University of Stuttgart
Institute of Automotive Engineering

FKFS
RESEARCH IN MOTION.

Source: Dr. Ing h.c. F. Porsche AG

Sustainable Energy & Powertrain Solutions: from Electrification to Hydrogen and E-Fuels

Prof. Dr.-Ing. André Casal Kulzer
Director, Automotive Powertrain Systems, IFS Univ. Stuttgart
Board of Management, FKFS Stuttgart

19.06.2025, Milano
Sustainable fuels (bio-fuels & e-fuels) for CO_2 neutral internal combustion engines

Powertrain means the total combination in a vehicle, of **propulsion energy storage system(s), propulsion energy converter(s)** and the **drivetrain(s)** providing the mechanical energy at the wheels for the purpose of vehicle propulsion, plus **peripheral devices**. Source: Reg. (EU) 2017/1151

„It is **not the strongest**
of the species that **survives,**
nor the most intelligent
that survives.
It is the one that is
most adaptable to change.

Charles Darwin

Sustainable Energy & Powertrain Solutions

Sustainable Energy & Life Cycle Analysis

Sustainable Powertrain Solutions

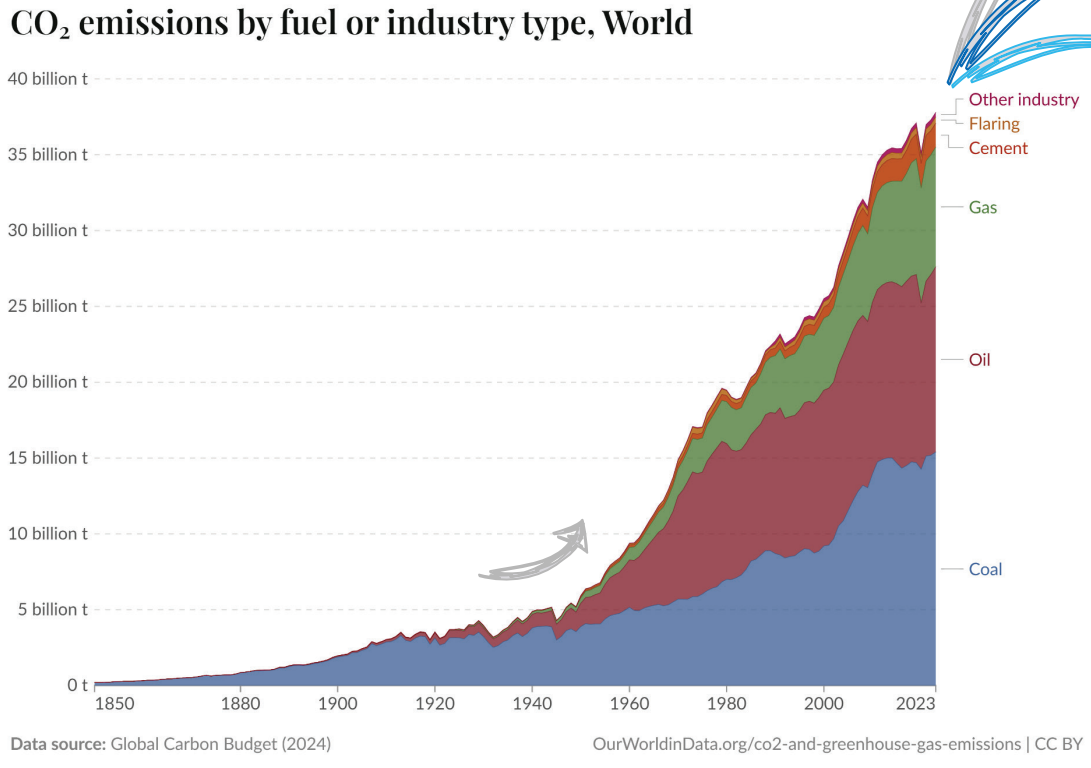
Main Take-Aways

Sources: United Nations; Dr. Ing h.c. F. Porsche AG

Prof. Dr.-Ing. André Casal Kulzer, Institute for Automotive Engineering, University of Stuttgart

Worldwide CO_2 Emission

Defossilization, i.e. Carbon-Neutral Energy is Priority!



Business as usual
linear energy consumption growth

Exchange by New Technology
slow exchange rate = slow impact

Circular Economy Strategy
additional impact on existing fleet
= fast response

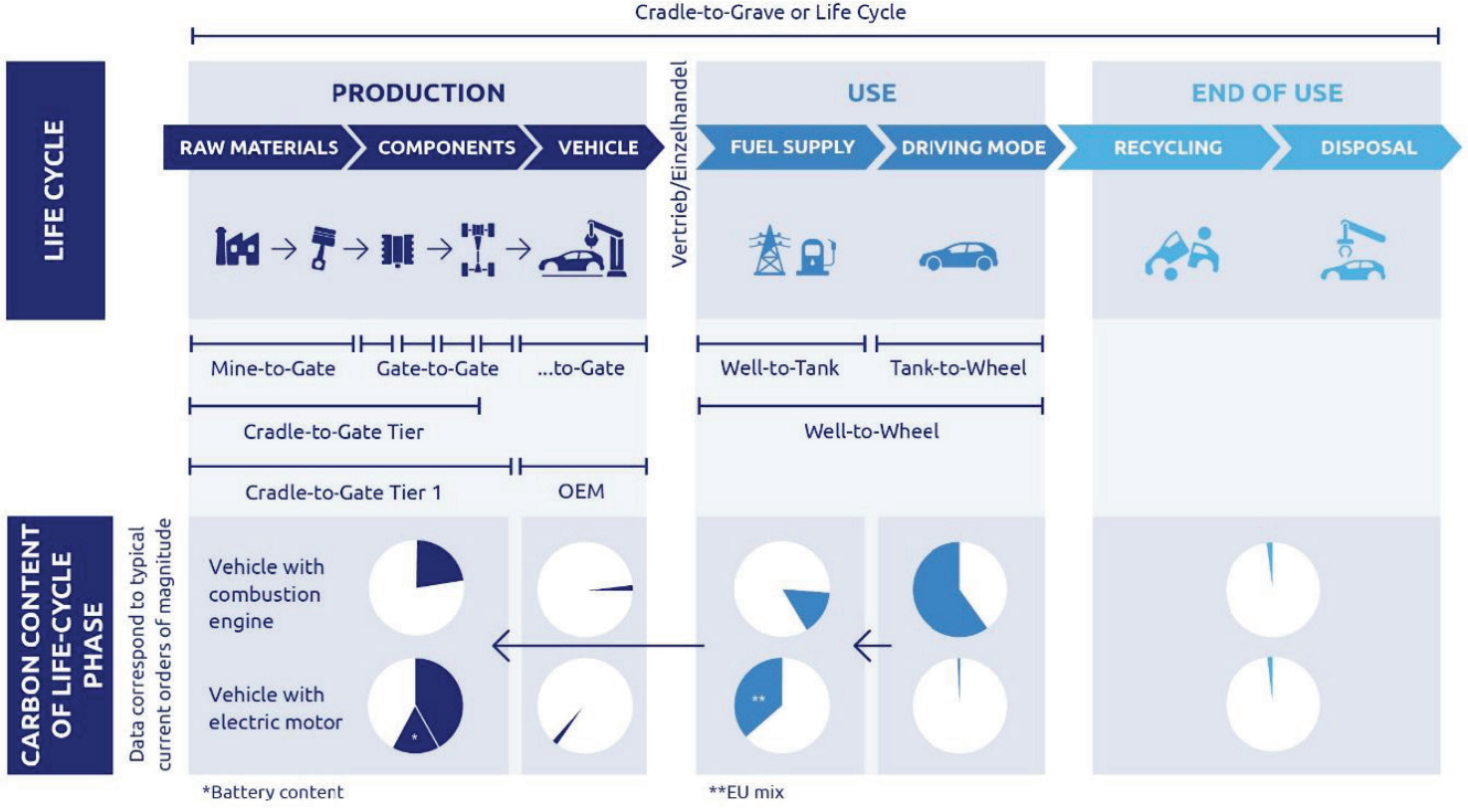
Effective measures to reduce climate impact:

- focus on **circular economy** regarding **energy, CO_2 and material resources**
- make **renewable energy** impact **existing & new applications** (electric and molecular energy)
- new **efficient technologies** considering **circular economy** and **life-cycle-analysis**, considering **high recycling rates**

Source: https://ourworldindata.org

Life Cycle Assessment – German Government Expert Group (2024)

Diverse CO_2-hotspots along vehicle life cycle (combustion engine vs. electric motor)

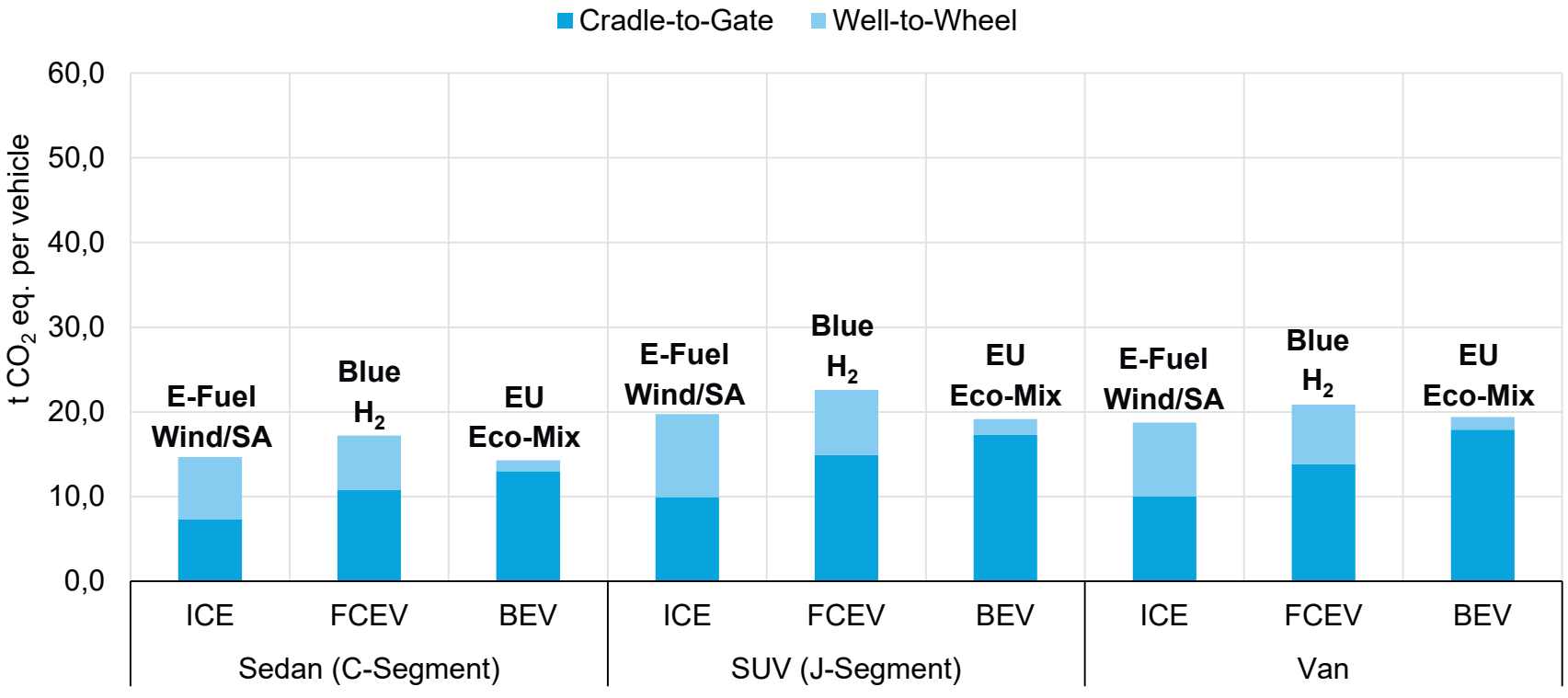


AS A RESULT OF ELECTRIFICATION, THE FOCUS IS SHIFTED TO THE "CRADLE-TO-GATE TIER 1" PHASE

Source: Expert Group Transformation of the Automotive Industry (ETA), https://expertenkreis-automobilwirtschaft.de , "A CURRENCY FOR CLIMATE ACTION: AN APPEAL FOR A GLOBALLY HARMONISED CARBON ACCOUNTING METHODOLOGY IN THE SUPPLY CHAINS OF THE AUTOMOTIVE INDUSTRY", 17.04.2024, Federal Ministry of Economic Affairs and Climate Action (BMWK)

Life Cycle Assessment – CO_2 of Current Powertrain Technologies

Classification – **Ecological Best Case Scenario** – Today – 200.000 km

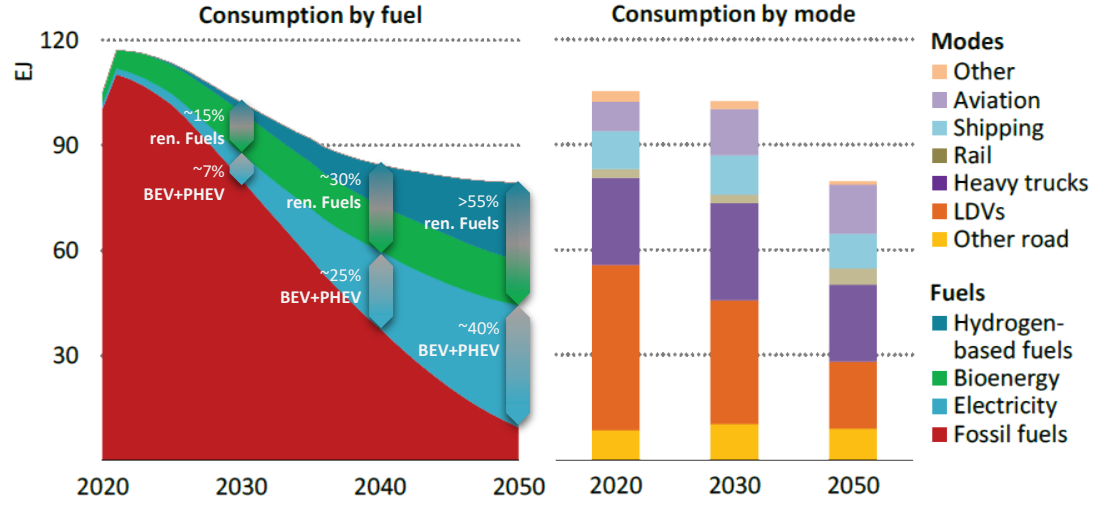


Source: T. Stoll, H.J. Berner, A. Kulzer: "An Analysis of the Greenhouse Gas Potential of Current Powertrain Technologies", 45th International Vienna Motor Symposium, 2024

IEA 2021 Report: Worldwide Global Pathway to Net Zero CO_2 by 2050

Sustainable mobility will be possible by electrification + renewable fuels$_{CO2\text{-neutral}}$

Figure 3.22 ▷ Global transport final consumption by fuel type and mode in the NZE global pathway to net-zero CO_2 emissions in 2050



Electricity and Hydrogen-based Fuels account for more than 70% of Transport Energy Demand by 2050

Note: LDVs = Light-duty vehicles; Other road = two/three wheelers and buses.

Source: International Energy Agency, 2021 Report *renewable Fuels: CO_2-neutral bioFuels and eFuels

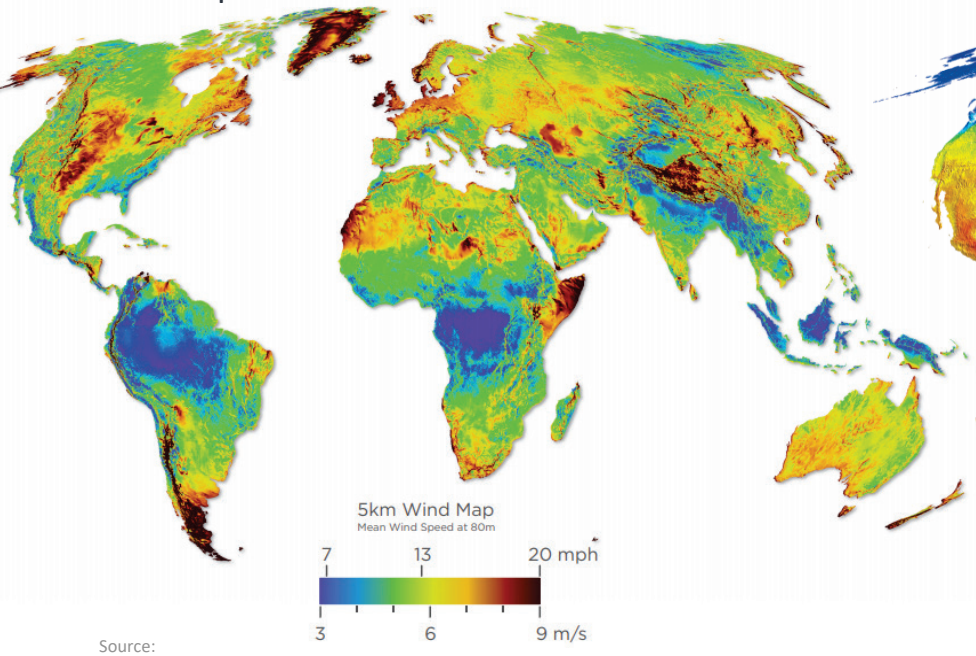
Surplus of Renewable Energy

Challenge: Harvesting, Transport and Storage of Wind and Solar Energy

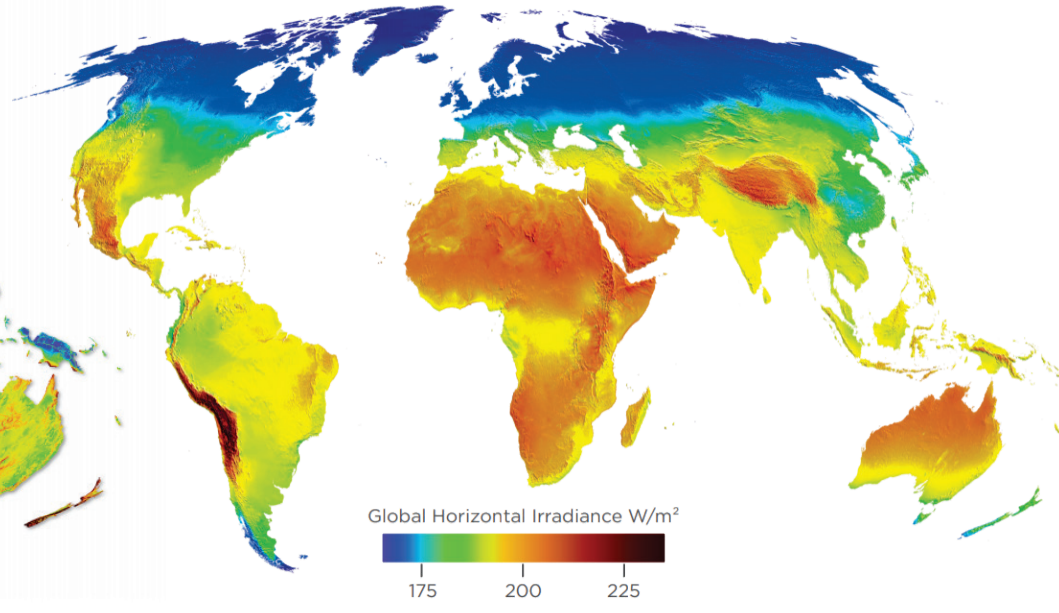
Production potential is huge!
900x HEC/a

… but **located** far away from demand centers and **intermittent** – **storage** needed!

Wind Speed



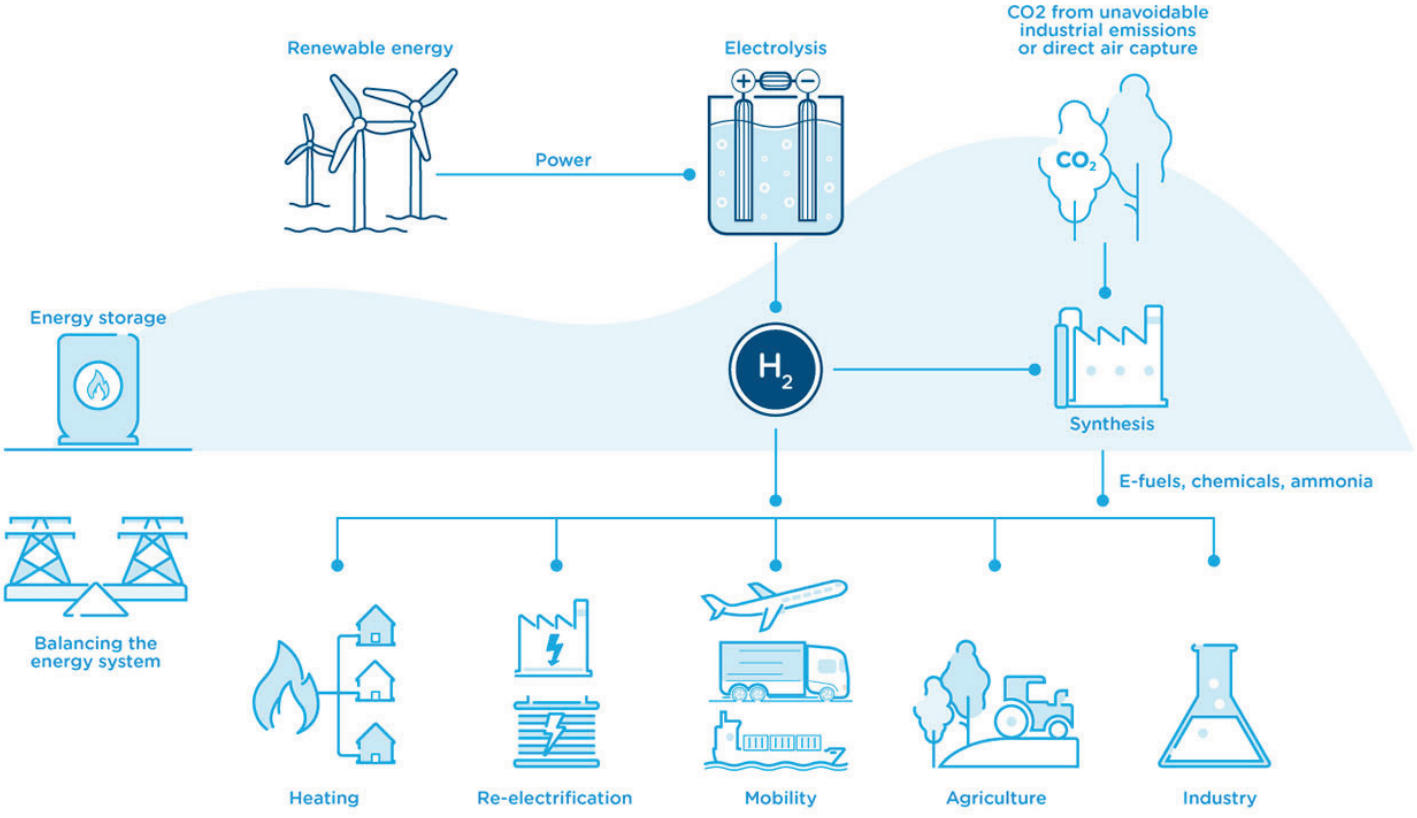
Solar Irradiation



Source:
https://www.vaisala.com/sites/default/files/documents/Vaisala_global_wind_map.pdf?utm_content=Wind-Map
https://www.vaisala.com/sites/default/files/documents/Vaisala_global_solar_map.pdf?utm_content=Solar-Map

Renewable Energy, Storage and Transportation

Solution for intermittency & import of renewable energy: storage, e.g. Power-to-Molecules (PtX)



Source: https://ramboll.com/net-zero-explorers/explainers/power-to-x-explained w/ additional inputs

Sustainable Development demands for Diversity

Diversity in energy, technology & infrastructure are just as important as biodiversity in the ecosystem

Sustainable Energy & Powertrain Solutions

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Main Take-Aways

Sources: United Nations; Dr. Ing h.c. F. Porsche AG

Prof. Dr.-Ing. André Casal Kulzer, Institute for Automotive Engineering, University of Stuttgart

Sustainable Powertrain Solutions

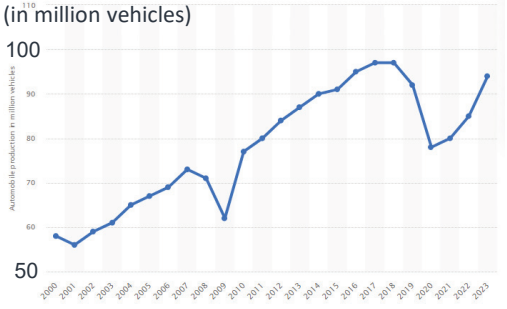
Powertrains in the World

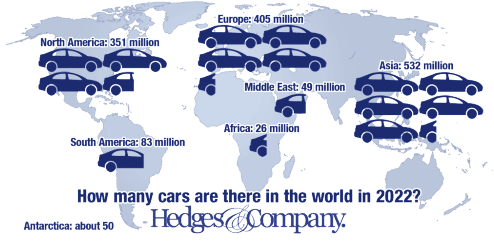
Worldwide Mobility Demand will Continue to be Significant

~1.5 billion existing vehicles on Earth in 2024 vs. **~90 million** new vehicles per year

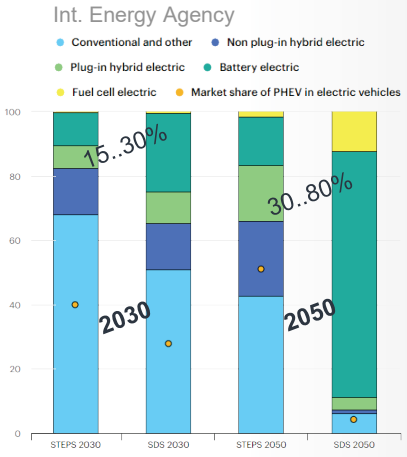
Estimated worldwide motor total vehicle production from 2000 to 2023

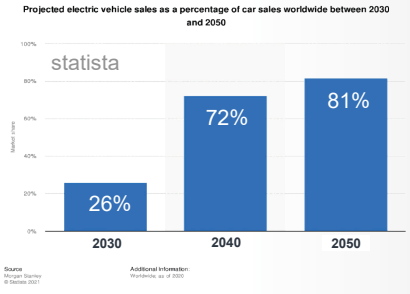
(in million vehicles)



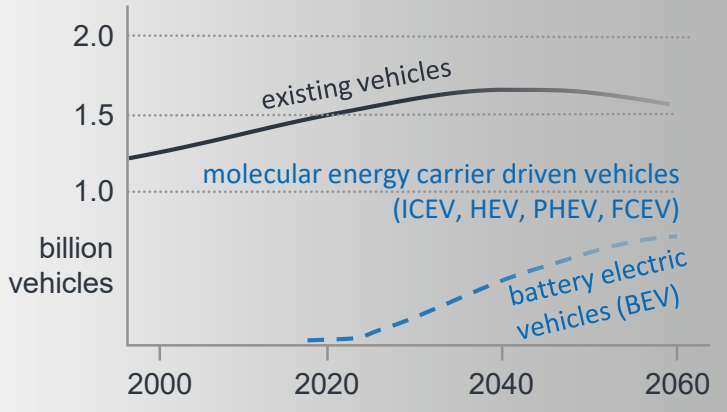


Future electric vehicle registrations share





~ 1.5 billion vehicles on the road today and in the future



All old / new vehicles and its electric charge / fuel will have to contribute for transport defossilization towards CO_2-neutral energy / electrons / molecules

Sources: IEA, Statista, schematic draft

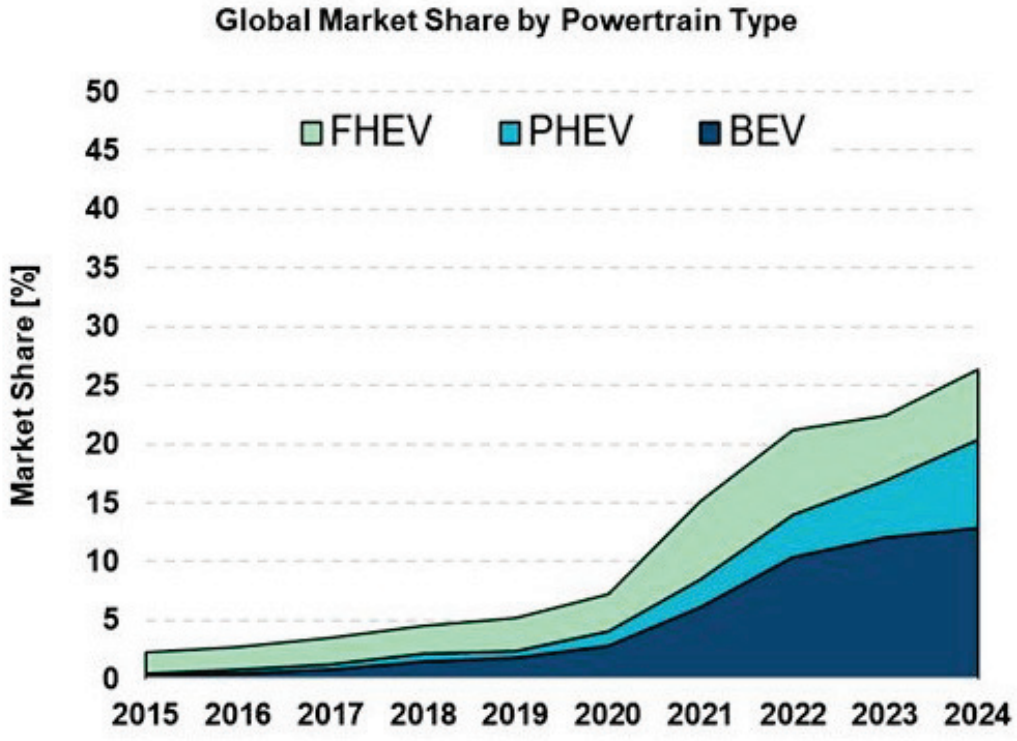
https://hedgescompany.com/blog/2021/06/how-many-cars-are-there-in-the-world/

https://www.statista.com/statistics/262747/worldwide-automobile-production-since-2000/ , https://www.statista.com/statistics/1202364/ev-global-market-share/

https://www.iea.org/data-and-statistics/charts/car-market-share-by-powertrain-in-selected-countries-and-globally-in-the-stated-policies-scenario-and-the-sustainable-development-scenario-2019-2030-and-2050

Electrification Trend Expansion in Global Market Share by Powertrain Type

2024 new pass car registrations: ~ 13% BEV; ~ 13% hybridization → ~ 87% with xICE

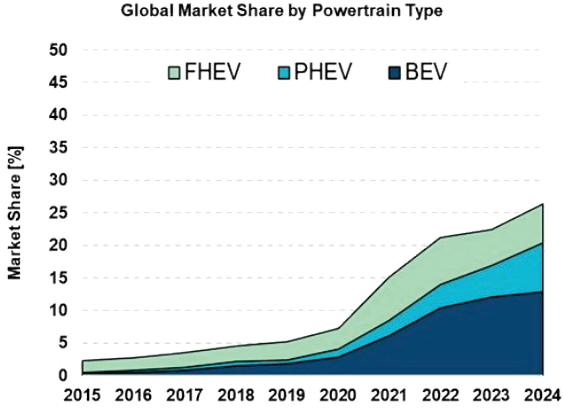


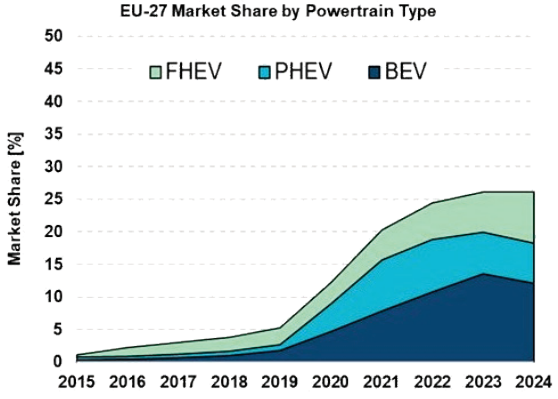
BEV = Battery electric vehicle; **PHEV** = Plug-in Hybrid Electric Vehicle; **FHEV** = Full Hybrid Electric Vehicle, which has some EV driving capability; **MHEV** = Mild Hybrid Electric Vehicles, 48V (not included in the graphs)

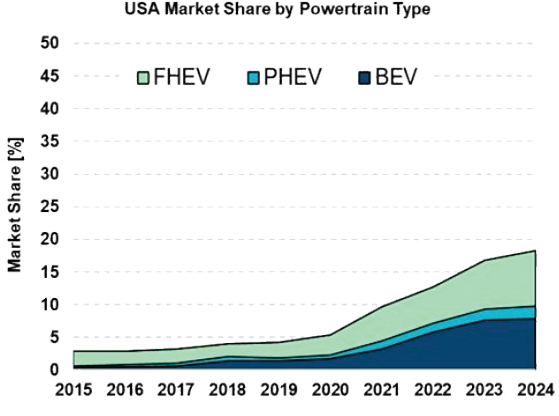
Source: https://www.linkedin.com/posts/graham-conway_2024-LD-Sales-Volumes-activity-7298413522651095040-7Npo/?utm_source=share&utm_medium=member_android&rcm=ACoAAABYPYEBcGSG6AWaaShG4pW8Od4d3k8-WQk ,
https://www.linkedin.com/company/marklines-automotive-information-platform-/?lipi=urn%3Ali%3Apage%3Ad_flagship3_detail_base%3BuVNt3RyfTPKP02mXhDpn3Q%3D%3D

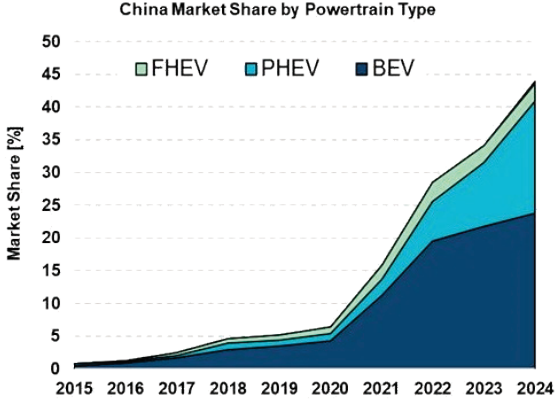
Electrification Trend Expansion in Global Market Share by Powertrain Type

2024 new PC registrations: ~ 13% BEV, ~ 13% hybridization (~ 87% with xICE)









Market

- shows diverse trends!
- Hybrids increasing fast

Hybridization

best of both worlds
for the customer?

- lower cost
- no need for charging infrastructure
- no range anxiety

ICE Demand

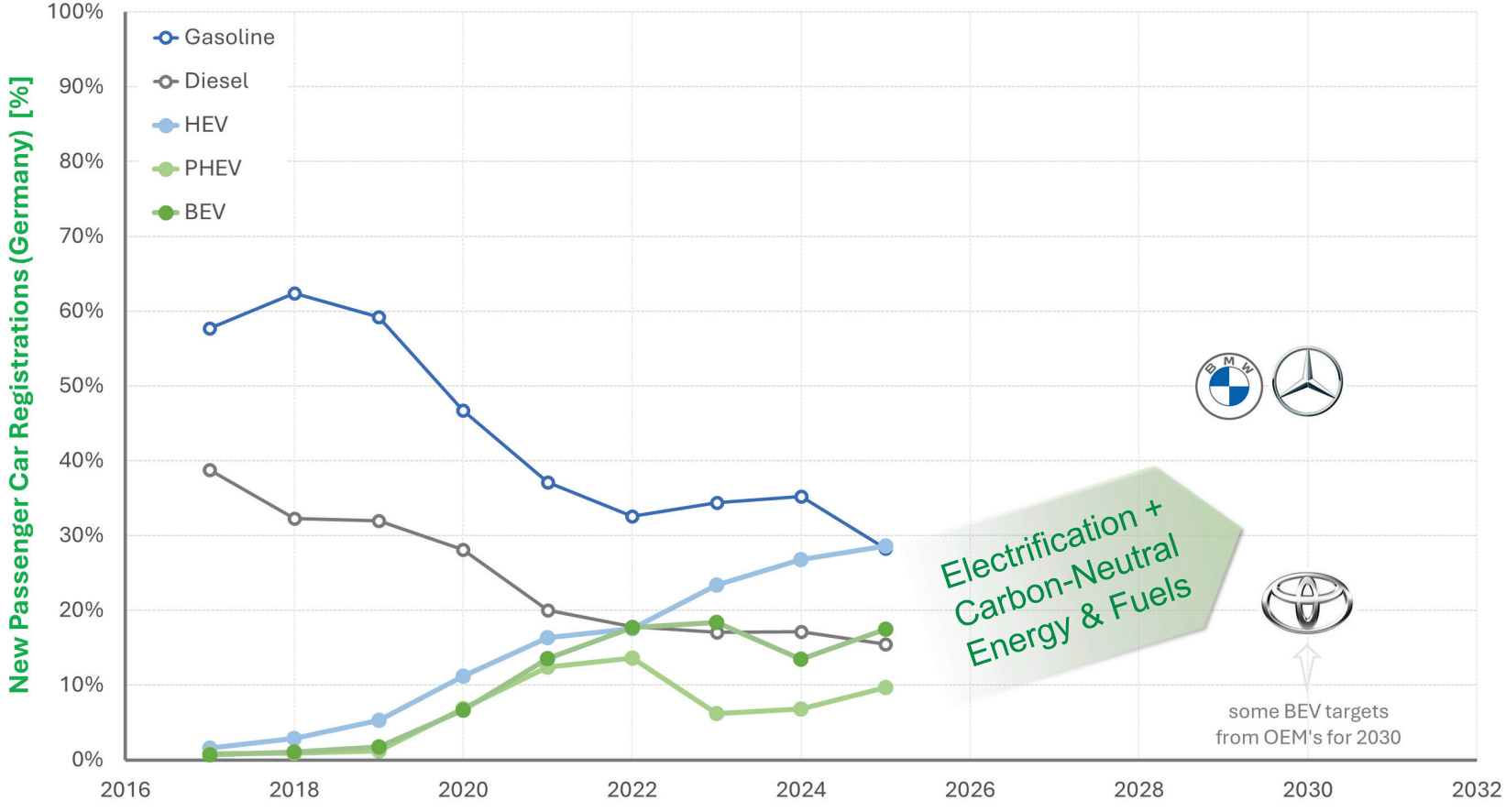
- ICE efficiency and technology development are relevant for a Carbon-Neutral future!

BEV = Battery electric vehicle; **PHEV** = Plug-in Hybrid Electric Vehicle; **FHEV** = Full Hybrid Electric Vehicle, which has some EV driving capability; **MHEV** = Mild Hybrid Electric Vehicles, 48V (not included in the graphs)

Source: https://www.linkedin.com/posts/graham-conway_2024-LD-Sales-Volumes-activity-7298413522651095040-7Npo/?utm_source=share&utm_medium=member_android&rcm=ACoAAABYPYEBcGSG6AWaaShG4pW8Od4d3k8-WQk ,
https://www.linkedin.com/company/marklines-automotive-information-platform-/?lipi=urn%3Ali%3Apage%3Ad_flagship3_detail_base%3BuVNt3RyfTPKP02mXhDpn3Q%3D%3D

Germany's New Passenger Car Registrations Status and OEM's Trends

New pass car registrations in 2030 – around ~ 30% BEV + ~ 50% (P)HEV



Source: https://www.kba.de/

Sustainable Powertrain Solutions

Electrification
- Potential in Development

Facts on Specific Energy vs Power & Efficiency vs Cost

BEV best efficiency & eFuels+ICEV overall cost competitive

Energy vs Power

Molecular storage / (e)Fuels+H_2
→ highest **spec. energy** [MJ/kg]

Electric Motor
→ highest **spec. power** [kW/kg]

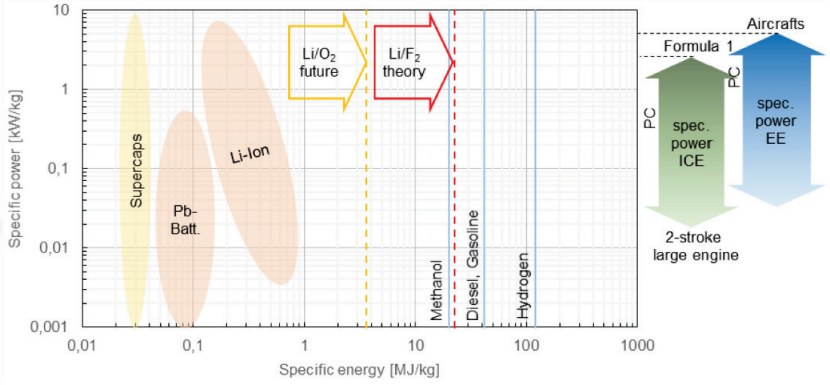


Figure 3: Ragone diagram for different energy carriers, data from [Ts15], [va07], [Pe14]. Estimations for Li/F2 from [ZL11] and Li/O2 from [va14].

Efficiency vs Cost

BEV → 2 ~ 3x more **efficient**

eFuels+ICEV → overall **cost** competitive

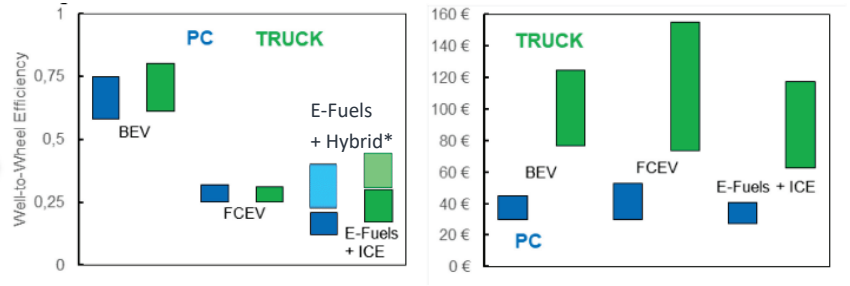


Figure 6: (left) well-to-wheel efficiency for selected drivetrains according to [Kr18]: min. and max. scenarios including liquification, compression, CO_2 from point sources. (right) mobility costs according to [Kr18]: min. and max. scenarios incl. fuel, infrastructure and vehicle value loss.

Source: "Electrification and E-Fuels – The Future of Otto- and Diesel-Engines", Härtl, Kraus, Jaensch, Technical University Munich, 43rd International Vienna Motor Symposium 2022
*FVV Projects ICE2025+ & ICE2030 & Powertrain 2040

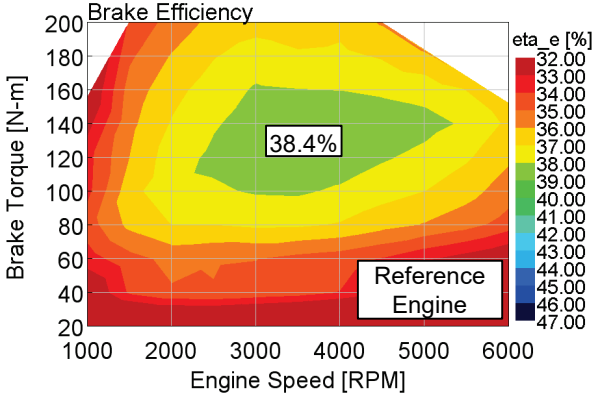
Sustainable Powertrain Solutions

Hybridization & IC-Engine - Potentials in Efficiency

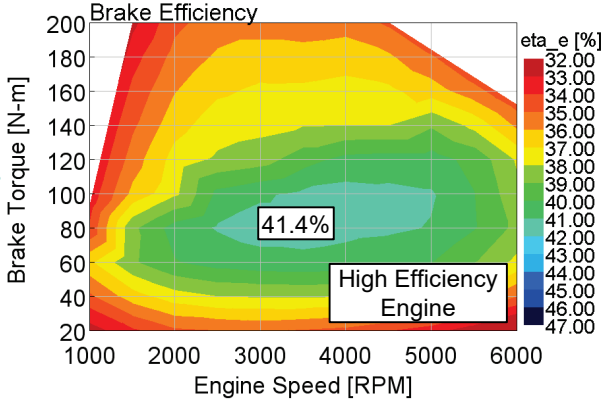
Next Generation ICE Concept Development

Maximizing Efficiency up to 50%$_{\text{Hybrid Vehicle}}$ and CO_2-neutral emissions w/ low-carbon fuels

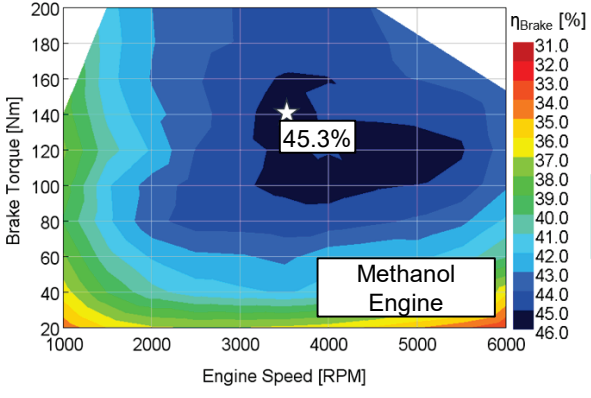
VW EA211 TSI evo
- State-of-the-art
- Gasoline
- 1.5 l, 4 cyl
- 96 kW, 200 Nm
- ε = 12.5
- s/b = 1.15
- VVT
- Cylinder deactivation



Improvements
- Downsizing (1.5 l → 1.0 l)
- Variable compression ratio
- High turbulence
- EGR

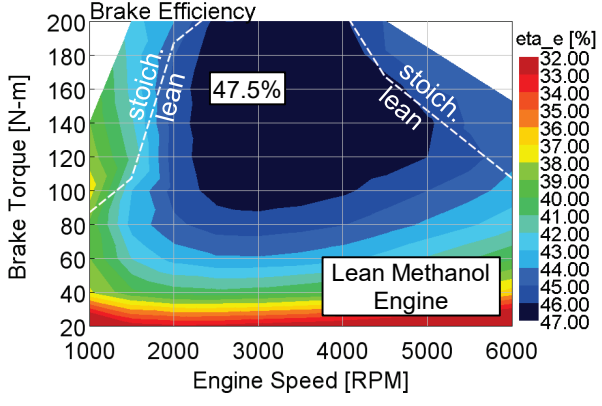


Methanol Engine
- Increase the compression ratio by ~ 4
- Knock-free operation
- Lower wall heat losses
- Lower exhaust energy losses



Change of Fuel
- Methanol

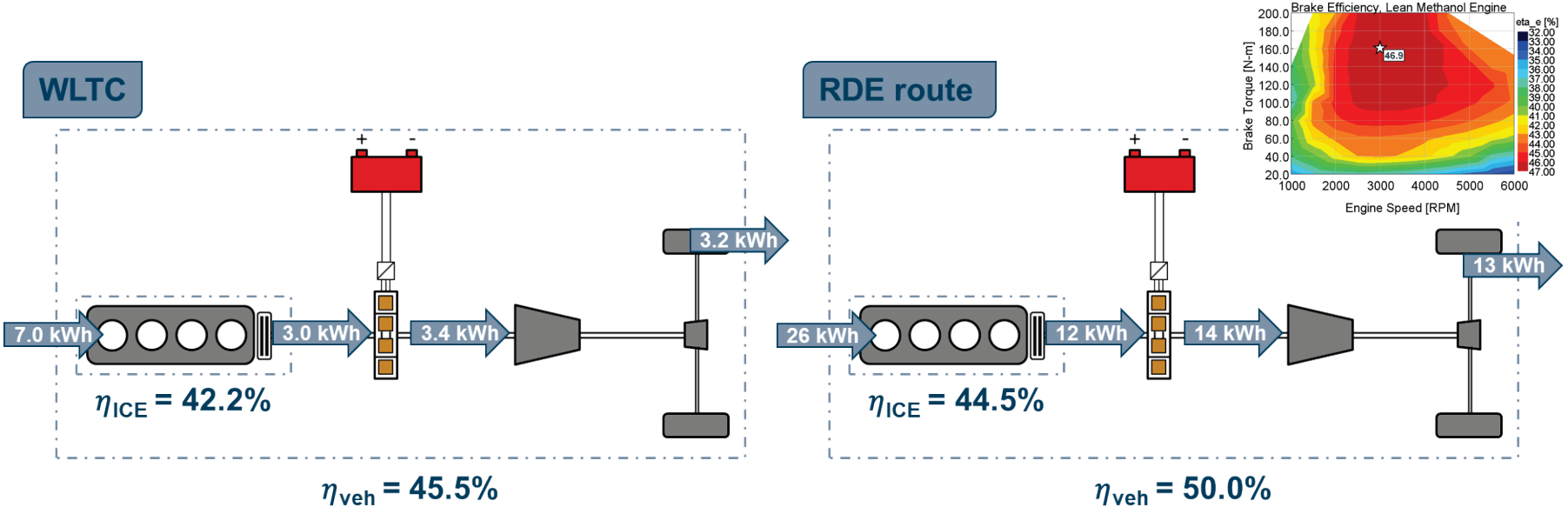
Lean Combustion
- λ = 1.7



Source: FVV research project „ICE2025+“

Potentials of P2-Hybrid Technology with Sustainable Fuel Combination

eFuels Target: Maximizing Efficiency towards 50%$_{HEV}$ and CO_2-neutral emissions



[Cell capacity: 3.25 Ah; Battery voltage: 554 V; El. motor power: 35 kW]

- Optimal powertrain dimensioning for WLTC & rule-based strategy derived for entire database
- Powertrain prioritizes electric driving, while load point shifting (up/down) is less relevant due to specific map characteristic of the Lean Methanol Engine

Source: FVV research project „ICE2030“

Motorsports-like P1-Hybrid Technology with eTurbo

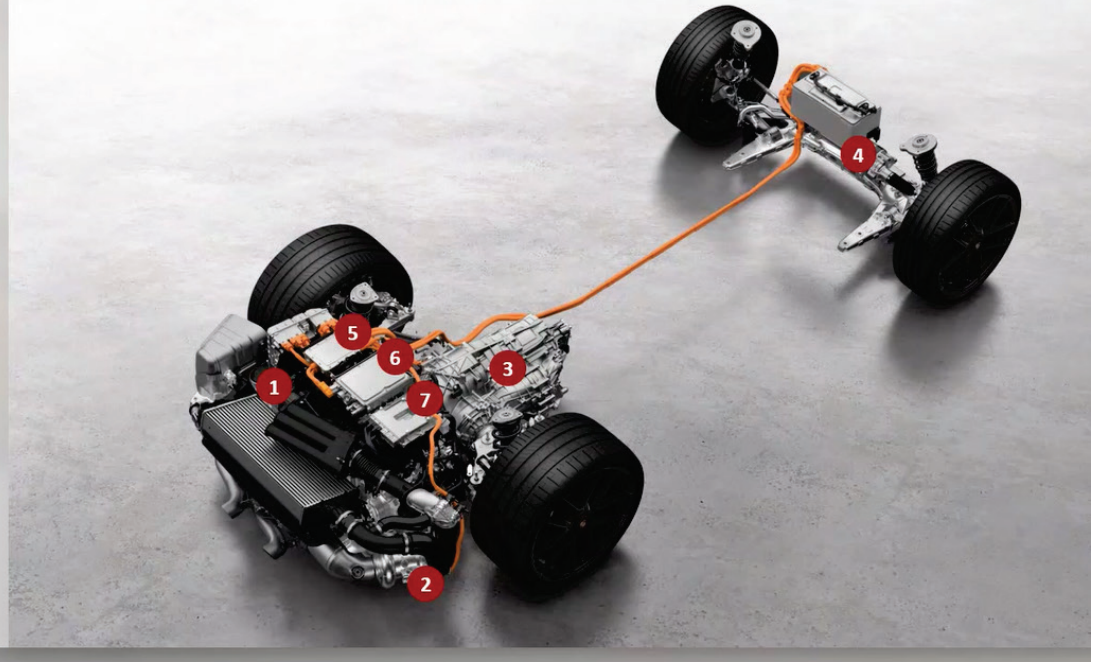
Porsche 992 II GTS/Turbo, 9A3-Engine w/ eMotor + eTurbo

The new Porsche 911 GTS

SYSTEM OVERVIEW OF PERFORMANCE HYBRIDISATION

t-hybrid

1. 3.6-litre six-cylinder flat engine
2. Electric exhaust turbocharger (eTurbo)
3. Integrated electric motor in the PDK
4. 400-V lithium-ion battery
5. High-voltage distribution box
6. Pulse inverter of integrated electric motor in PDK
7. Direct current converter



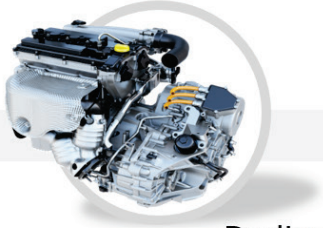
PORSCHE

Source: Porsche, Motortechnisches Seminar, RWTH Aachen, 08.07.2024

Next Generation ICE Concept Development

Future of ICE

DHE



Dedicated hybrid engine (DHE)

Efficiencies up to 45%

Innovative combustion controls

D-REX

Dedicated range extender (D-REX)

Leverage of existing engine platforms

Strong cost focus

Advanced-development

Advanced combustion

H_2-ICE

Passive pre-chamber spark plug

H_2-ICE (HD/LCV/PC/Racing)

Source: Prof. U. Grebe, AVL, Engine Congress, Baden-Baden 2024

Sustainable Powertrain Solutions

Renewable Synthetic Fuels - Development and Potentials of eFuels

Haru Oni – strong wind! … for Lower-Carbon Fuels

"Porsche focuses on a double-E: E-mobility and E-fuels"

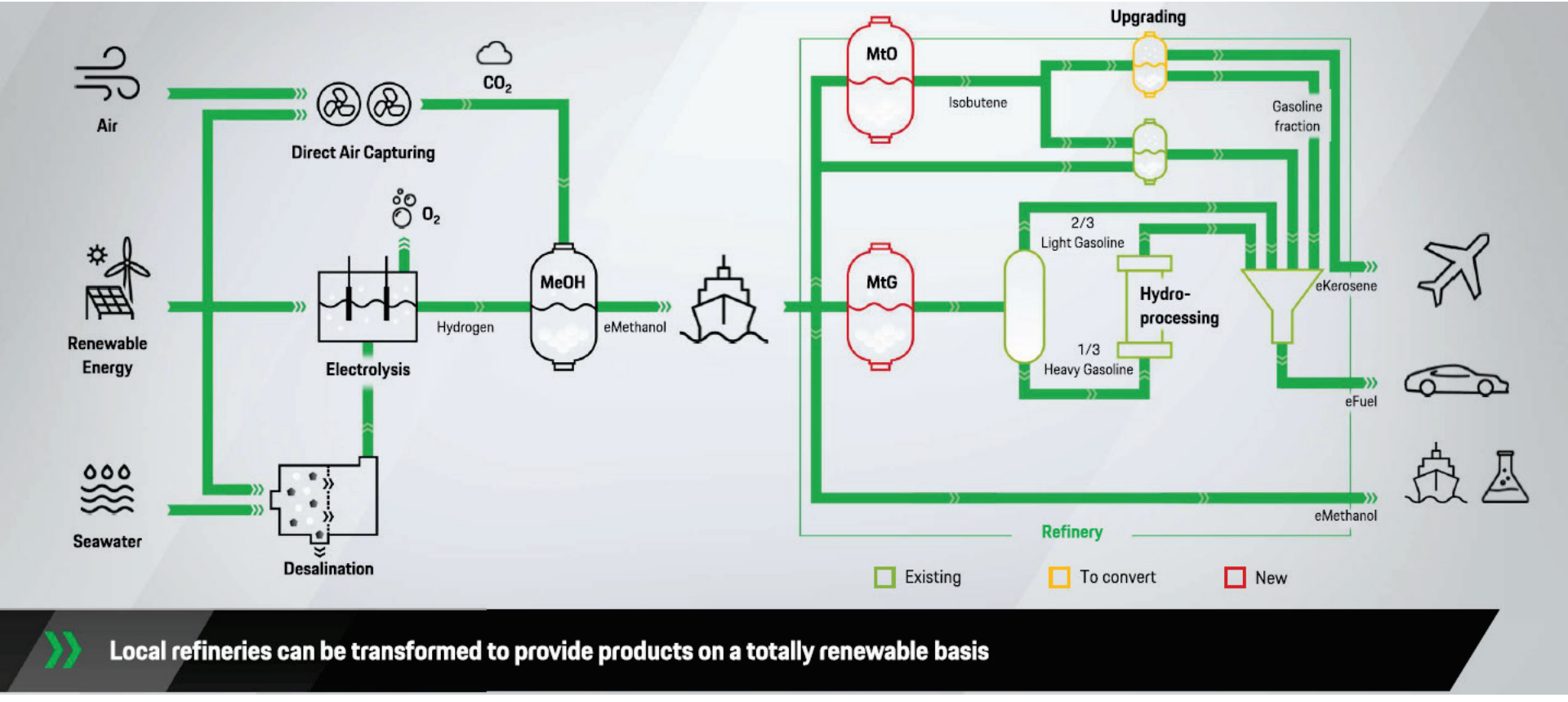
E-Fuels pilot plant from HIF, Siemens Energy and Porsche

eFuels erklärt

Quelle: https://newsroom.porsche.com/de/2023/nachhaltigkeit/porsche-wie-werden-efuels-tatsaechlich-nachhaltig-christophorus-407-32795.html
https://newsroom.porsche.com/de/2022/unternehmen/porsche-vorstandsvorsitzender-oliver-blume-verbrenner-motoren-efuels-elektrostrategie-29024.html

Green Hydrogen based eFuels Production

Global production chain of eFuels based on MtX

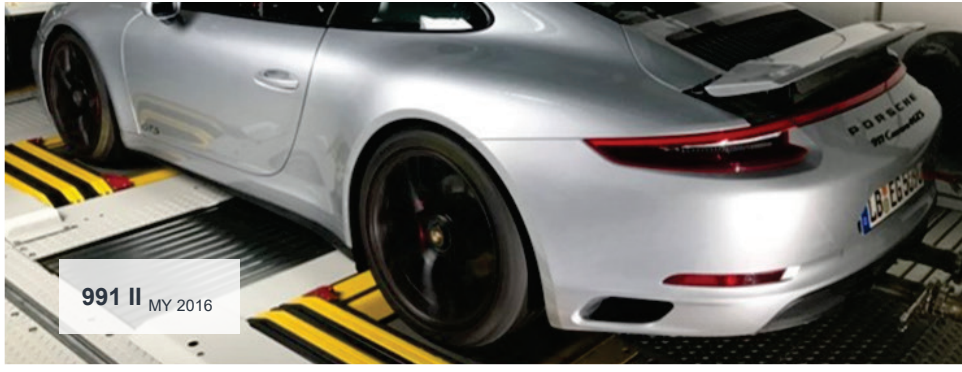


Local refineries can be transformed to provide products on a totally renewable basis

Source image: Dums et al., “Haru Oni: the entry into the mass production of renewable energy for the mobility of the future”, Int. Engine Congess, Baden-Baden, 2023

Testing eFuel performance & emission

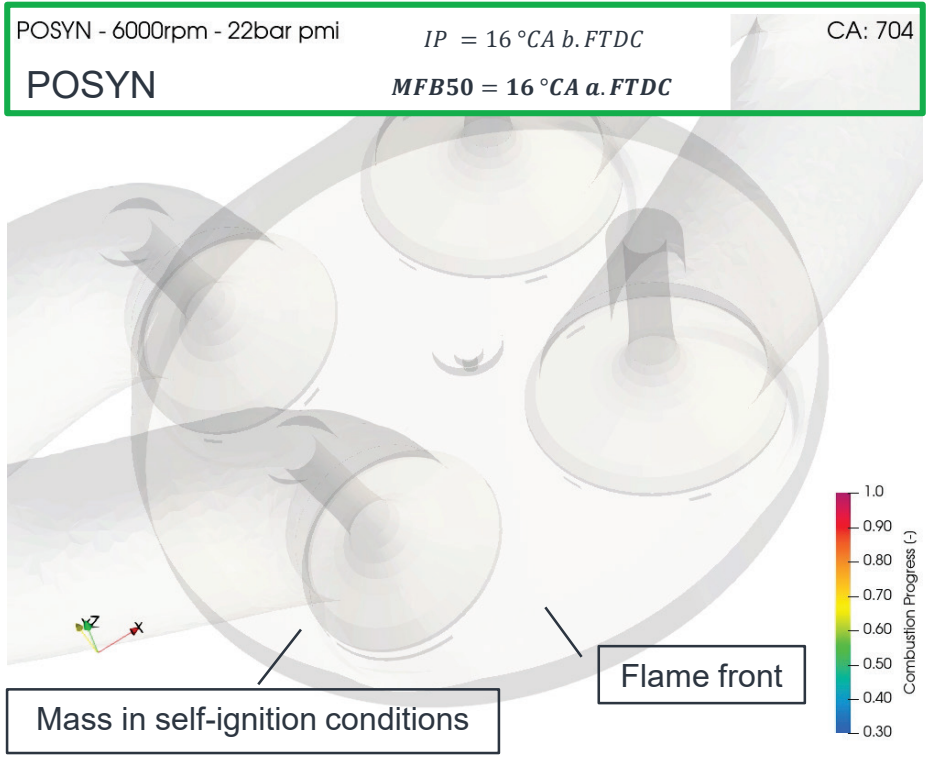
Porsche high-performance single cylinder engine & existing fleet vehicle testing

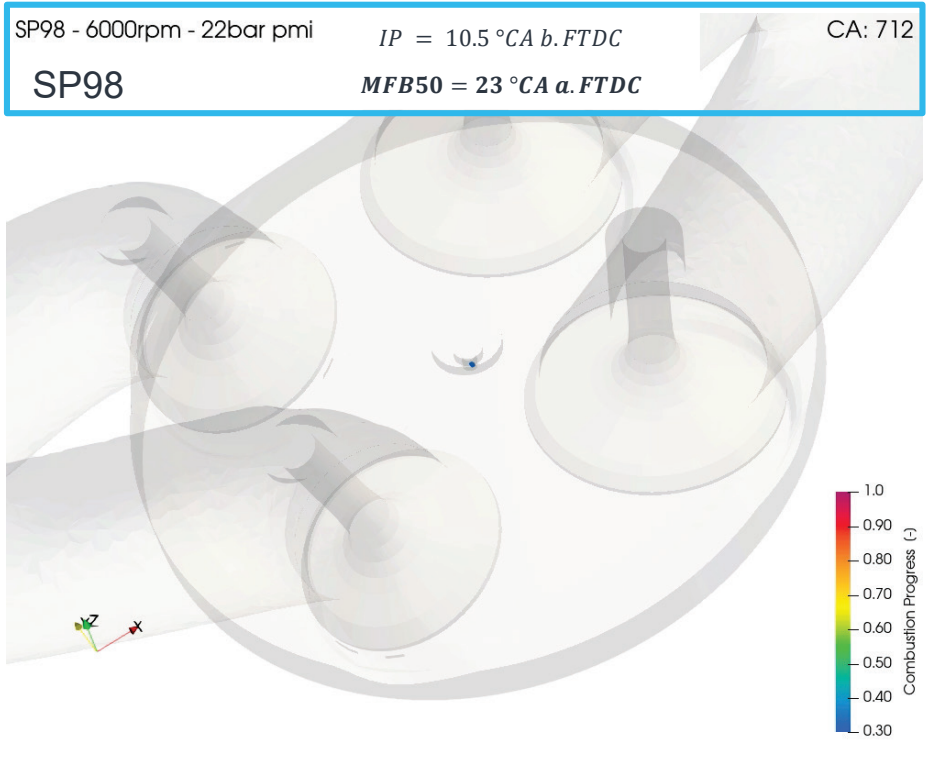


Source: Kulzer, A., Deeg, H., Villforth, J., Schwarzenthal, D. et al., "Sustainable Mobility Using Fuels with Pathways to Low Emissions," SAE Int. J. Adv. & Curr. Prac. in Mobility 2(4):1870-1892, 2020, https://doi.org/10.4271/2020-01-0345

Development method for eFuel formulation

Case study eFuel POSYN vs. SuperPlus 98: combustion and knock analysis





Source: Chiodi, M., Cupo, F., Vacca, A., Rossi, E., Bargende, M., Kulzer, A., Villforth, J., Deeg, H., " Alternative Fuels and Engine Design as Integrated Development Process through 3D-CFD Simulations," Int. Stuttgart Symposium, 2022

Sustainable Energy & Powertrain Solutions

Sustainable Energy & Life Cycle Analysis

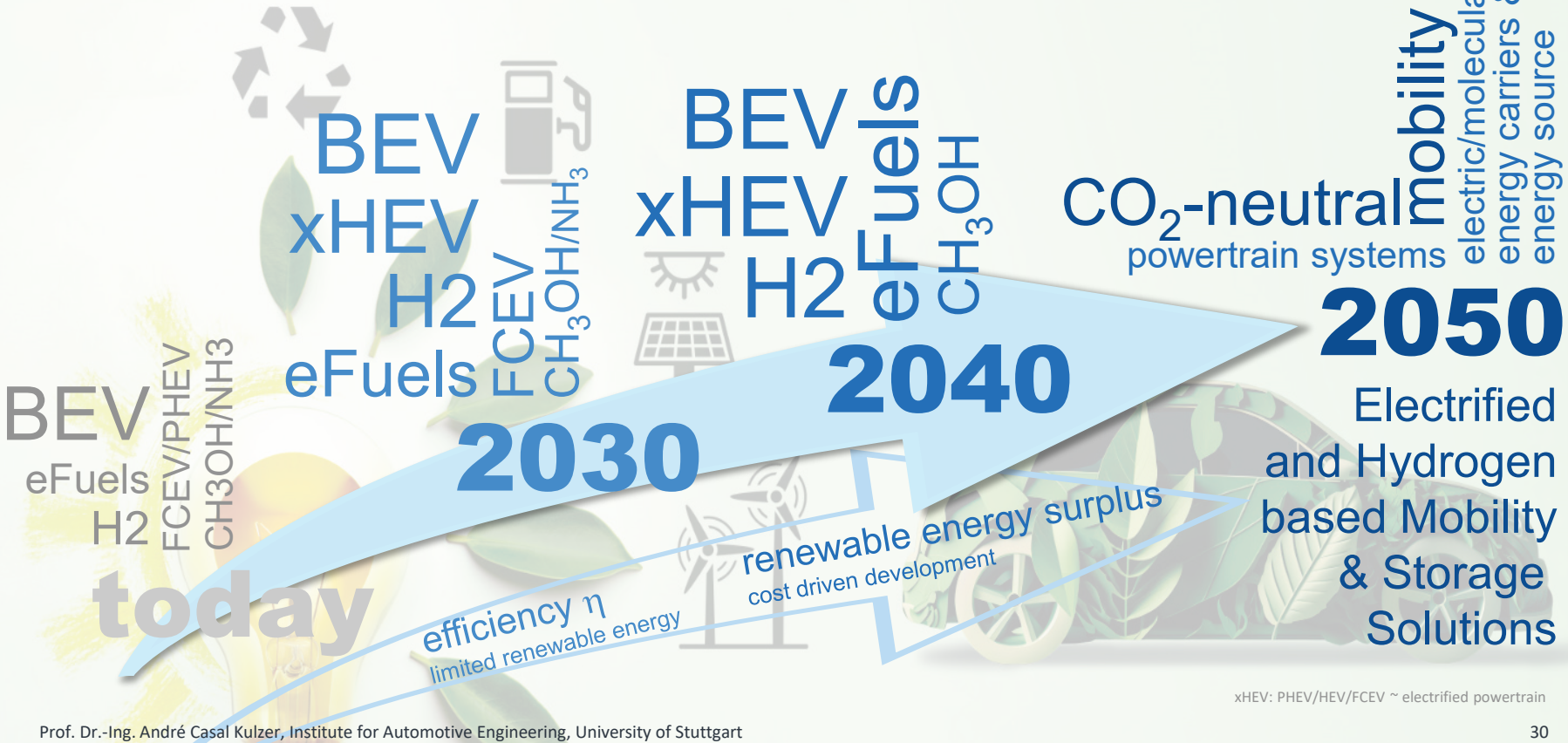
Sustainable Powertrain Solutions

Main Take-Aways

Sources: United Nations; Dr. Ing h.c. F. Porsche AG

Automotive Powertrain Systems 2030/2040/2050

Path towards sustainable powertrain systems and electrochemical/molecular energy carriers



xHEV: PHEV/HEV/FCEV ~ electrified powertrain

Main Take-Aways

- **The future of transportation will be an electrified mix of technologies!** Different solutions for different applications!

- **It's not only the powertrain, but also the energy source, energy carrier, infrastructure build-up and other bottlenecks!** Diverse powertrain system solutions will be needed as part of the transition to a GHG neutral future:
  1. use renewable energy and electrify where you can
  2. what you can't electrify, run on hydrogen
  3. what you can't run on hydrogen, run on bio/synthetic fuels

  This is a plea for electrification and for combustion engines – ICE's are without alternative in many applications – they will get more attractive when there is so much green electricity that energy efficiency no longer plays such an important role

- **But most of all, we need motivated and skilled students, engineers & scientists to tackle these challenges!**

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Driven by dreams…

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