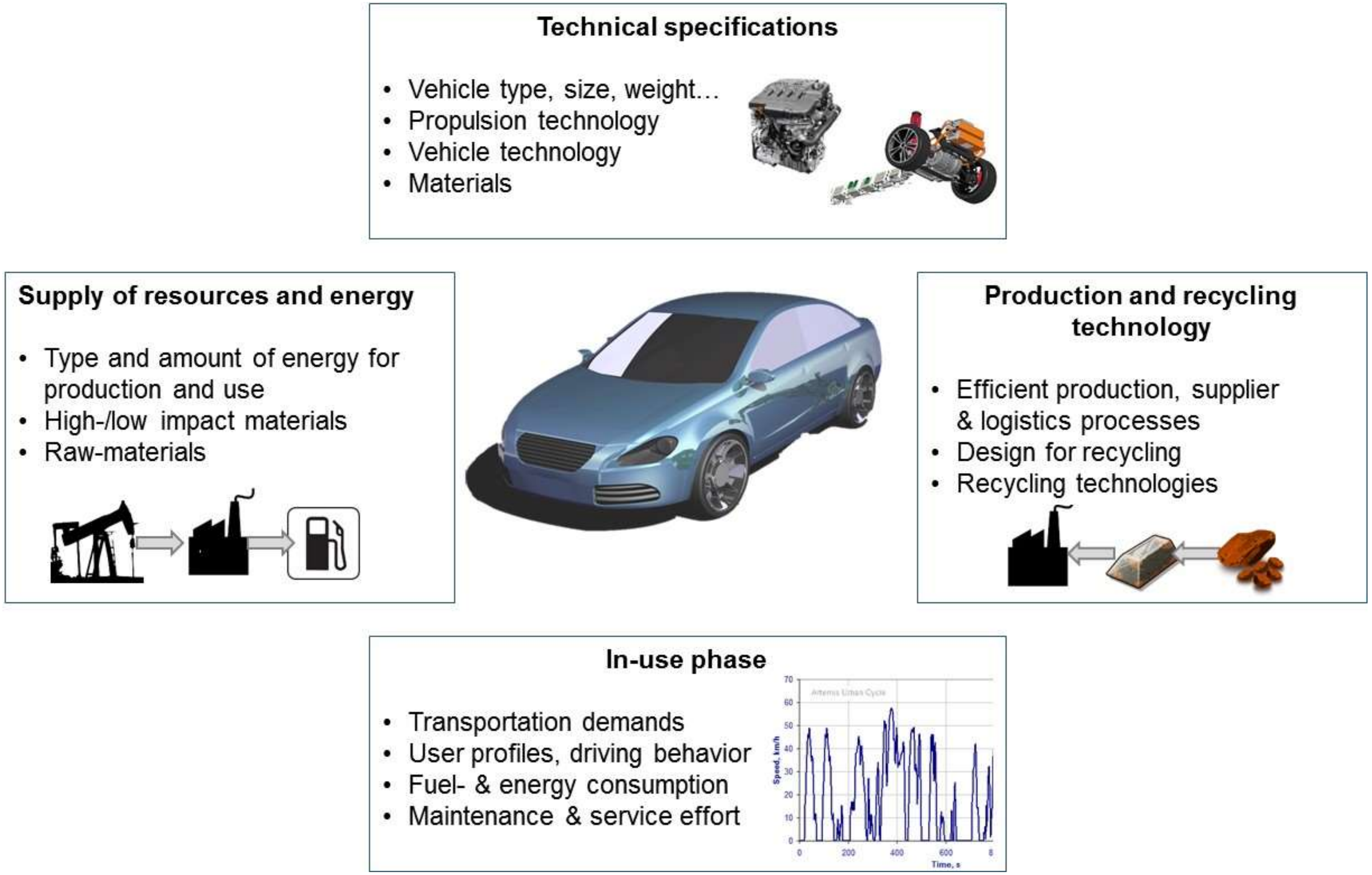
Example:

Comparison of different propulsion technologies, WTT and TTW: Electric car vs. Gasoline / Diesel car

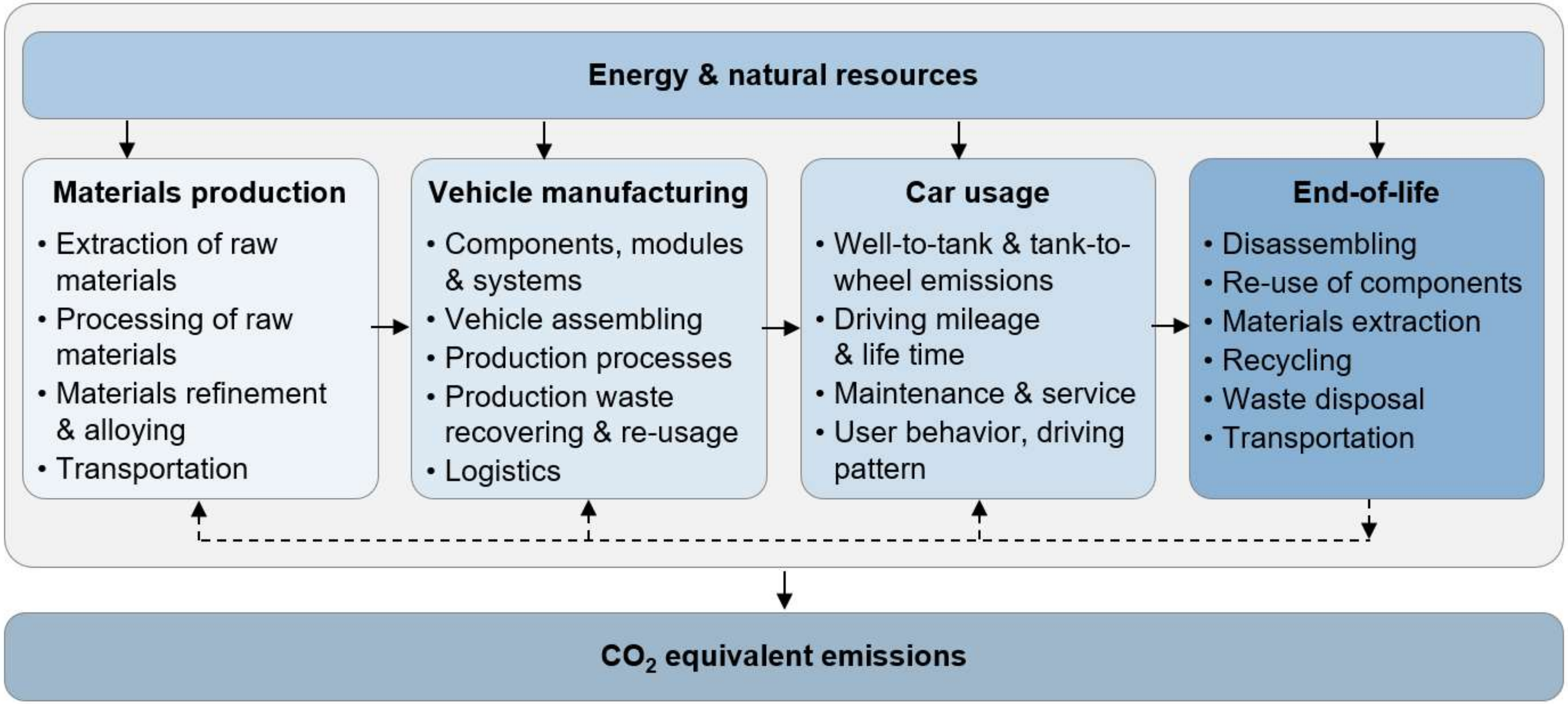
Remark: Calculation of CO_2 emissions out of fuel consumption by use of factor 26.2 for Diesel and factor 23.2 for Gasoline fuel: *liter/100km * factor =* CO_2 *[g/km]*

Life-Cycle - related consideration of technologies

Life-Cycle Assessment (LCA): Evaluation of technologies and products under consideration of the entire life-cycle (production, use-phase, end-of-life-phase). Standardized procedure, e.g. according to ISO 14040, ISO 14044.

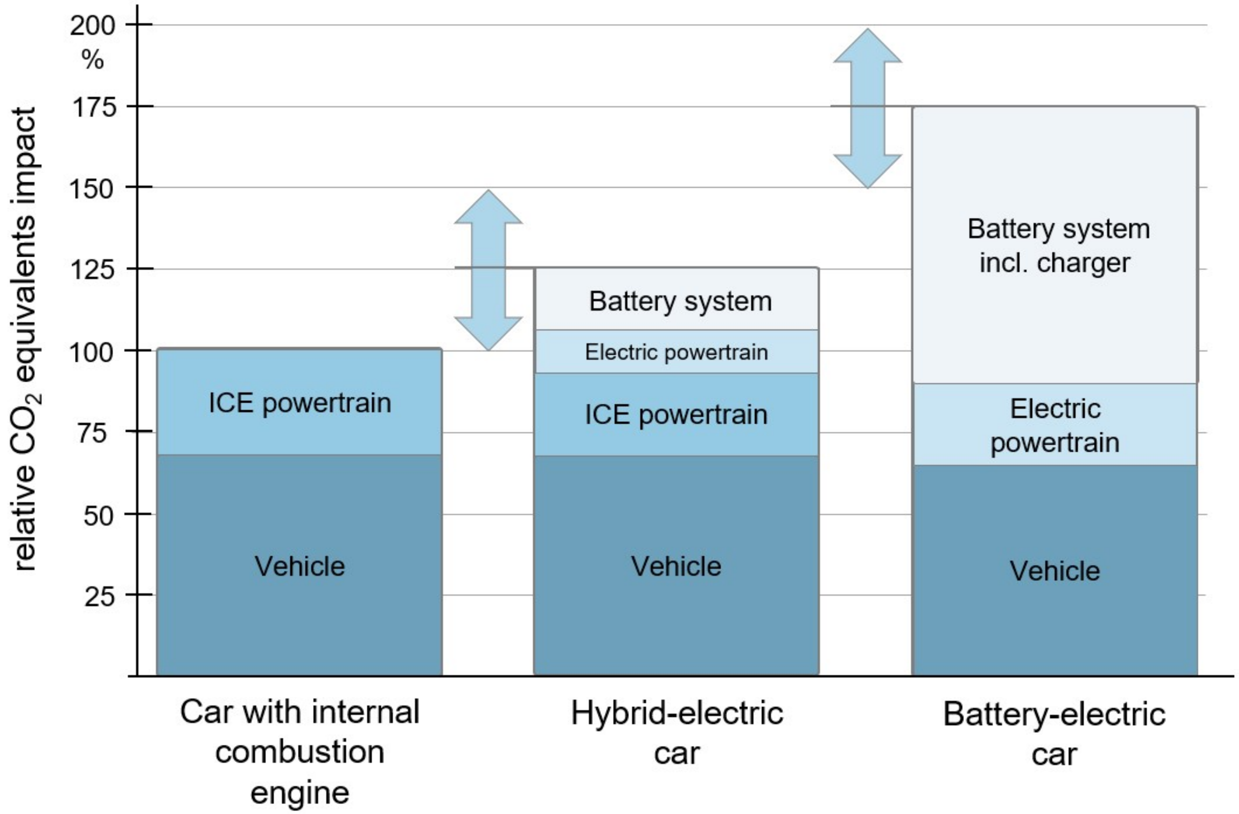


Life-cycle assessment – a tool for objective technology evaluation



Life-Cycle - related consideration of technologies

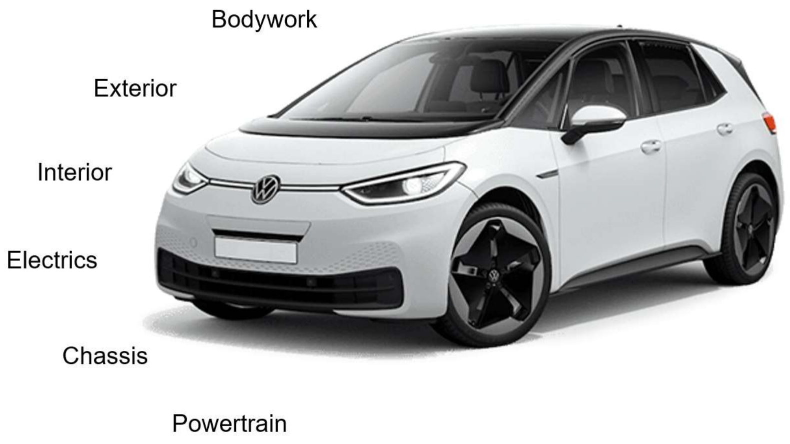
CO_2 - impact of vehicle production in comparison

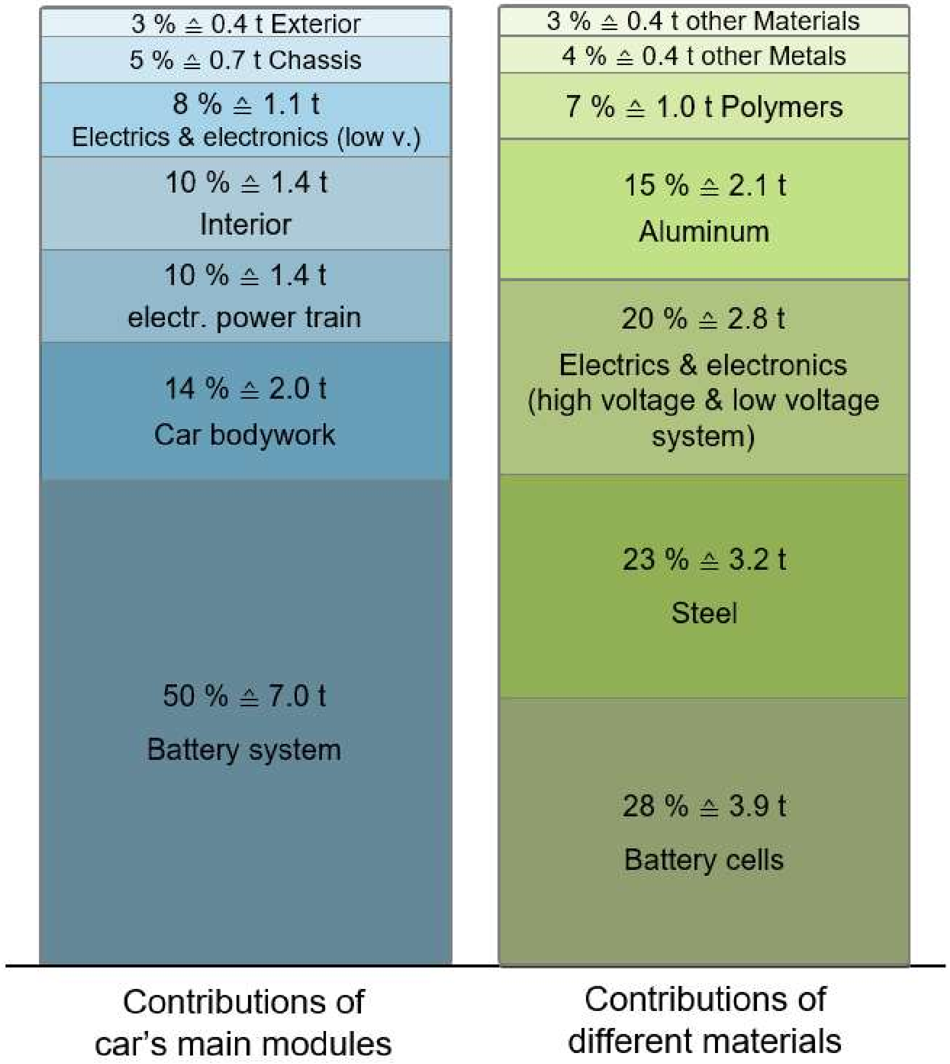


Battery-electric car production

Carbon footprint and relevant materials

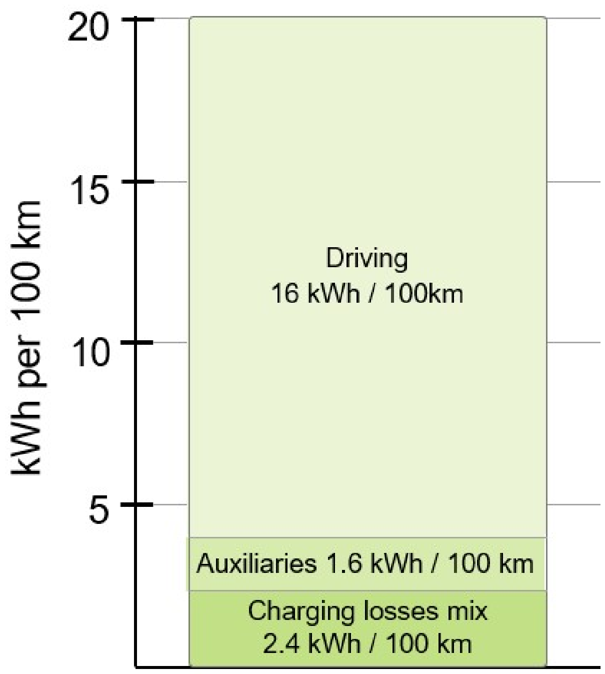
Exemplary compact car





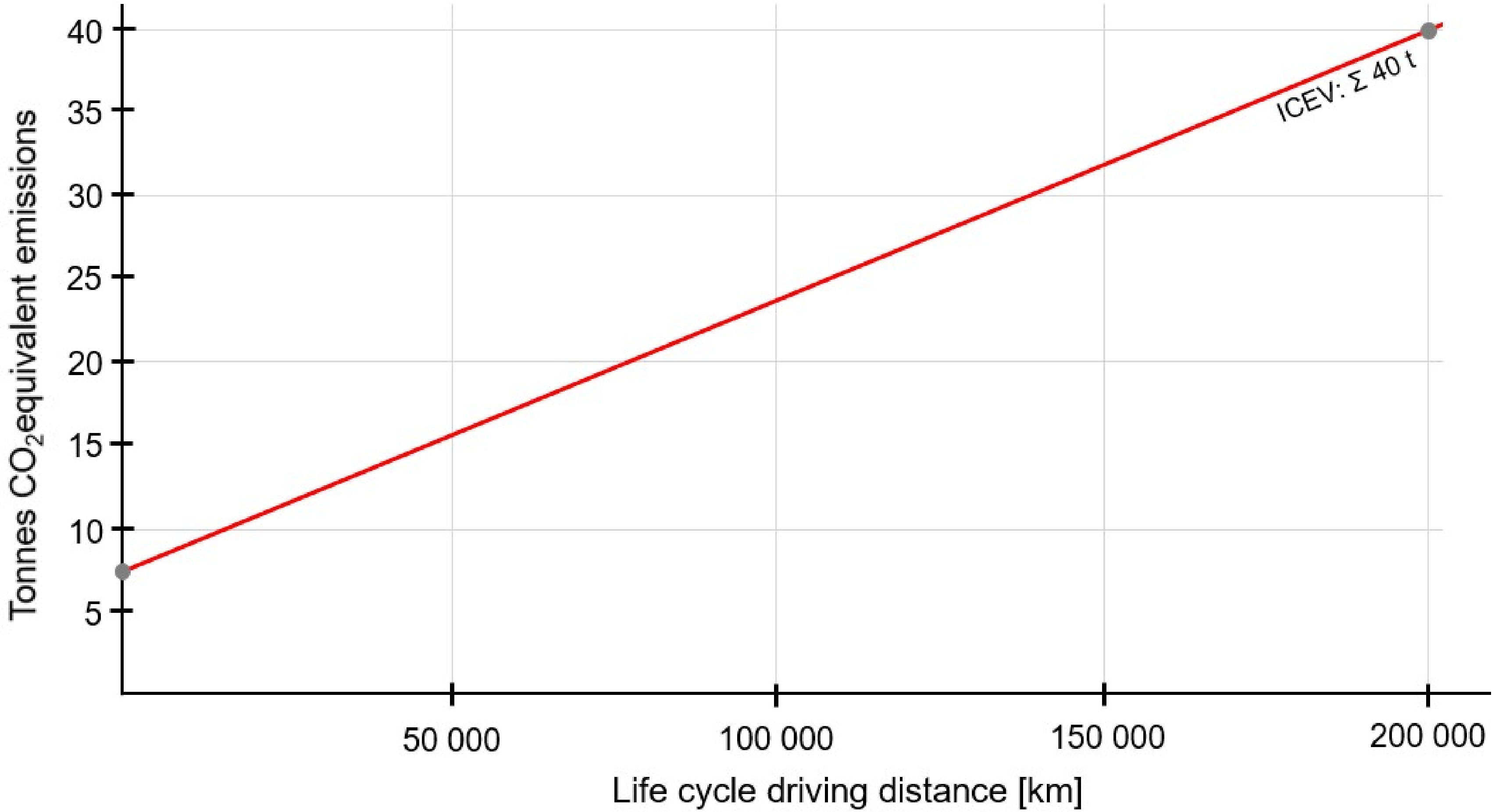
Battery-electric car usage

Energy consumption of the exemplary compact car



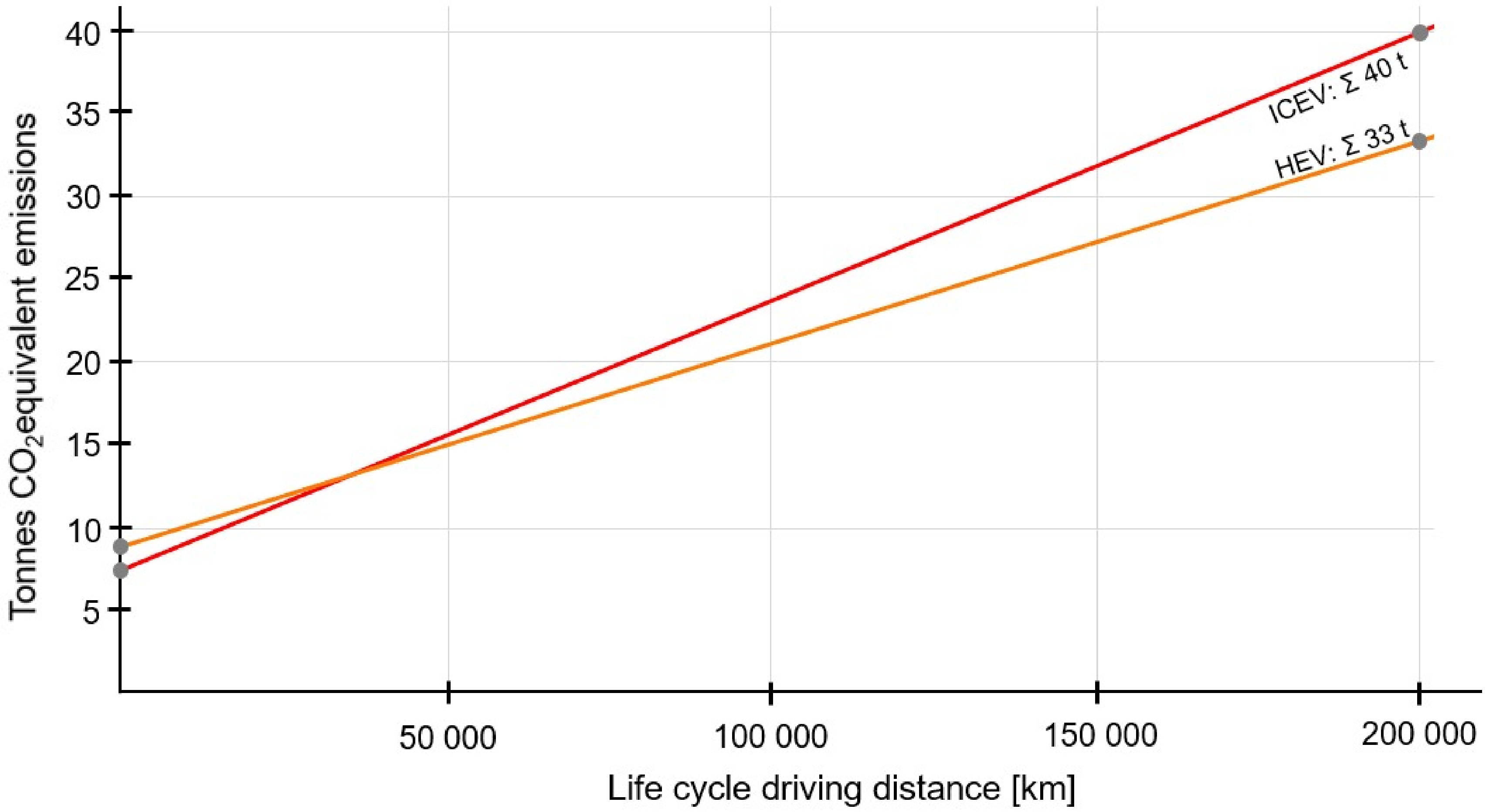
Total life cycle carbon footprint in comparison

Compact cars with different propulsion technologies

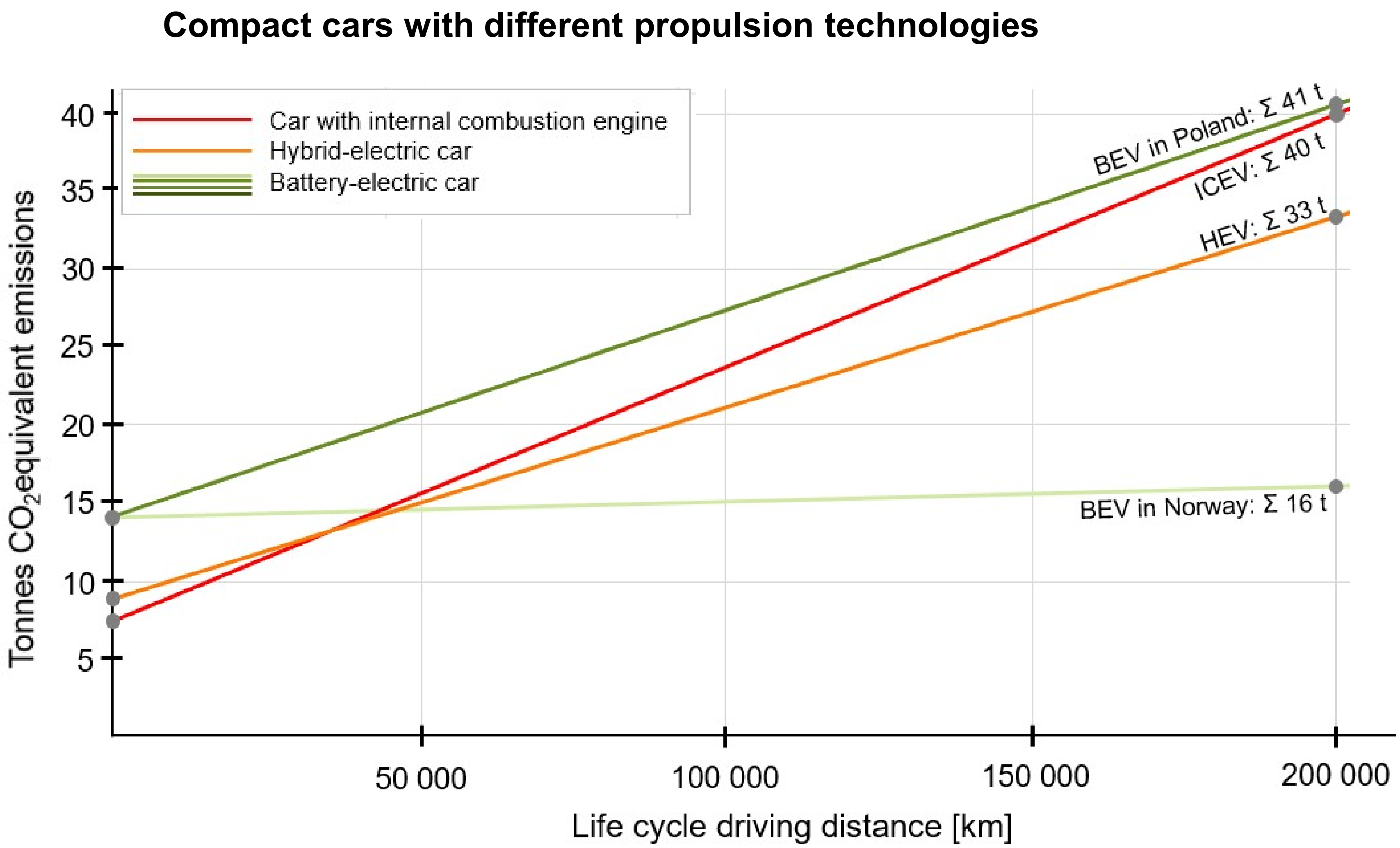


Total life cycle carbon footprint in comparison

Compact cars with different propulsion technologies

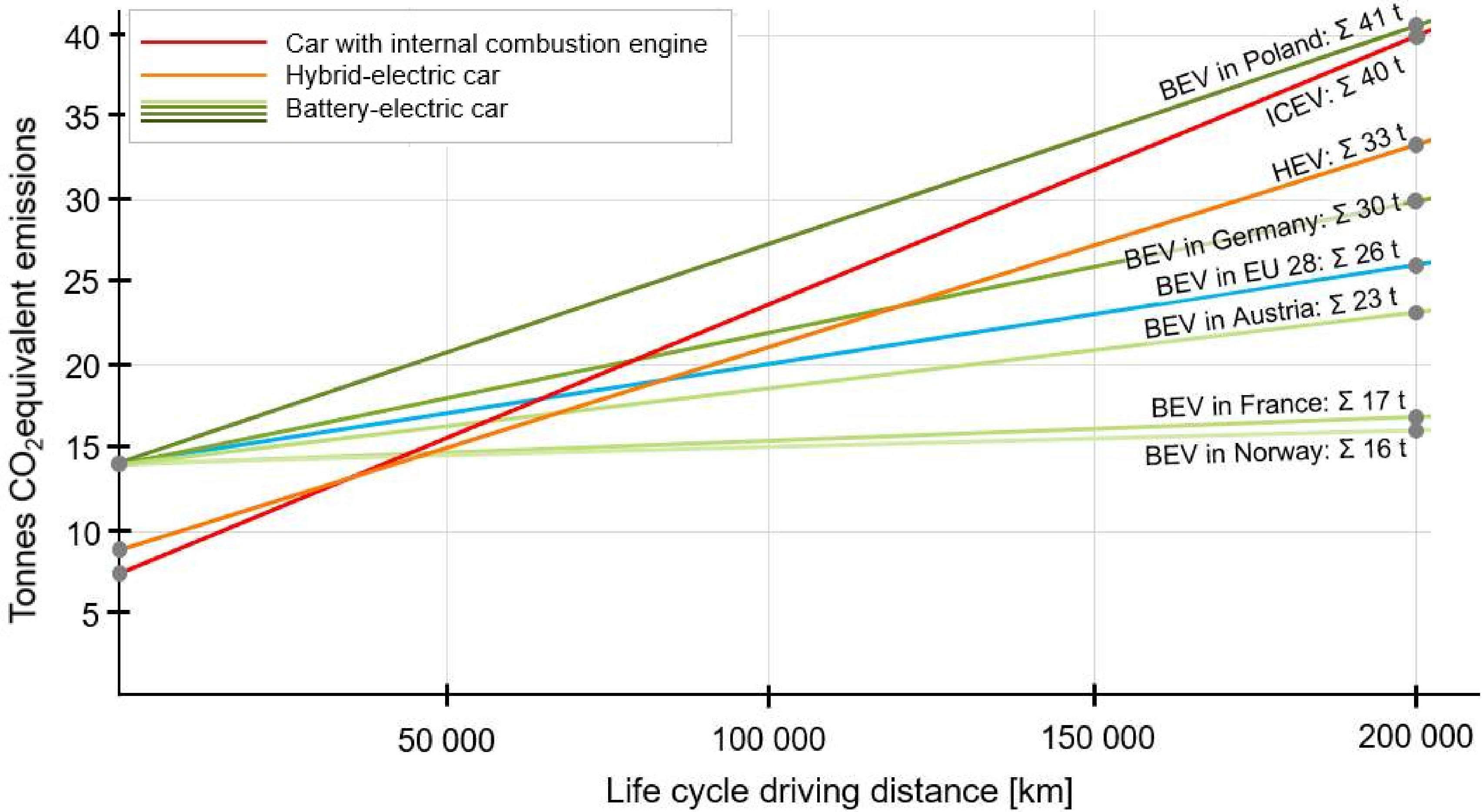


Total life cycle carbon footprint in comparison

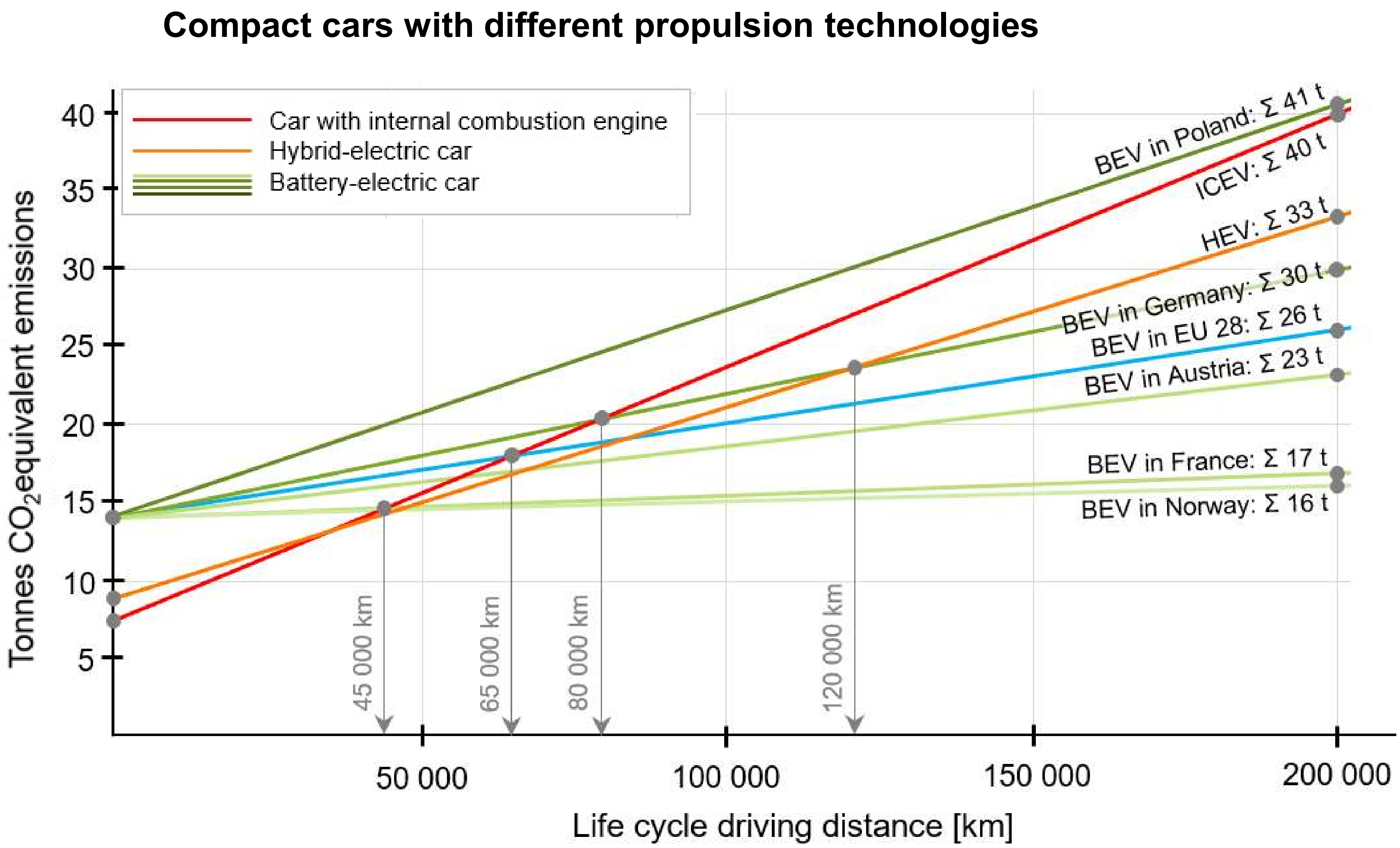


Total life cycle carbon footprint in comparison

Compact cars with different propulsion technologies



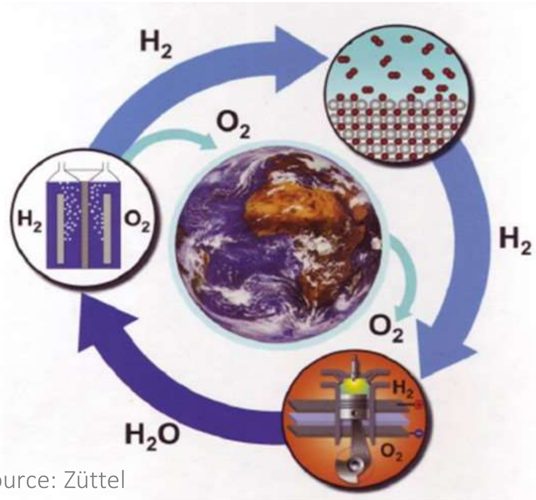
Total life cycle carbon footprint in comparison



Alternative fuels: a possible solution?

Hydrogen: Fuel for a closed energy circle

Electric Energy



Source: Züttel

Electric / mechanical output

ships, (airplanes) … research

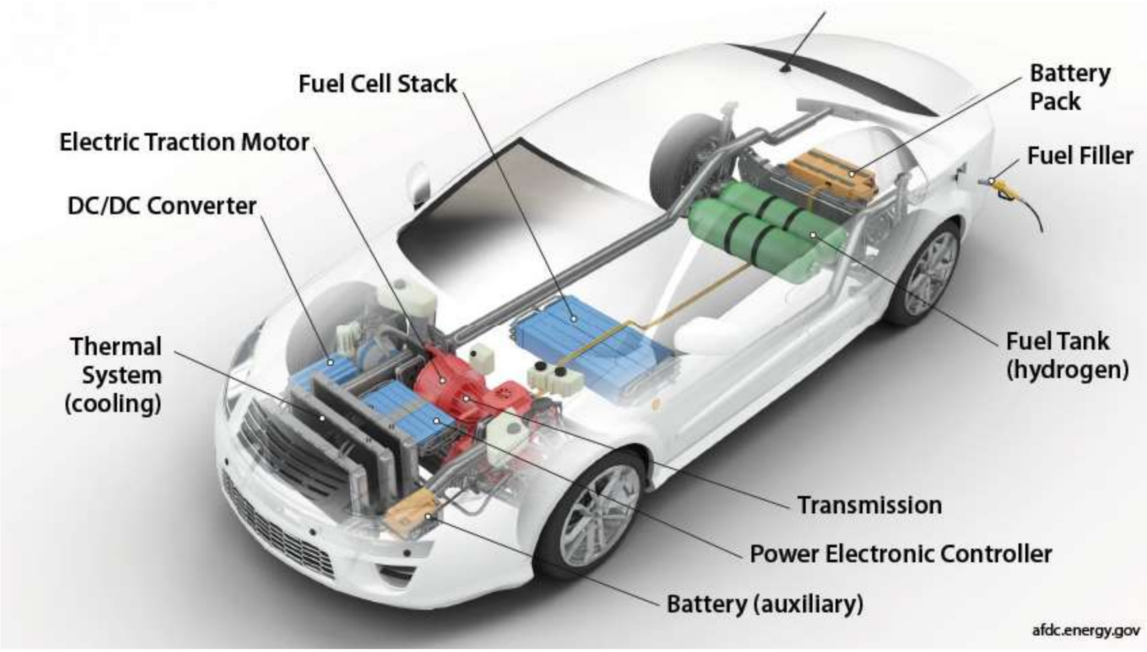
Sources: ABB, NASA

in use today: commercial vehicles, trains, (cars)

Source: Hyundai

Source: Toyota

Fuel-cell vehicles



Hydrogen is seen as the fuel for future mobility. Advantage is the potential for CO_2 emission free operation.

Fuel cell systems provide good efficiency behavior in comparison with internal combustion engines.

Main challenges for a broad application of hydrogen as fuel are hydrogen generation and storage.

Some numbers:

- Hydrogen fuel consumption of a typical personal car: 0.7 – 1.6 kg/100km
- Energy content of hydrogen:120 MJ/kg = 33,3 kWh/kg
- Hydrogen costs: 6 – 10 € per kg
- CO_2 footprint of hydrogen production from natural gas: 8.5 – 11 kg CO_2 per kg H_2
- CO_2 footprint of hydrogen production from wind / solar energy: potentially near zero.

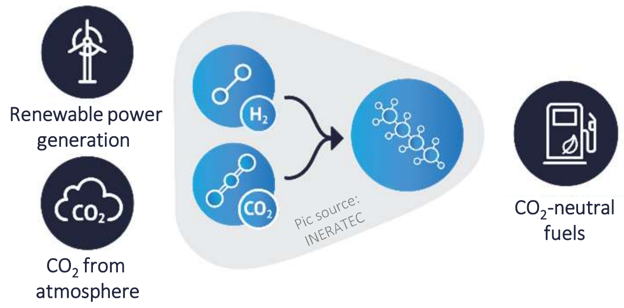
Alternative fuels

State-of-the-art:

- GTL – gas to liquid: made of natural gas (methane, CH_4)
- CTL – coal to liquid: made of coal (historical)
- BTL – biomass to liquid: made of different bio-sources

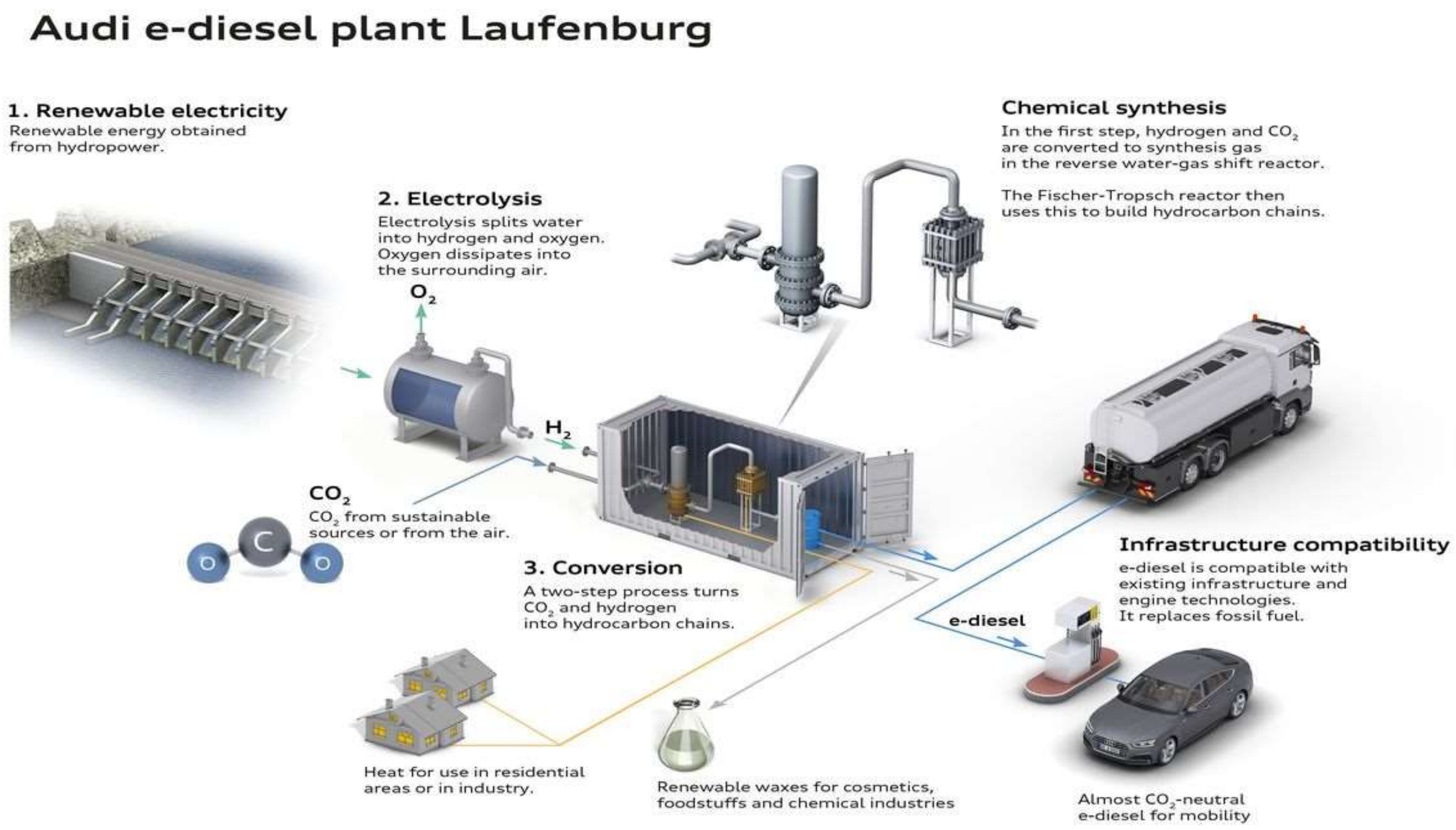
In development with future potentials:

- PTL – power to liquid: fuel (hydrocarbons) made of H_2, CO_2 & CO by electrolytic conversion of water (production of H_2) and synthesis of CO_2 & CO.
  - + result is synthetic fuel that can have similar characteristics as gasoline or diesel.
  - + use of existing tank systems and infrastructure possible
  - + different application possible, e.g. cars, trucks, ships, airplanes, construction machines
  - + electric energy is needed (a lot); use of green electric energy results in sustainable fuel
  - + => CO2 reduction out of the atmosphere … theoretically CO2 neutral fuel possible.
  - \- Worse production efficiency, high electric energy consumption
  - \- market-relevant volumes after 2030 expected (@ Shell)



Alternative fuels

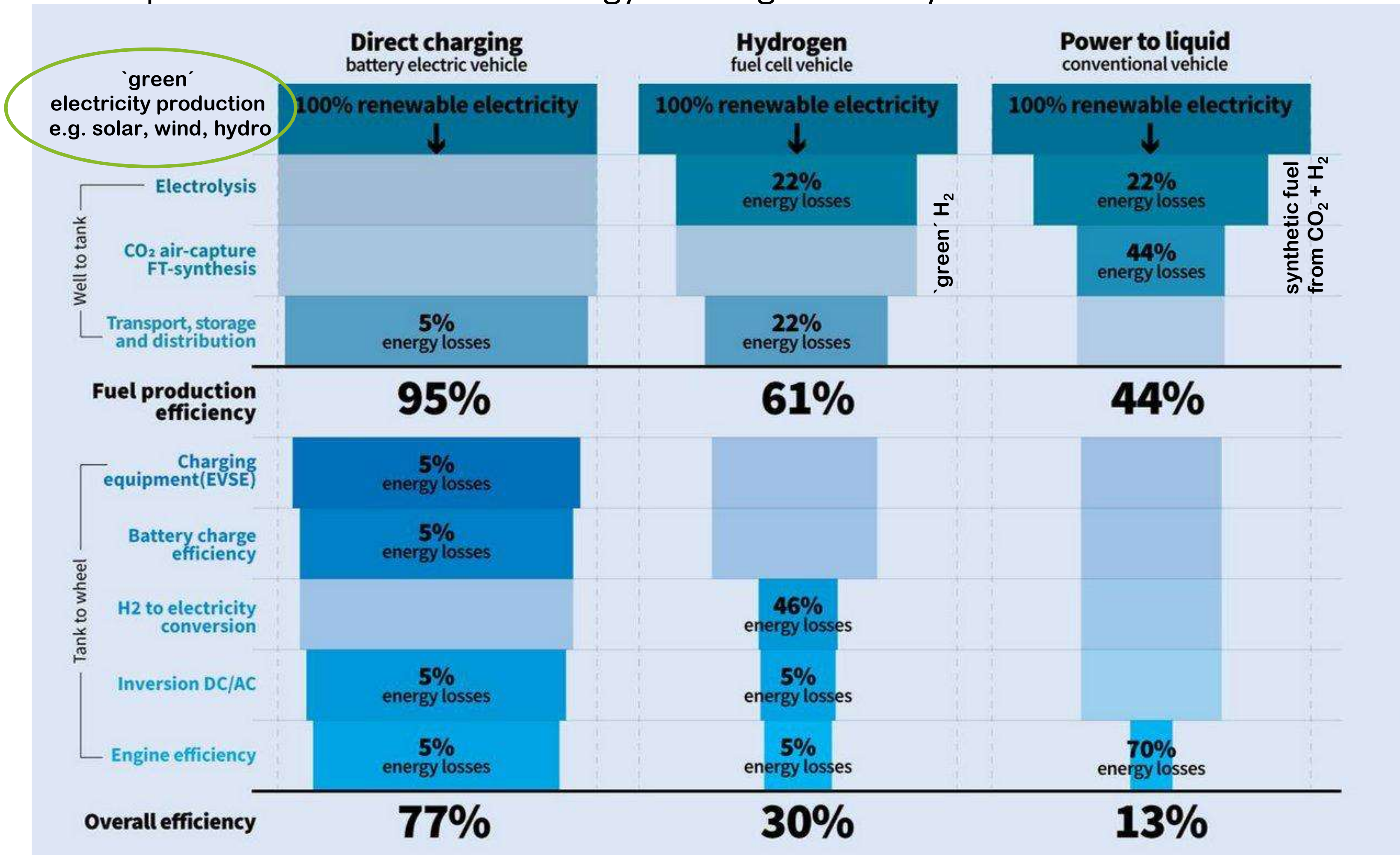
Exemplary study:



Source: Audi

Under “Green Deal” aspects: WTW-efficiency of different propulsion technologies

Assumption: renewable initial energy – the “green” way



Source: Transportation & Environment

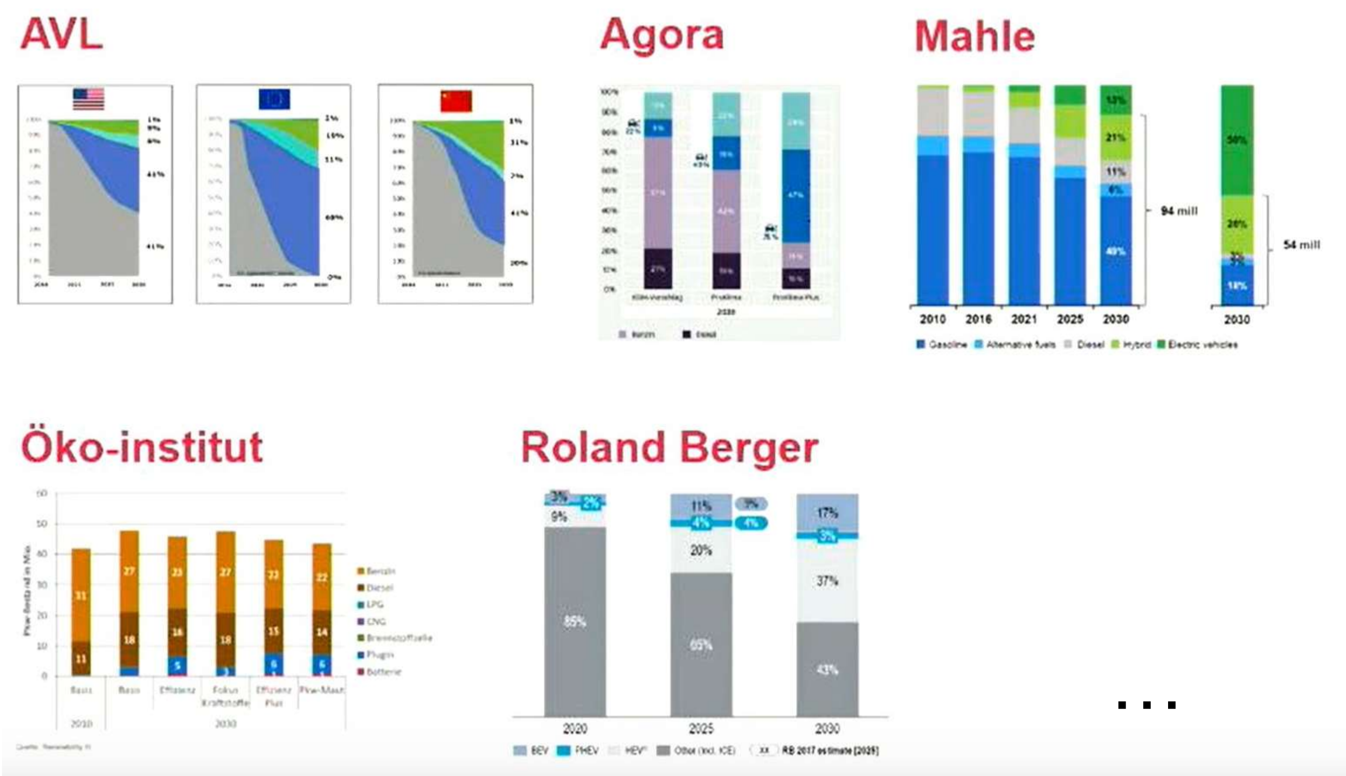
FTG

Outlook

Prognosis of propulsion technologies

Market expectations of powertrain technologies

- ➔ Most stakeholder expect that ICE-based power trains remain the major automotive propulsion system within the next about 5 - 6 years, in combination with electric drives in hybrid cars.
- ➔ The marked shares of electric cars will increase steadily, and very strong from 2028/2030 on.



Source: Eichlseder

Car manufacturers changed their power train development strategies

2015 - 2018: Efficiency improvement of ICE, reduction of exhaust emissions

- Direct fuel injection systems
- Downsizing, turbo-charging
- Reduction of engine friction
- Efficient combustion processes
- Multi-point ignition
- New combustion processes, e.g. HCCI
- Alternative fuels for clean efficient combustion
- Multi-stage catalytic converters for exhaust gas after treatment
- Particulate filter for gasoline direct injection
- Hybrid power train systems

2022: Electrification

- ~~Direct fuel injection systems~~
- ~~Downsizing, turbo-charging~~
- ~~Reduction of engine friction~~
- ~~Efficient combustion processes~~
- ~~Multi-point ignition~~
- ~~New combustion processes, e.g. HCCI~~
- ~~Alternative fuels for clean efficient combustion~~
- ~~Multi-stage catalytic converters for exhaust gas after treatment~~
- ~~Particulate filter for gasoline direct injection~~
- Hybrid power train systems
- Electric cars

Prognosis of propulsion technologies

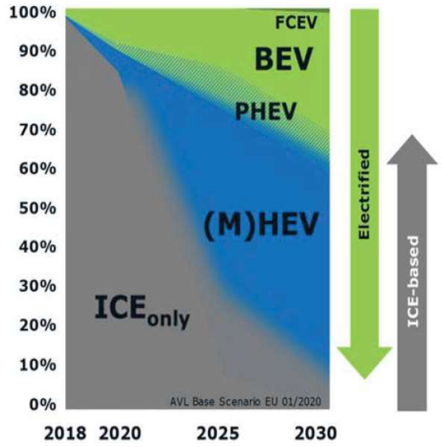
… taking a look into the crystal ball (1/2) …

BEV:

Rising market shares for sure, depending on legislative boundary conditions, incentives for customer and restrictions of ICEV.

Status 2022: Largest growth is expected in Europe (especially in countries with strong incentives, e.g. Germany). China has strong pushes in local cities / regions. In USA, California has the highest rates of growth, with some other states following.

It is expected, that in Europe and China, BEV will have about 50 % sales share in 2030. In USA, this number might be lower with about 30 %.



PHEV:

PHEV have been a promising technology for car manufacturers in Europe and China, but the sales numbers stagnate this time. In EU and China, specific legislative boundary conditions (e.g. combined test cycles for CO_2 emissions) supported PHEV significantly. But it seems that customers do not make use of the possibility to charge the car at the grid. In this way, the real-life benefits of this technology are limited. There is a trend to larger battery capacity – and consequently larger electric driving range on PHEV, but due to the cost factor, this is applied just in some premium cars.

It is expected, that PHEV sales will not increase in a relevant way in the next years, because the (former) driving range limitation of BEV becomes more and more obsolete.

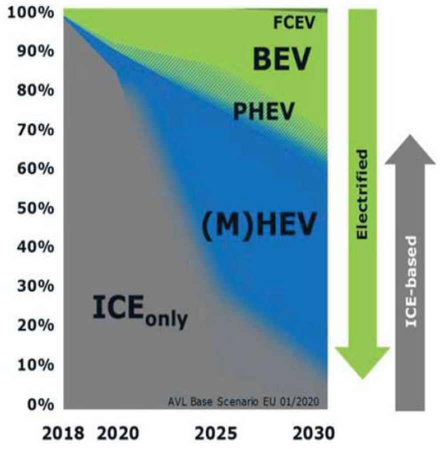
Prognosis of propulsion technologies

… taking a look into the crystal ball (2/2) …

HEV:

HEV sales significantly increase this time in all markets, because OEM make use of the relatively simple possibility to modify existing ICE-based powertrains. In addition, the realization of different technological approaches enables a large variation of HEV according to the actual vehicle requirements – from mild hybrids (MHEV) to full hybrids (HEV) with the opportunity to drive a certain distance purely electric.

HEV market share will further grow in Europe, China and USA. It is expected that Gasoline-HEV will replace Diesel engine driven cars in most segments because of economic reasons and better customer acceptance.



ICEV:

The sales of cars driven by ICE only will reduce in the same way as the market shares of BEV and HEV will increase. The relatively simple and economically reasonable opportunity to electrify ICE powertrains, resulting in hybrids, leads to the fact, that highly sophisticated (and expensive) ICE technology will less be applied – with the exception of some super sport cars. For OEM, it is easier and cheaper to combine standard Gasoline engines with electric drive units to fulfill the legislative targets.

In this way, new technologies and breakthroughs are not expected for ICE. Open question this time is the use of carbon-neutral fuel. If supported by governments, this could push ICE technology for longer-lasting applications, but it is likely that also in this way, hybrid technologies will convince.

Thx for your attention!

Contact:

Associate Prof. Dr. DI. Mario Hirz

Institute of Automotive Engineering
Graz University of Technology

Inffeldgasse 11/2, 8010 Graz

E-Mail: mario.hirz@tugraz.at
Web: http://www.ftg.tugraz.at