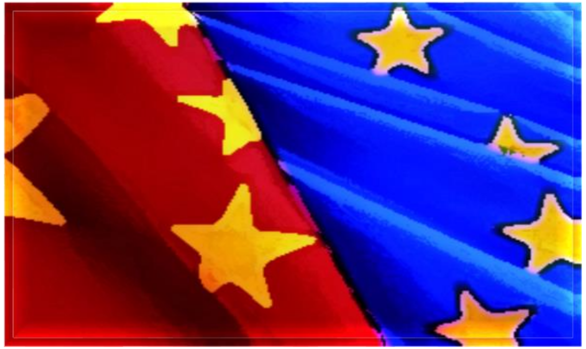
4th Sino-EU Workshop on New Emissions Standards for Motor Vehicles (March 2021)

Vehicle propulsion and fuel technologies: an overview of their development to meet future worldwide emissions standards for LD vehicles



Dr. Piotr Bielaczyc, BOSMAL Automotive Research & Development Institute Ltd

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History &
Main drivers of
powertrain development trends

Early light-duty vehicle development

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- Electric vehicles appeared in late 1860s - **earlier than internal combustion engines** (ICE 1876).
- Popularity was **boosted** by **low maintenance** as they **does not require complicated start procedures** or preheating, and had no emissions.
- 1888 - first four wheeled electric car is developed by A. Flocken.
- 1899 - the "La Jamais Contente" FR first electric vehicle which **exceeded 100 km/h**.
- 1900 - electric vehicles **top selling** road vehicles in US with **28%** of the market.

Detroit Electric Brougham: Early electric urban mobile

Specifications

1918 Detroit Electric Brougham Price, new: $ 2940; Wheelbase: 100 in

Engine: Electric, DC current; **Suspension:** Front - semi-elliptic leaf springs

Rear - semi-elliptic leaf springs; **Brakes:** Drums, mechanically operated on rear wheels

Early light-duty vehicle development

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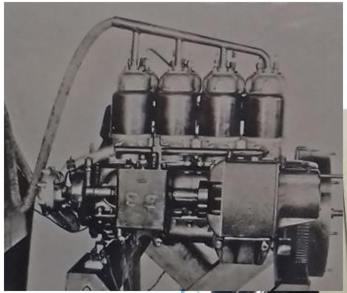

Source: SAE Congress 2018

1912 Cadillac Model 30

Specifications

1912 Cadillac Model 30

Price, new: $ 1800

Wheelbase: 116 in

Engine

V-8 CID, L-head

Power: 40 HP, Bore: 4.5”, Stroke: 4.5”

Splash lubrication

Transmission – 3 speed manual, no synchronizers

…and from that point, the **EV era ended**,

…do you know why?

WLTP & RDE are fully global topics

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WLTP

- The WLTP is already the laboratory procedure used for the majority of cars sold globally (India still to join – 2021)
- The number of large/medium markets not using WLTP (e.g. USA, Russia, Brazil) is getting smaller…
- Developing countries which do not currently have any formal emissions requirements likely to move straight to WLTP in the future

RDE

- UN regulation and global technical regulation (GTR) on RDE currently under development
    - Agreements made on certain items (e.g. temperature/altitude range)
    - Other technical items remain subject to scrutiny/debate (EU-Japan-S. Korea)
    - Plan to submit to GRPE session in January 2021
- The EU, India, China, South Korea and Japan either already have RDE in force, or have confirmed plans for its implementation before 2023/24
- The USA (EPA-CARB) has no formal RDE test requirement, but has RDE-like provisions for defeat device detection
- Australia and Brazil are strongly considering introducing RDE (no dates confirmed)

“This United Nations global technical regulation (UN GTR) aims at providing a worldwide harmonised method to determine the levels of Real Driving Emissions (RDE)…”

All vehicles and all internal combustion engines produce particulate

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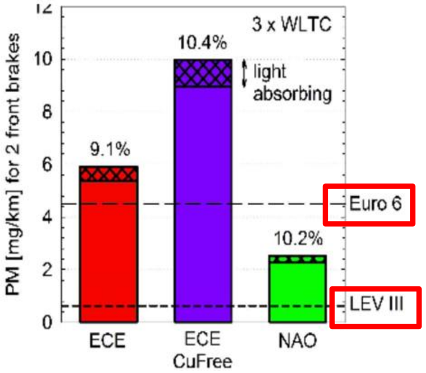
Nowadays, exhaust emissions of particulate are much lower (especially with DPF/GPF) and so non-exhaust emissions (brakes, tyres, clutch) are becoming more important than in the past

Let’s not forget about particle number emissions from vehicles which
- don’t burn carbon (H_2)
- don’t burn any fuel / don’t have a combustion engine of any kind



Brake PM
Source: Ilmenau Uni, 47th PMP meeting

Vehicle Engines Produce Exhaust Nanoparticles Even When Not Fueled

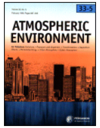
Topi Rönkkö†*, Liisa Pirjola‡, Leonidas Ntziachristos§, Juha Heikkilä†, Panu Karjalainen†, Risto Hillamo∥, and Jorma Keskinen†

Environmental Science & Technology

Particulate emissions from laser ignited and spark ignited hydrogen fueled engines

Akhilendra Pratap Singh, Anuj Pal, Neeraj Kumar Gupta, Avinash Kumar Agarwal

International Journal of Hydrogen Energy



Non-exhaust PM emissions from electric vehicles

Victor R.J.H. Timmers [a], Peter A.J. Achten [b]

Which powertrain technologies will survive and which won't? Which new ones will come into use?

LDV powertrain development in the EU (Euro 7)

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LONG-TERM DEVELOPMENT → for Euro 7/China 7/others and to meet long-term CO_2 requirements

- Further development of SI DI engines (lean burn?); majority direct injection
- Alternative fuels development (HVO, DME, Ethanol, Methanol, CNG/LNG)
- Reducing share of Diesel engines – new solution Diesel Hybrid
- HCCI/GCI engines
- CNG fuelled SI engines, GPF for all SI engines
  - GPF for PFI affects direct injection cost:benefit ratio
- Hybridization → MHEV, PHEV
- Electric powertrain → BEV
- E-fuels
- Hydrogen ICE
- Fuel cells and hybrid fuel cells

Not only electrification!

SI powertrain developments – selected examples

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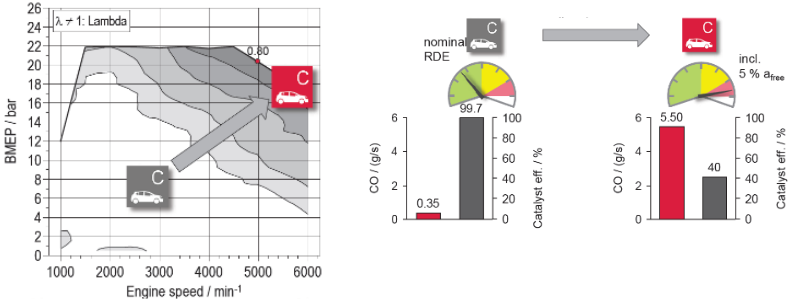
Engine/combustion

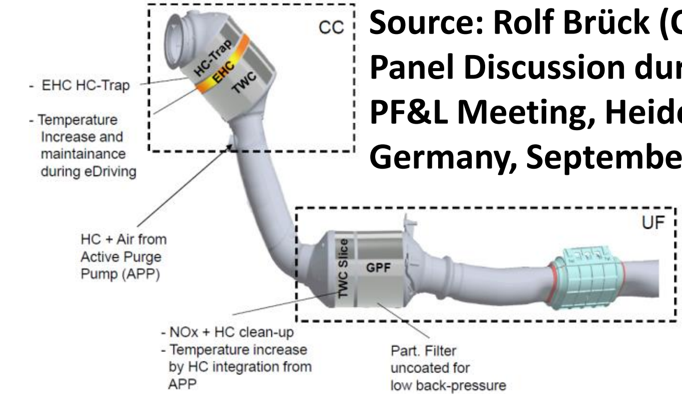
- "Map flattening" to λ1 to avoid enrichment, reduce fuel consumption and aid aftertreatment
- Increase in fuel injection pressure (to 500 bar – or more)
- Load partitioning powertrain electrification, intelligent energy management (route planned based on navigation system input)
- Management of knock/temperature via water injection
- Ongoing discussions on the subject to higher RON fuel and alternative fuels such as methanol



Source: Bamugarten et al. (FEV), 2018

Aftertreatment

- Three-way catalyst is now almost 50 years old, but continues to be optimised
- GPFs now well established for direct injection engines; full control of PN at 10 nm will require further optimisation (often 2 filters), expansion to other engine/fuel types
- Introduction of legislative limits for additional pollutants would require significant optimisation work, since standalone solutions are not currently known



Source: Rolf Brück (Continental), Panel Discussion during SAE PF&L Meeting, Heidelberg, Germany, September 2018

SI powertrain developments – GDCI and SPCCI

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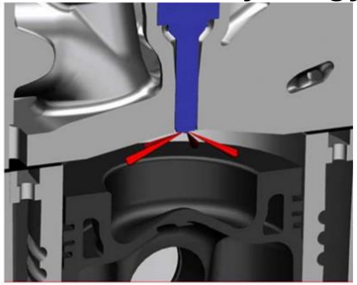
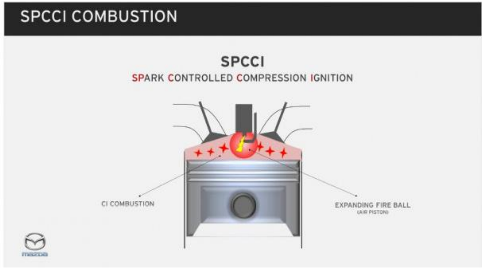
GDCI = engine redesign revolution

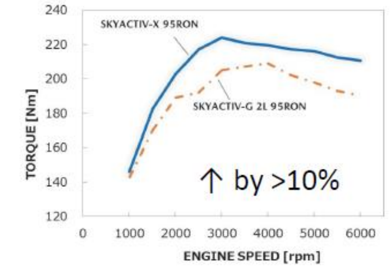
- GDCI = gasoline direct-injection compression ignition, also known by other names
- “22% better thermal efficiency than a current conventional spark-ignited gasoline engine with direct fuel injection and 11% better than a 2L diesel engine”
- In addition to efficiency – also emissions advantages/aftertreatment synergy



GDCI Multi-Cylinder Engine for High Fuel Efficiency and Low Emissions

Mark Sellnau, Wayne Moore, James Sinnamon, Kevin Hoyer, Matthew Foster, and Harry Husted
Delphi Powertrain





SPCCI: already in use

- *Spark Controlled Compression Ignition,* overcoming two issues: maximizing the compression ignition zone and achieving a seamless transition between compression ignition and spark ignition
- **Super lean burn** allows improvement of efficiency by 20-30% over previous SKYACTIV-G

Sources: Delphi; Mazda, 28th Aachen Colloquium, 2019; mazda.com

CI powertrain developments – selected examples

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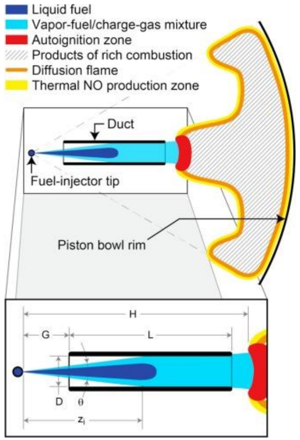
Engine/combustion

Ducted fuel injection – idea has regained attention (e.g. Mueller et al., 2017; Millo et al., 2021)

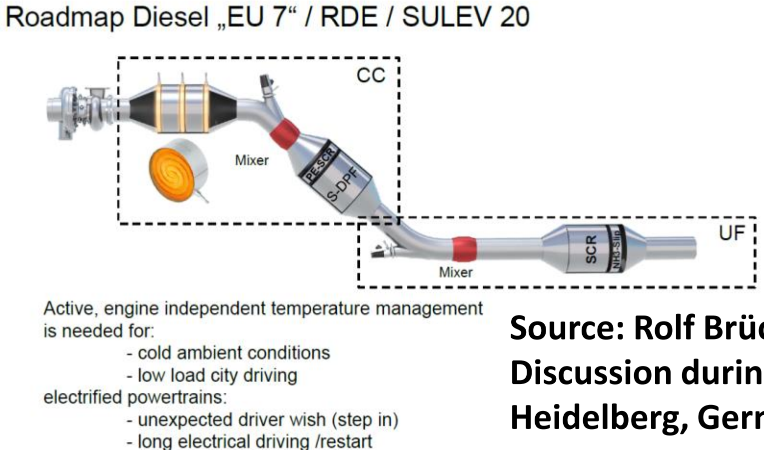
Ongoing improvements to turbochargers; turbo electrification



Mueller et al., 2017

Aftertreatment

Various proposals have been put forward for aftertreatment capable of achieving low real-world NOx, even for boundary conditions exceeding current RDE requirements. Some form of external energy input is likely to be required: electrically heated catalyst or burner, although some systems are only passively heated. US/China N_2O limits may be implemented in EU – optimisation required



Source: Rolf Brück (Continental), Panel Discussion during SAE PF&L Meeting, Heidelberg, Germany, September 2018

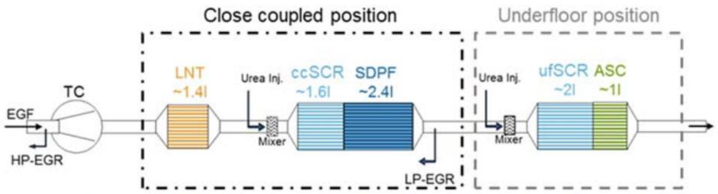
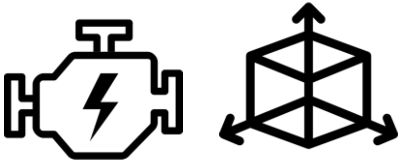


Figure 3: Exhaust aftertreatment system layout

Source: AECC, Vienna Motor Symposium, 2019

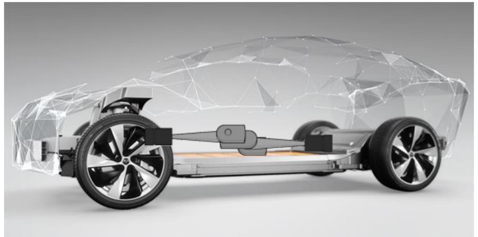
Range extenders: a question of ICE type, size, shape and location

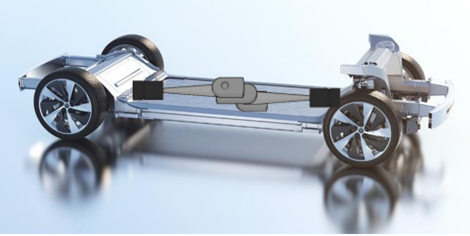


Range extenders are a feasible way of increasing use of EVs in markets/areas with low charger density

Range extender ICEs are subject to different requirements and therefore different designs and concepts can be leveraged

Transient response is not an issue and operating point can be fully optimised





Rotary (Wankel), opposed piston and free piston designs are all mentioned in this context – may influence general ICE development and even create new trends
Consideration of “dead weight” means that range extenders and all associated systems (aftertreatment, fuel storage/delivery, mechanical couplings) need to be light, with every kg saved offering additional pure electric range

In addition to weight, packaging is becoming ever more important:

- The so-called EV “skateboard” platform lends itself to long, flat engines – i.e. the exact opposite of current engine designs
- Space at the front of the vehicle is at a premium (excellent passive cooling)

"High-brid" or "low-brid"? Real world performance is what counts

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Hybrid / EVs | Plug-in Hybrids

Shocking News! Plug-in Hybrid Cars Need To Be Plugged In!

September 21, 2017

Plug-in hybrid users branded 'ridiculous' for not charging their cars

November 12, 2018 / by Richard Aucock

"The analysis has shown that the average CO_2 output is 168 g/km in day-to-day use"

- Plug-in hybrids (PIH) can have very low tailpipe CO_2 emissions, but this is offset (at least partially) by CO_2 generated in the production of electricity (which varies significantly – from fully renewable to coal)
- **Low real-world PIH tailpipe emissions require that the battery be charged (!) *("Who knew?")***
- Many PIH purchased by companies to operate as fleet vehicles (high mileage, high proportion of motorway driving) because of tax incentives
- Vehicle users were unwilling to charge at home (own cost) – or physically unable to
- Employees don't always have access to suitable charging facilities at work/while traveling on business
- **As a result, both FC and tailpipe CO_2 for PIH can be massively higher than advertised – significantly higher than an equivalent vehicle with a Diesel engine**
- A lack of suitable charging points / appropriate charging behaviour defeats the purpose of PIH and forces use of the combustion engine, which must deal with the dead weight of the hybrid system+battery
- Thus, the real-world CO_2 benefits of PIH can be zero-to-negative, even if carbon-free electricity is available

Sources: gas2.org, motoringresearch.com, themilesconsultancy.com

EVs are still subject to the laws of physics (and finance) – nothing for free!

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Zero emission hype

Zero emissions won't be possible until a "perpetuum mobile" is invented.

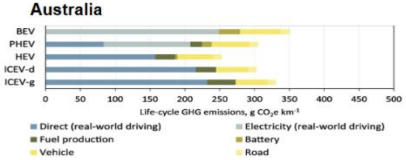
"Perpetual motion, the action of a device that, once set in motion, would continue in motion forever, with no additional energy required to maintain it. Such devices are **impossible** on grounds stated by the first and second laws of thermodynamics." *Source: Encyclopaedia Britannica*

Not only CO_2: power generation creates PM/PN, SO_x, NO_x, CO, NH_3, PAH, etc (varies by fuel type)

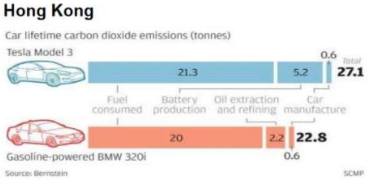
	Household heating	Road transport	Energy	Industry	Agriculture	Other
PM_{10}	42%	11%	10%	17%	15%	5%
$PM_{2.5}$	57%	11%	12%	10%	4%	6%
NOx	14%	39%	31%	3%	5%	8%
SOx	13%		78%	7%		2%

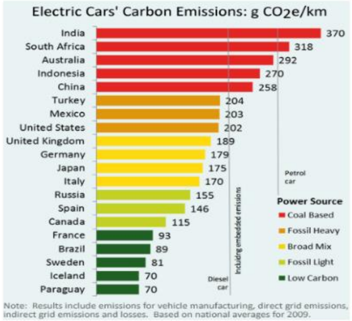
Sources: B. Zhmud, ACI Base Oils & Lubricants Summit, Florence, Italy, 2018;
K. Keiji, "Diversified electrification" Vienna Motor Sympoiusm 2019;
European Environment Agency 2019

Zero emission? Not quite.

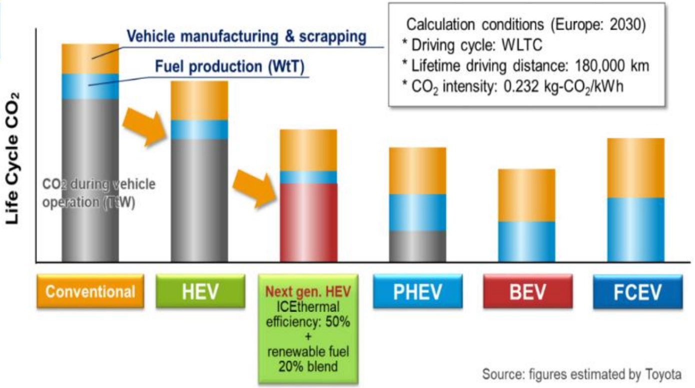


Ref.: P. Wolfram, T. Wiedmann, Applied Energy 206 (2017) 531-540.



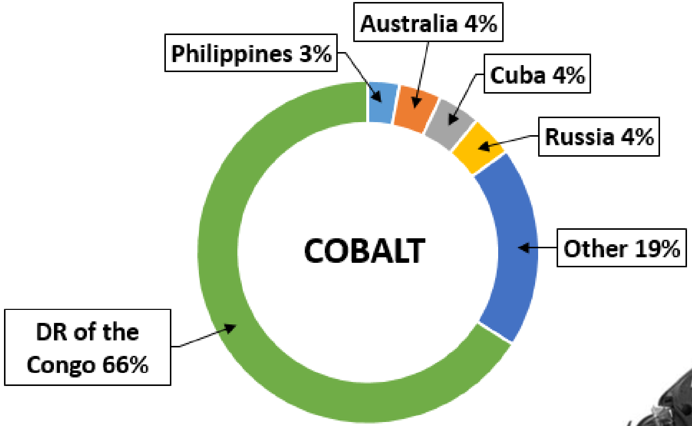


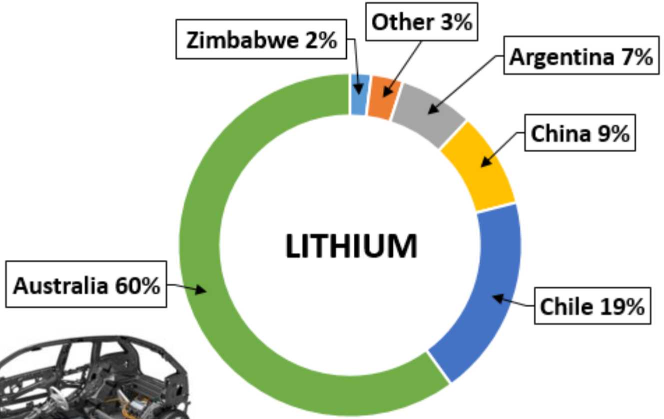
Source: Euan Mearns, Energy Matters, 2017

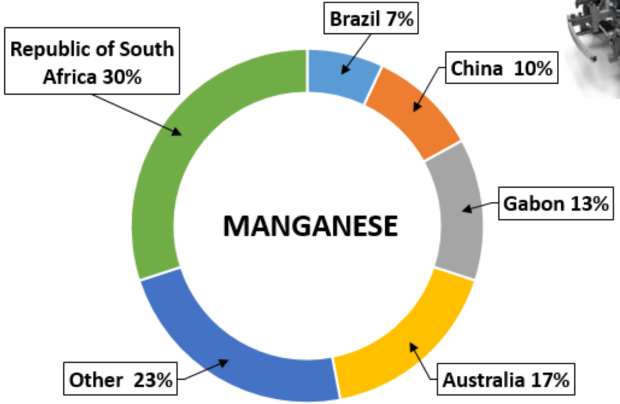


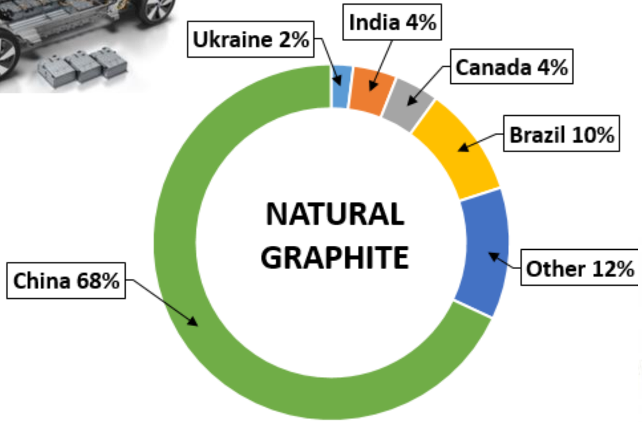
Source: figures estimated by Toyota

Raw materials needed to produce lithium-ion electric









Very rapid development in alternative means of transport (especially urban): electric bicycles, scooters, electric tricycles (especially in China), **all equipped with batteries**.

This causes intense competition for key raw materials – see graphs.

ENERGY SOURCES – FUEL OPTIONS

Electricity alone will not work as a source of energy in all situations – which other fuel types will remain in use/come into use?

Hydrogen: lightening the load?

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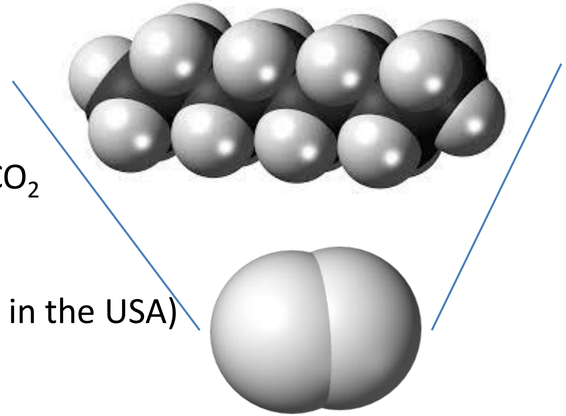
The concept has a long history and has been abandoned several times in the past. Has the time finally come for H_2 in road transport? CO_2 legislation and concern over electrical powertrains' weak points is driving very strong interest in H_2



Usage in ICE – stepping stone from current technology:

- dual fuel (potentially including retrofit)
- bi-fuel (potentially including retrofit) – to overcome range concerns
- monofuel (dedicated engine designs to make use of very high RON) – zero CO_2

Usage in H_2 fuel cells:

no combustion, no NO_x; FCEVs already on the market (Toyota; Hyundai + Honda in the USA)
Seen as a key route for the HD sector to reduce (even eliminate) CO_2 emissions

Problems of production and storage:

Water is stable and so electrolysis is energy-intensive – ongoing research into catalysts and maximising use of renewable electricity
Locations with high solar flux and access to water could become H_2 hotspots
Storage and transport of gaseous fuels (also when liquified) is challenging – very low overall efficiency for small quantities
Highly uneven, mostly underdeveloped infrastructure: USA and China both have <100 H_2 refuelling points…but Japan has >130
General and sector-specific safety concerns remain – not clear to what extent the public accept H2 as safe

Fuel cell electric vehicles (FCEVs)

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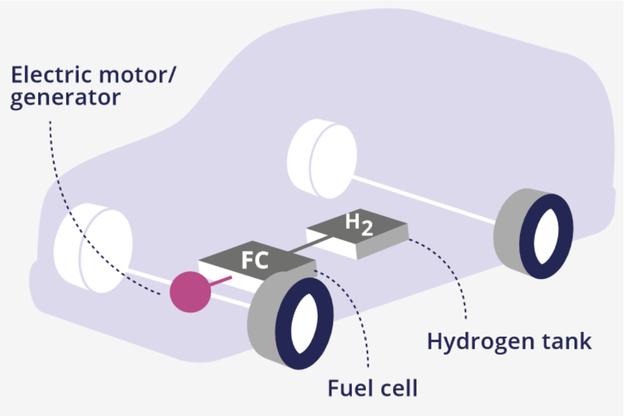
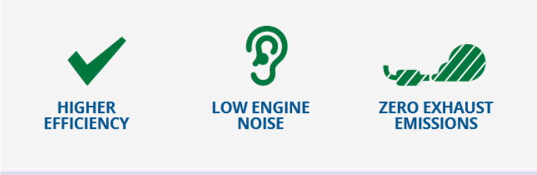
FCEVs are entirely propelled by electricity. In this case, the electrical energy is not stored in a large battery system, but is instead provided by a fuel cell 'stack' that uses hydrogen from an on-board tank combined with oxygen from the air. The main advantages of FCEVs over BEVs are their longer driving ranges and faster refuelling. Because of the current size and weight of fuel cell stacks, FCEVs are better suited for medium-sized to large HD vehicles and buses and longer distances.



ADVANTAGES



Source: Electric vehicles in Europe; EEA Report | No 20/2016

DISADVANTAGES

Fuel cell electric vehicles use a fuel cell to create on-board electricity, generally using compressed hydrogen and oxygen from the air.

Further technological development is needed for FCEVs to improve their durability, lower the costs and establish a hydrogen fuelling infrastructure, including standalone stations or pumps for hydrogen.

Indicative electric driving range: 160-500 km (increases with effective energy recuperation)

Hybrid Fuel Cell Powertrain

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- Electric vehicles combined with batteries and equipped with fuel cell technology – an **innovative** and **favorable** solution
- Concept offers zero emission from tank-to-wheel
- So far, the automotive industry has **focused mostly on pure battery versus pure fuel cell approaches**
- This powertrain concept is a combination of battery and fuel cell technologies in a single dedicated hybridized powertrain architecture, benefitting from all possible synergies available
- **High range can be achieved (>> 600km)**
- Effective hydrogen storage still a **challenge**

- This approach toward a hybridized fuel cell vehicle **overcomes** the current barriers of electromobility as the driveability performance, but **there is still much to do in term of optimization**
- **Heavy duty sector could act as an incubator for fuel cell technology, later passing to light duty**

Source: Hybrid Fuel cell Powertrain. Electric & Hybrid Technology International. January 2018.

Fuel Cell Challenges

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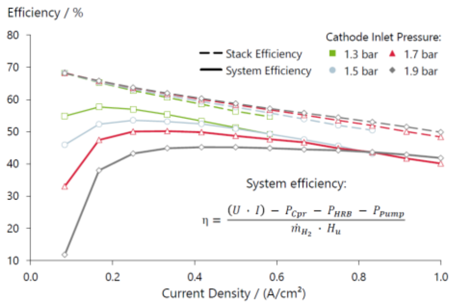
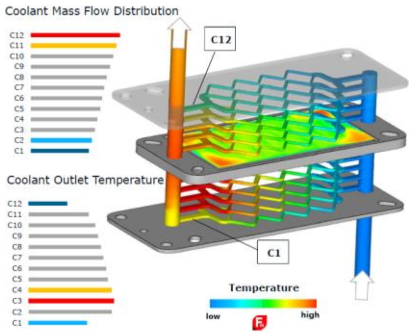
- **Efficiency:** achieving efficiency high at high current densities, with implications for FC size and weight and the possibility of using smaller cells

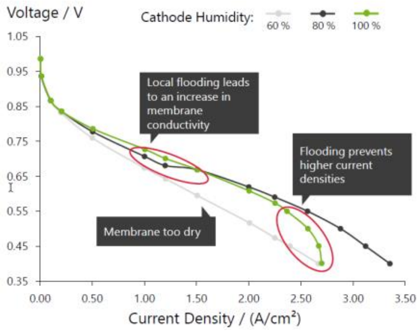
- **Thermal management:** generally moderate temeperatures, but no exhaust flow to carry away heat, other design requirements complicate cooling

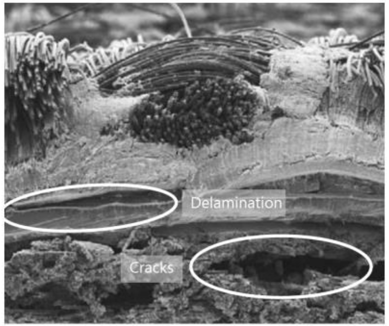
- **Durability/reliability/long-term performance:** mitigation of cold start effects (i.e. damaging impact of water and ice), general humidity management and avoidance of blockages

- **Hydrogen fuel:** general considerations and concerns (storage, dosing, safety, legal considerations, etc)





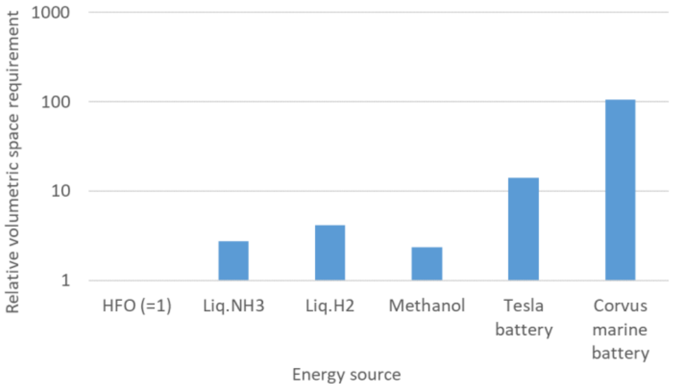




Main sources, image sources: S. Pischinger (FEV), SAE PF&L keynote, 22.09.2020; AVL Virtual Fuel Cell Development Webinar, 29.06.2020 – mobex.io
Additional sources: FEV, Ricardo (2020) – mobex.io

Beyond carbon: ammonia as fuel and/or hydrogen carrier

Ammonia is flammable and was first proposed as a fuel decades ago
Usage has been very limited, but it can be burned in practical combustion engines (RON=130). Emissions of concern are high levels of NO_x and NH_3, which can be remediated by suitable aftertreatment (SCR)
NH_3 is much discussed for marine applications, but seems highly unsuitable for road vehicles and especially for passenger cars.



However:
Formation of NH_3 via innovative methods (e.g. reverse fuel cells) can create a carbon-free energy carrier of high density (liquid ammonia). The energy intensity of the process can be aided by improved catalysis and processes can be powered by a high share of renewable energy.
Liquid NH_3 can be transported to its destination market and decomposed to $H_2 + N_2$, again aided by advanced catalysts. NH_3 boiling point -33°C (compare H_2 -253°C)

"Ammonia—a renewable fuel made from sun, air, and water—could power the globe without carbon" – *Science*, 2018

Sources: MAN (2019), ammoniaenergy.org (2020)

e-fuels: the promised fuel, delivered via green electrons

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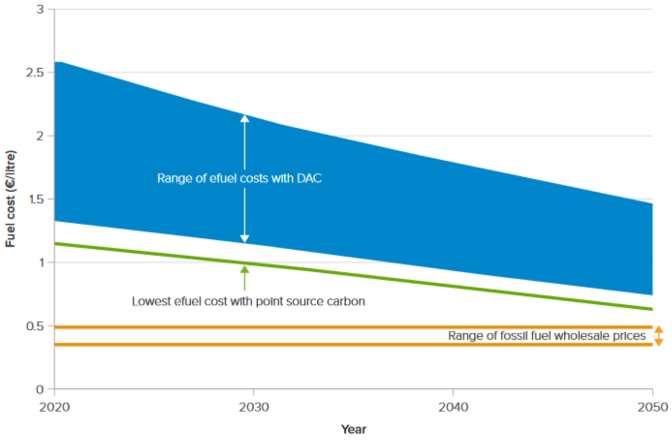
E-fuels are synthetic fuels created using hydrogen produced using sustainable electricity
Carbon input options are CO_2 obtained from biogenic/industrial processes, or even capture of CO_2 from the atmosphere

Why?
E-fuels: pathway to use renewable electricity, avoid heavy batteries and improve the sustainability of the current fleet – can be burned in a wide range of ICE
CO_2 capture from the atmosphere closes the circle

Technology readiness levels (TRLs) of the various sub-processes are higher than often assumed
Difficulties with scale-up and attracting funding; traditional business models not always suitable or relevant
High costs have proven problematic so far, but this situation will most likely change
Incremental improvements in cost efficiency via catalysis, photovoltaics, energy management, etc all play a part



In addition to large life-cycle CO_2 benefits and making use of existing fleet, modifications to fuel properties can potentially result in lower pollutant emissions = win-win-win situation

Image source: UK Royal Society Briefing DES6164 (2019); other sources: CONCAWE Report no. 14/19 (2019), Hanggi et al. A review of synthetic fuels for passenger vehicles (2019)

Alternative liquid fuels: TTW≠WTW, WTW≠vehicle LCA

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Tank to wheel (TTW) is a very small part (and a poor representation) of the full well to wheel (WTW) picture
However, WTW is not full LCA – it still excludes the impacts of powertrain manufacturing/disposal
Usage of alternative liquid fuels in the existing fleet is highly attractive from the full LCA point of view (embodied energy)

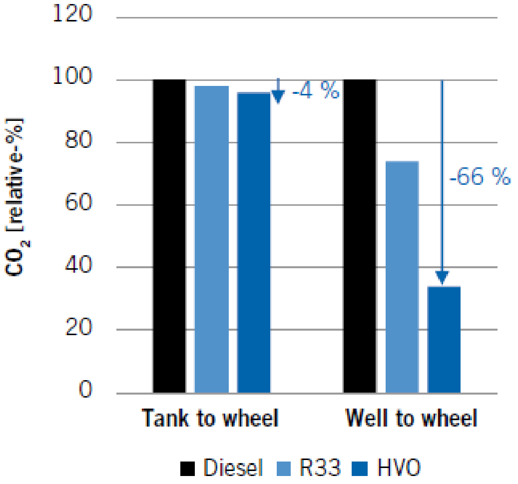

FIGURE 8 CO_2 emission for diesel and HVO in tank-to-wheel versus well-to-wheel consideration (© IAV)

- B30: -14 to -26%
- HVO: -60 to -82%
- BTL: -64% to -200%
- E-fuel: -93%

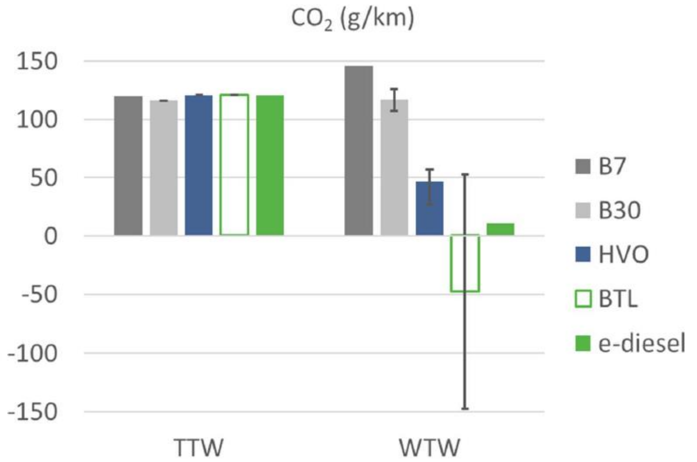

Image sources:
Demuynck et al., Improving Air Quality and Climate Through Modern Diesel Vehicles, MTZ Worldwide 81, 52-59 (2020)
Demuynck, J. Advanced emission controls and renewable fuels for low pollutants and lifecycle CO_2 emissions, AGVES presentation (2021)

Full LCA comparison: various powertrains vs typical 2020 ICE

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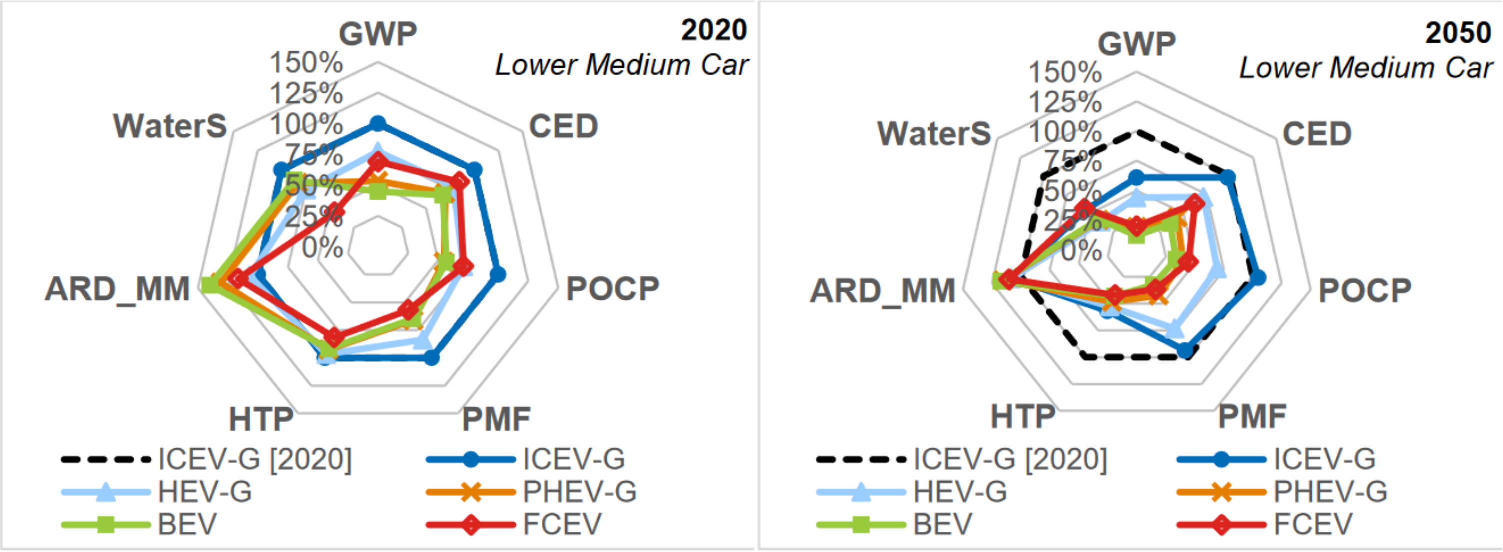
Figure ES4: Summary of the relative impacts for Lower Medium Cars for the most significant mid-point impacts for road transport, by powertrain for 2020 and 2050 (Tech1.5 Scenario)



Notes: Total emissions are presented relative to a 2020 conventional gasoline ICEV = 100%.
Powertrain types: G- = Gasoline; ICEV = conventional Internal Combustion Engine Vehicle; HEV = Hybrid Electric Vehicle; PHEV = Plug-in Hybrid Electric Vehicle; BEV = Battery Electric Vehicle; FCEV = Fuel Cell Electric Vehicle.
LCA impacts: GWP = Global Warming Potential, CED = Cumulative Energy Demand, POCP = Photochemical Ozone Creation Potential, PMF = Particulate Matter Formation, HTP = Human Toxicity Potential, ARD_MM = Abiotic Resource Depletion, minerals and metals, WaterS = Water Scarcity.

Source: https://ec.europa.eu/clima/sites/clima/files/transport/vehicles/docs/2020_study_main_report_en.pdf

Tank to wheel→well to wheel→life cycle

Only CO_2→ GHG+electricity→ 7 impact categories over full life cycle

Cost-effectiveness of emissions reduction measures

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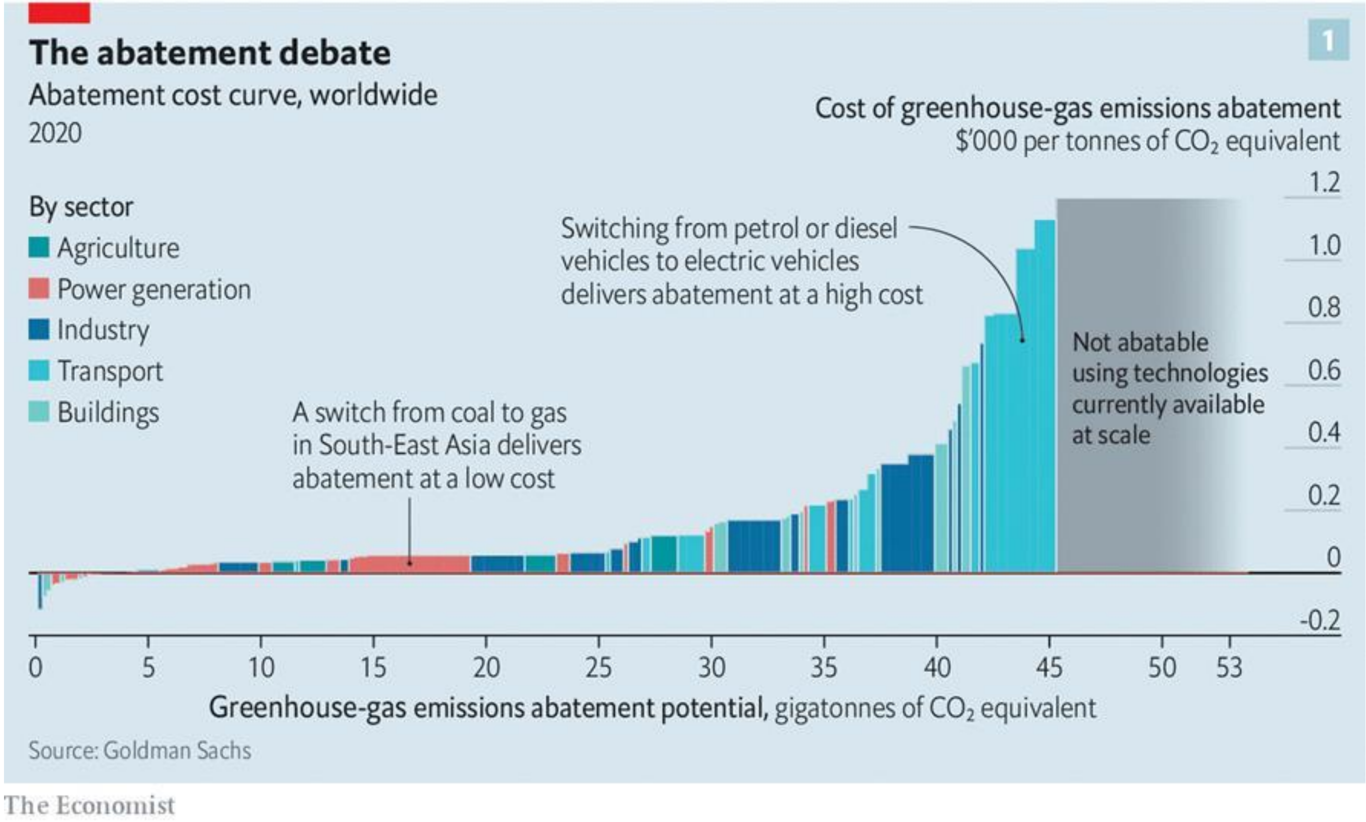

Source: Goldman Sachs (via The Economist), 2021

Forecast for global light vehicle sales by powertrain type

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Forecasting is generally extremely difficult and many assumptions must be made – many experts have been wrong before

Impacts from global politics, wars, pandemics, even individuals

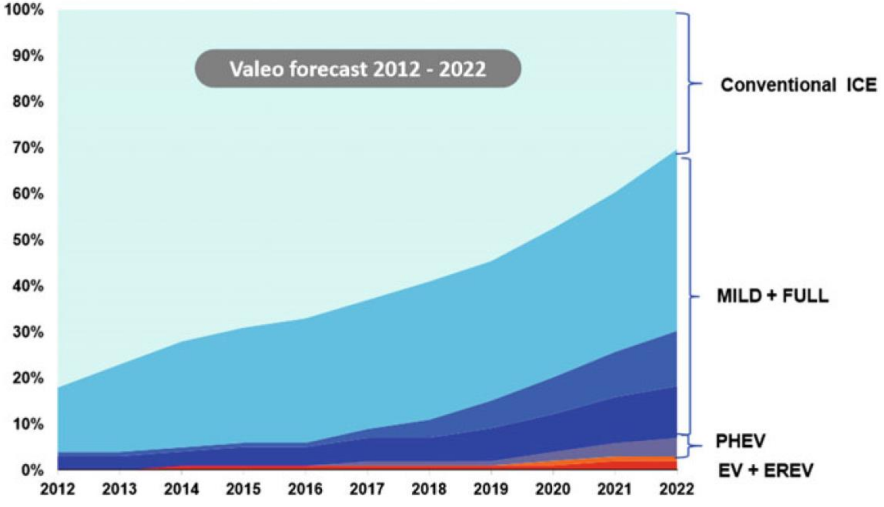
In the past the pure EV share was underestimated; now it is probably overestimated.

Mild hybrid engines are spreading; further electrification of conventional ICE is inevitable.

Problems with nomenclature remain – public confusion over plug-in/non-plug-in hybrids, "zero" emissions, etc

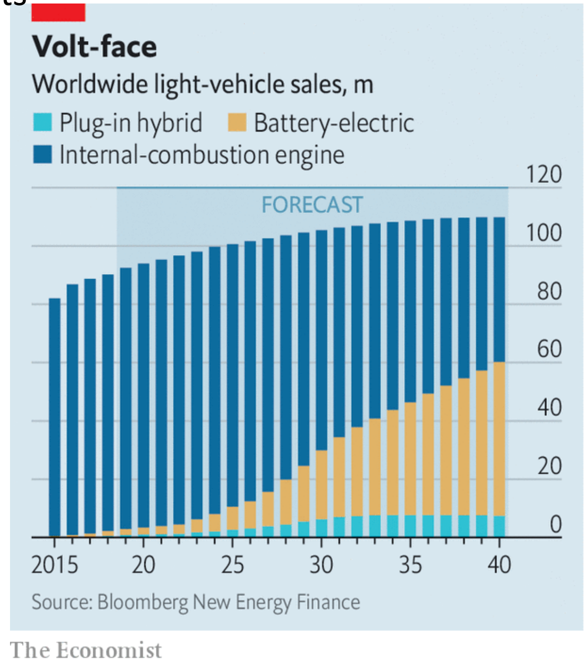
Legislation does not capture all available technologies or quantify their life-cycle benefits

Important to distinguish between *sales of new vehicles* and the *in-use fleet* (especially since modern cars often last for 20+ years)



Valeo, IEA-IA-HEV-Task 17 workshop (**2011**)

Bloomberg & The Economist (**2019**)



Conclusions

- **Despite huge pressure for powertrain electrification, it would be very difficult to give up on ICEs for road transport – important ICE market share will remain (mainly in various hybrid configurations and HD vehicles)**
- The IC engines used in hybrid powertrains with significant electrical range may strongly differ from those currently in use
- Demanding CO_2 standards are also in force and are strongly pushing hybridisation, electrification and use of low-carbon or non-carbon fuels (hydrogen)
- LCA gives a basis for fair comparisons – anlyses show that heavily electrified powertrains perform poorly for depletion of abiotic resources (minerals and metals)
- Fuel cells can be a solution for the road transport sector. There are certainly advantages, but there are still significant challenges to overcome before widespread commercialization is possible
- E-fuels (carbon-based, but synthetic) could be a good compromise between electrified powertrains and ICE
- Manufacturers have very strong incentives to work on electrification (mainly light duty), fuel cell (mainly heavy duty), as well as natural gas and hydrogen (both sectors)
- **Because of shortages of specific materials necessary for traction batteries, perhaps a better solution would be to hybridise ICE (running on sustainable fuels), which would needed smaller batteries**

Thank you – Questions welcome

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