Lecture 1 – Introduction

4A13 Internal Combustion Engines

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Resources

- Heywood, J.B., Internal Combustion Engines Fundamentals. McGraw-Hill, 2018
  https://idiscover.lib.cam.ac.uk/permalink/f/t9gok8/44CAM_ALMA51652608860003606

- Stone, R., Introduction to Internal Combustion Engines. Macmillan, 4th edition, 2012.
  https://idiscover.lib.cam.ac.uk/permalink/f/t9gok8/44CAM_ALMA51652608890003606

- Links to relevant papers.

Outline

Fundamental concepts in internal combustion engines (2L)

Overview of energy use in transportation, evolution of internal combustion and reciprocating engines, basic concepts and definitions, ideal constant volume and constant pressure cycles, efficiency, turbocharging and hybridisation

Spark ignition engines (1L)

Basic concepts and definitions, valve timing and volumetric efficiency, residual gases, intake and fuel injection systems, combustion in SI engines, autoignition and limits to combustion, spark timing and optimisation, effects of speed and load, SI engine maps, emissions

Compression ignition engines (1L)

Compression ignition process parameters, combustion under autoignition, fuel injection timing, torque and emissions, controlling NOx and soot, CI engine maps, principles of turbocharging and relevant physics, turbocharger matching

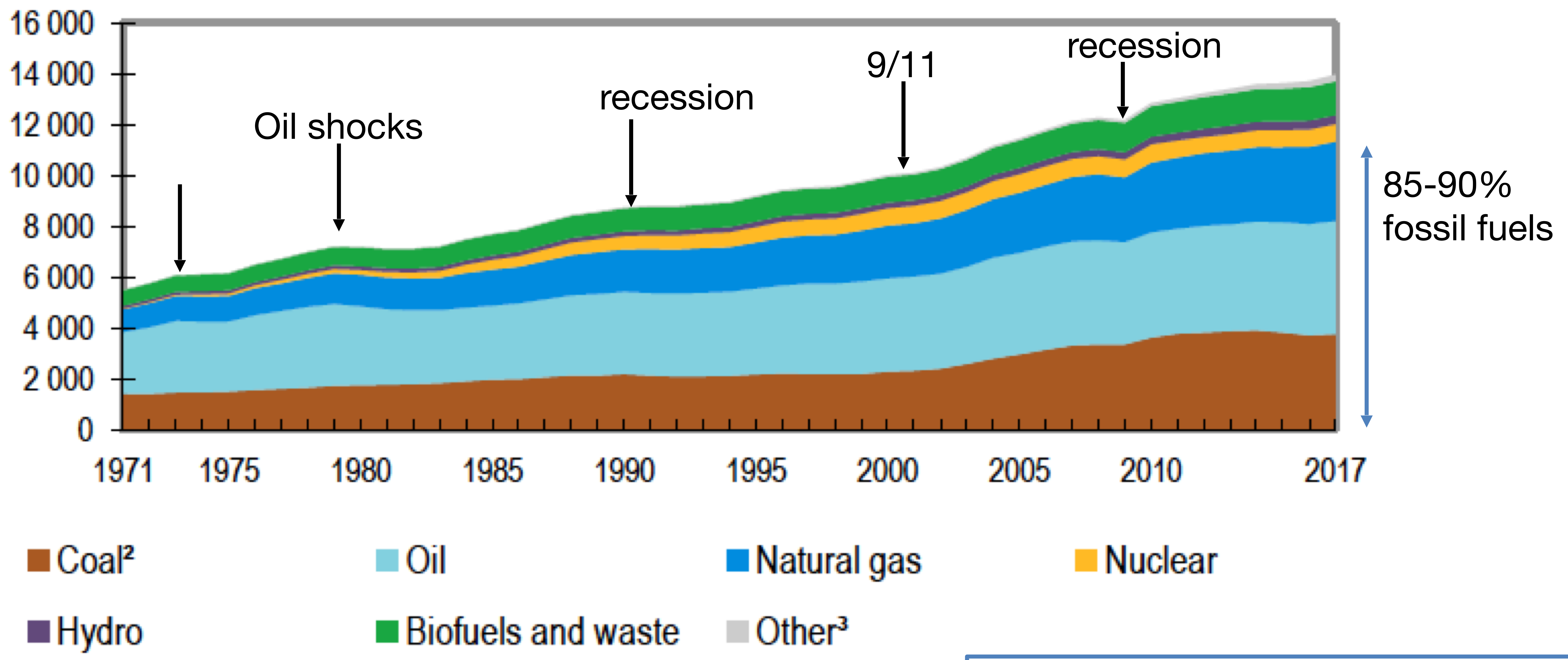
Emissions and aftertreatment (2L)

Combustion and engine out emissions, three-way catalysts, air-fuel ratio control, methods of in-cylinder control of NOx and soot, air-fuel ratio control, exhaust gas recirculation, selective catalytic reduction, particulate matter removal

Hybrid engines and future concepts (2L)

New developments in combustion engines. Hybrid powertrain concepts and designs (series, parallel), downsizing, turbocharging, electric powertrain efficiency and control concepts.

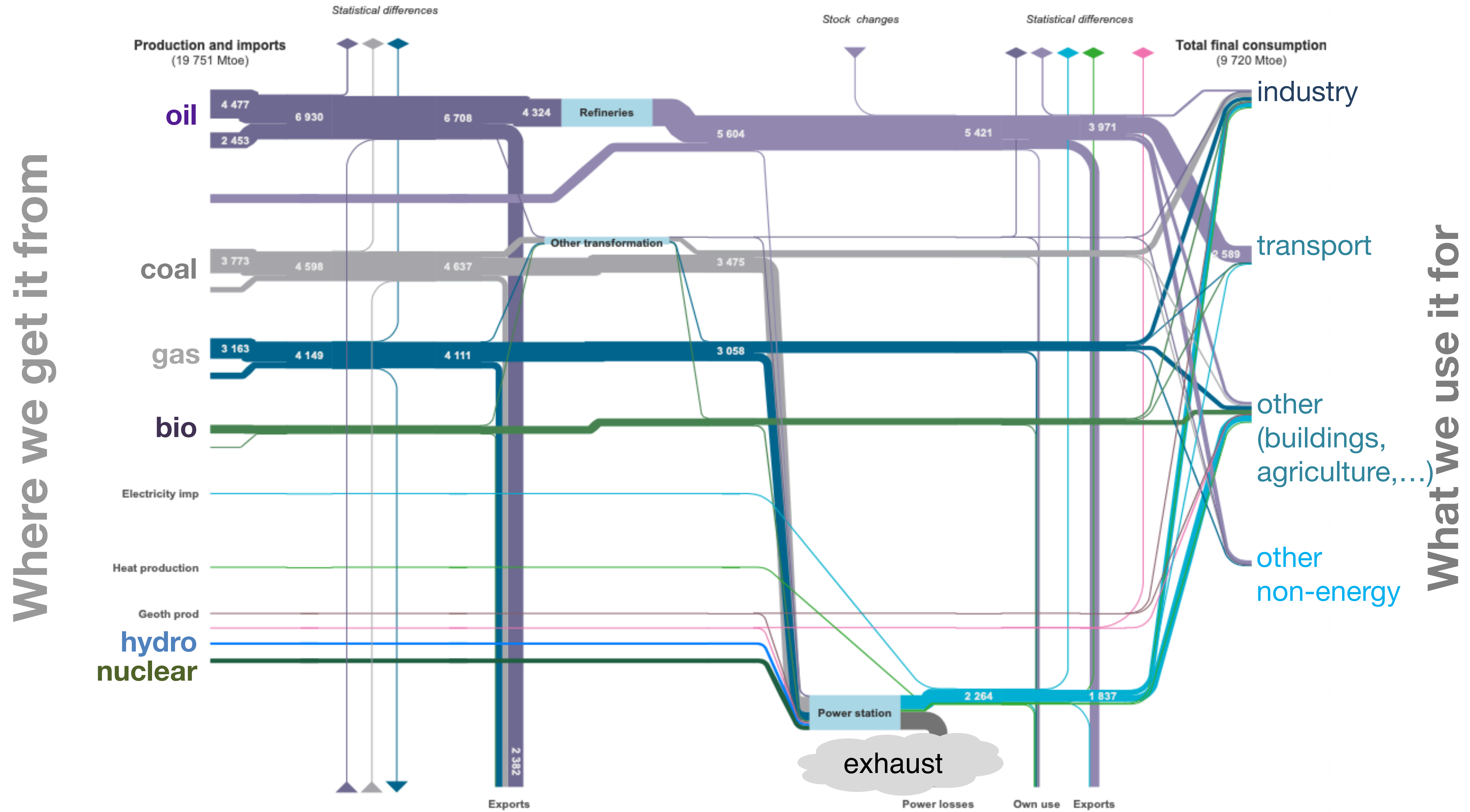
World[1] TPES from 1971 to 2017 by source (Mtoe)



One difficulty in replacing primary energy is the very large installed base of up to 80-90%.

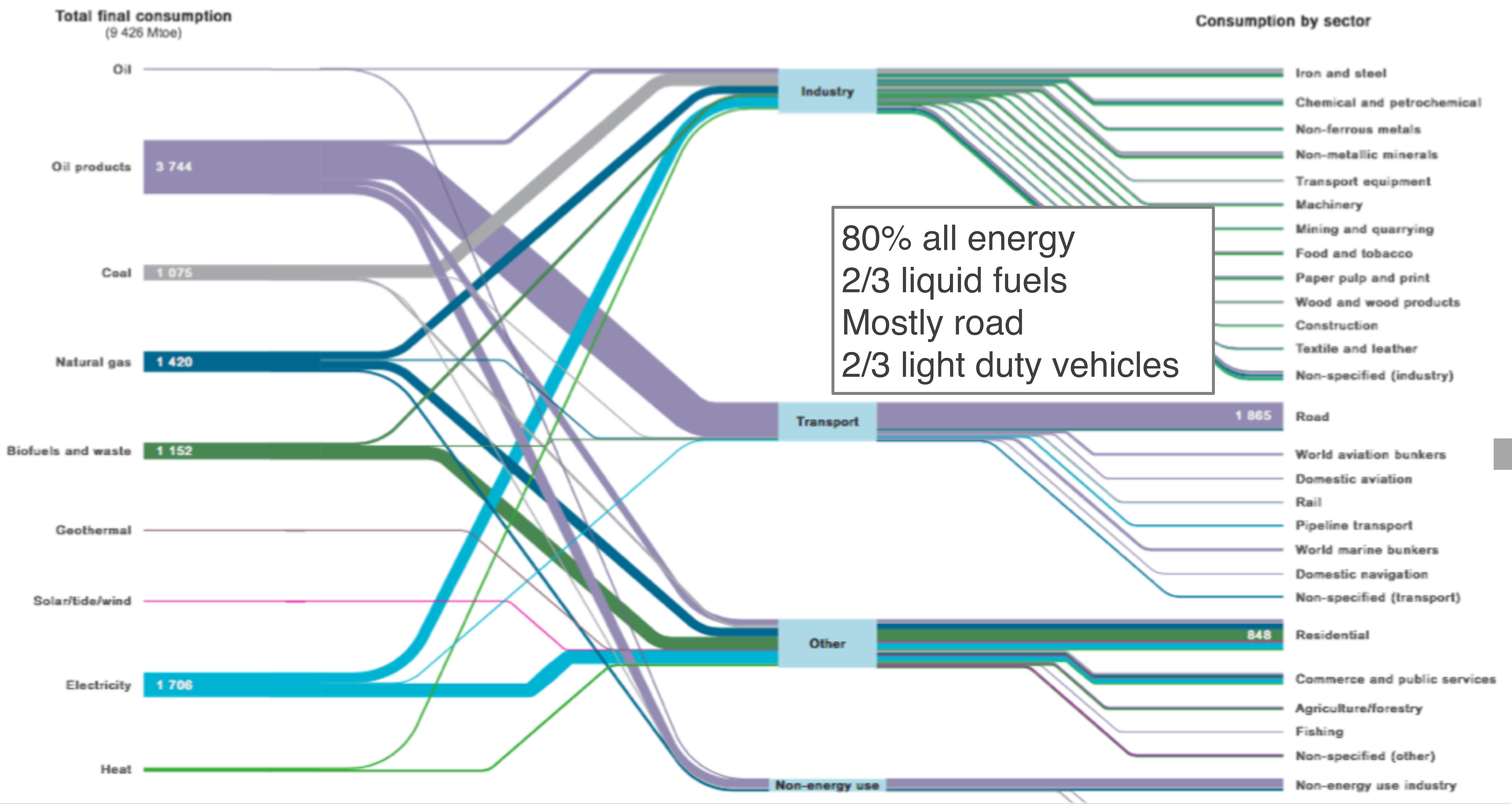
Source: IEA, 2019

BALANCE (2017)



World
Final consumption (2014)

Millions of tonnes of oil equivalent



80% all energy
2/3 liquid fuels
Mostly road
2/3 light duty vehicles

Transportation energy

Why are fossil fuels so popular?

Why are fossil fuels so popular?

7 cm

2 cm

Li-ion battery

Volume	20 ml
Mass	50 g
Energy	**10 Wh = 36 kJ**

200 Wh/kg

500 Wh/L

Petrol

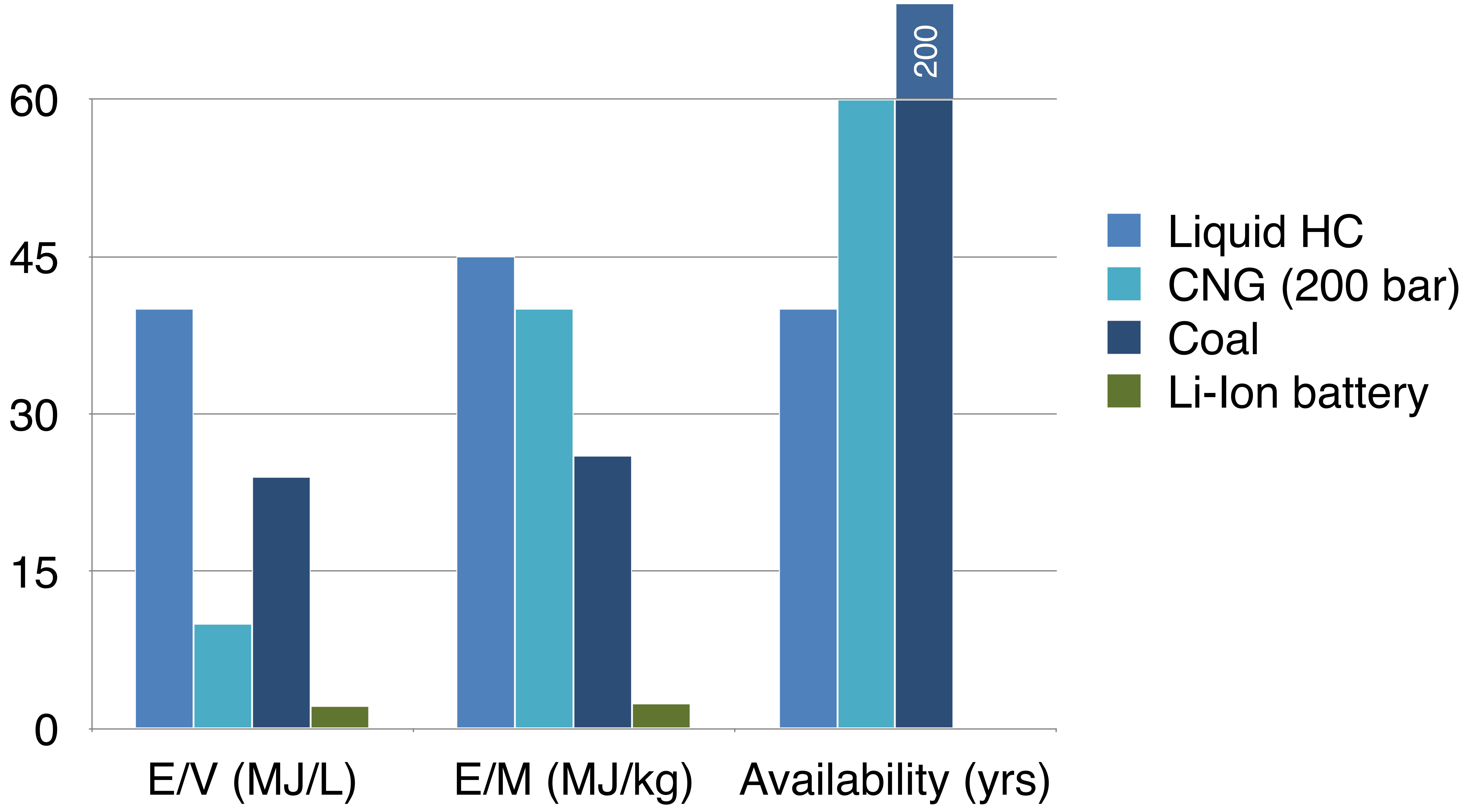
Volume	20 ml
Mass	15 g
Energy	**188 Wh ~ 680 kJ**

12,500 Wh/kg

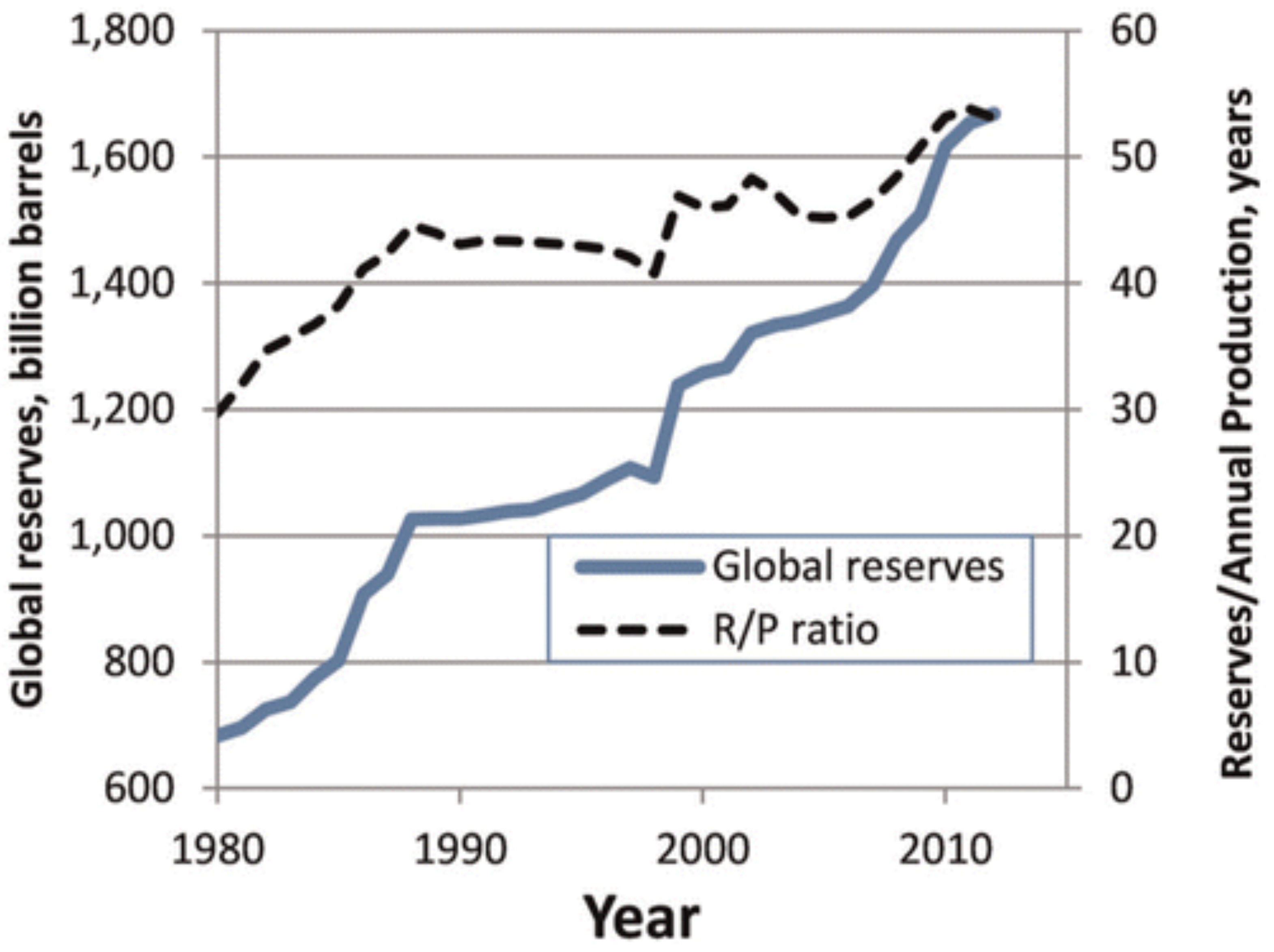
9,400 Wh/L

x 62 higher per mass
x 20 higher per volume

Fossil fuels are very energy dense and easily available



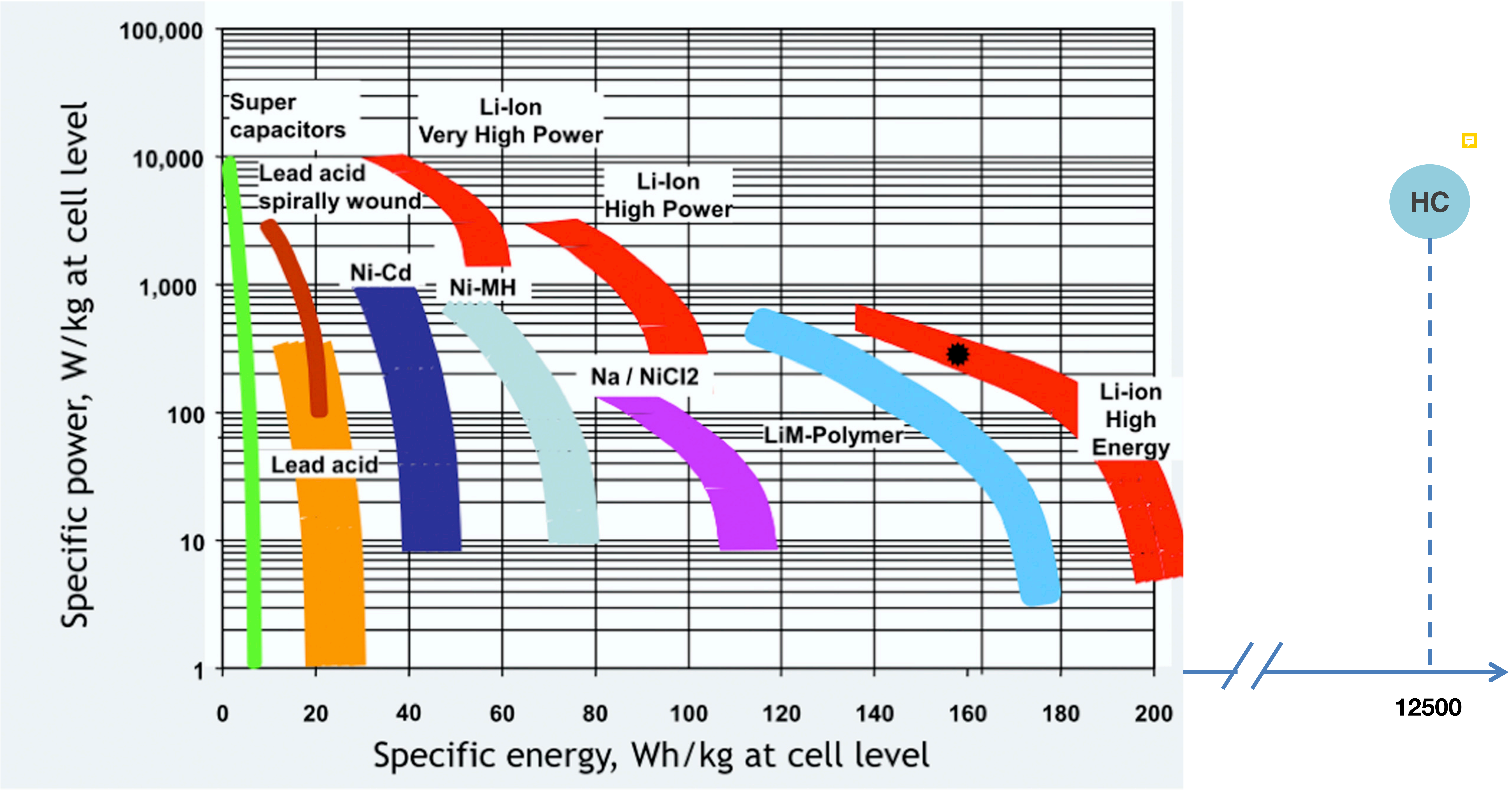
Oil reserves



Hydrocarbons have very high energy density

Simplest and lightest way from fuel to motion: thermo-mechanical conversion

Whereas batteries have tradeoffs in power available and maximum capacity

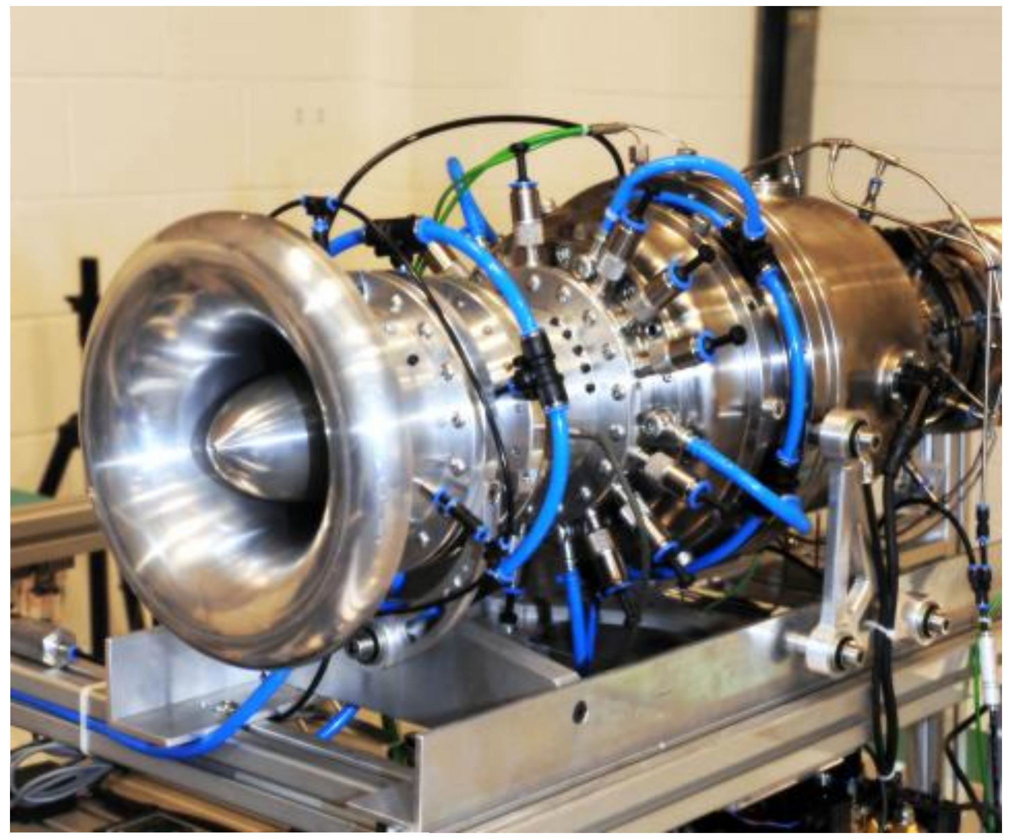


Why are reciprocating engines so popular?

Why reciprocate?

Low pressure ratio at small scales

High surface to volume ratio: high heat and viscous losses



BLADON JETS gas turbine

mazda rotary

Seal leakage limits compression ratio

Honda cvcc

BMW i3 range extender (647 cc)

Wärtsilä RT-flex96C
Bore 1 m x 2.5 m 2-stroke @ 100 rpm!

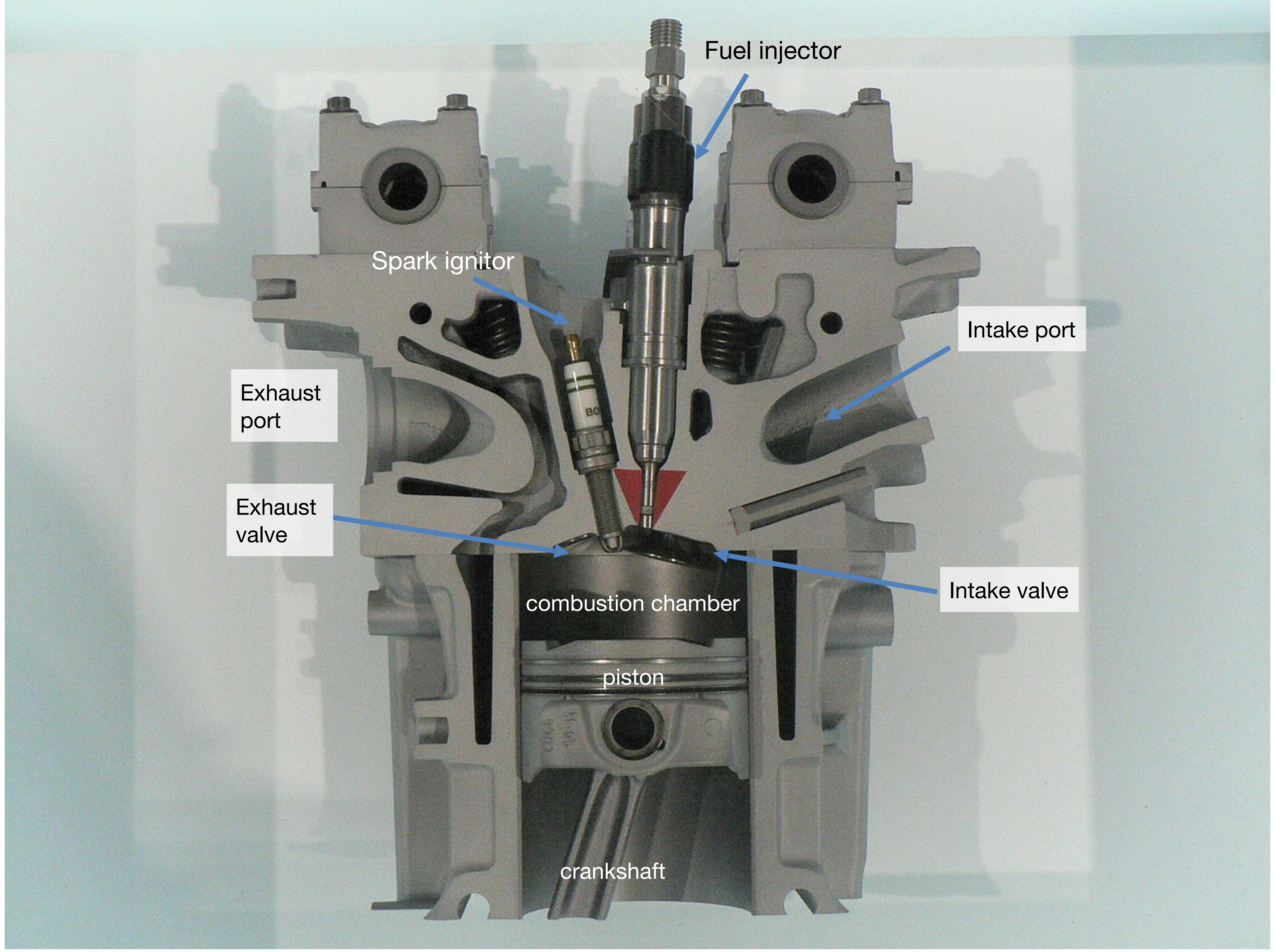
Highly scalable (number and volume)
Reasonably fuel flexible.

Good combination of simple design, scalability, robustness and efficiency

Spark-ignition engines

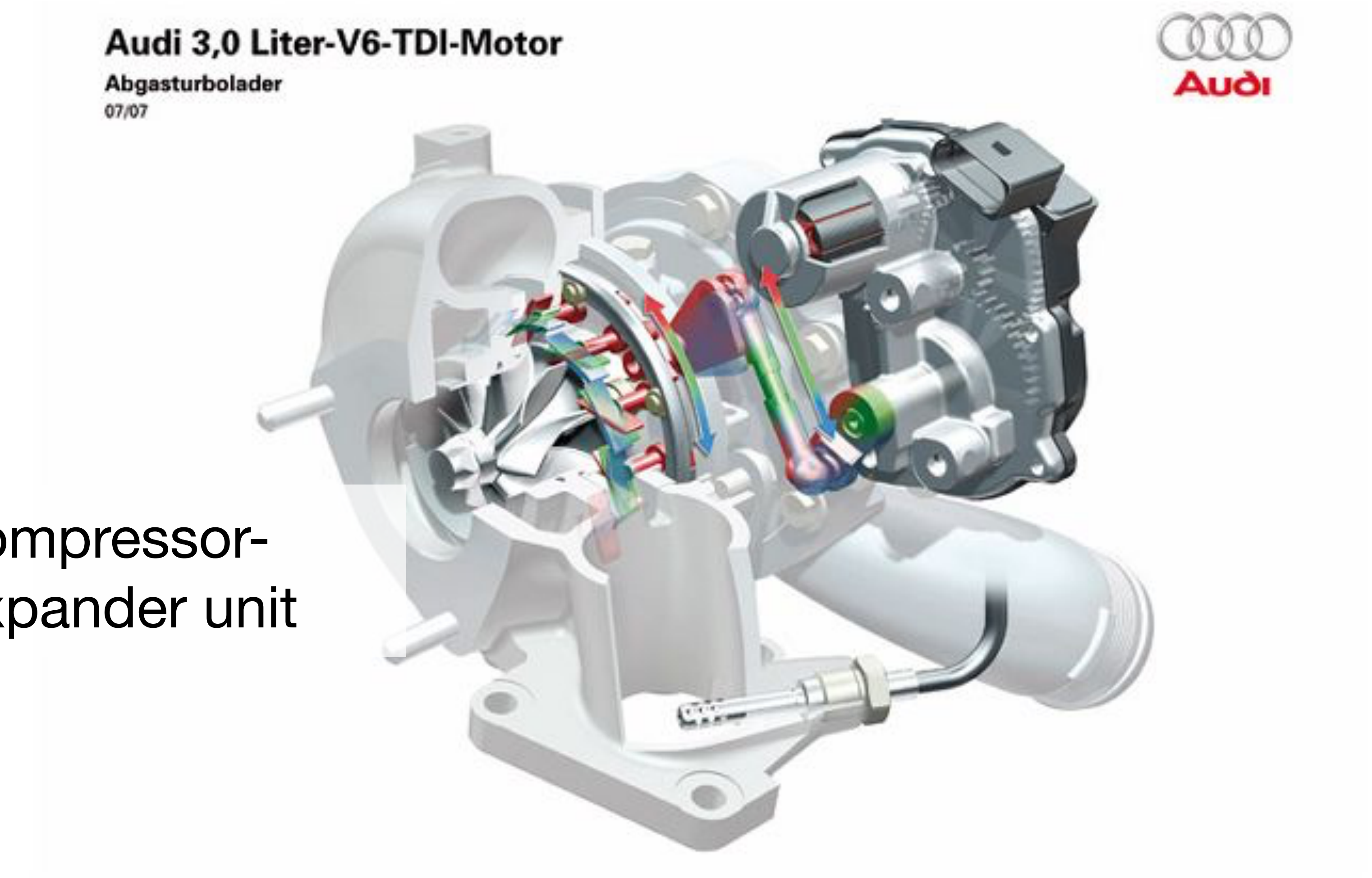
Port fuel injection

Spark ignition
- Injection: direct/indirect
- Fuel: resistant to autoignition
- Premixed stoichiometric charge (mostly)
- Peak efficiency: 25-30% (45% lab)
- High power density
- Emissions: HC, NOx
- Mid-torque at low speeds
- Lightweight



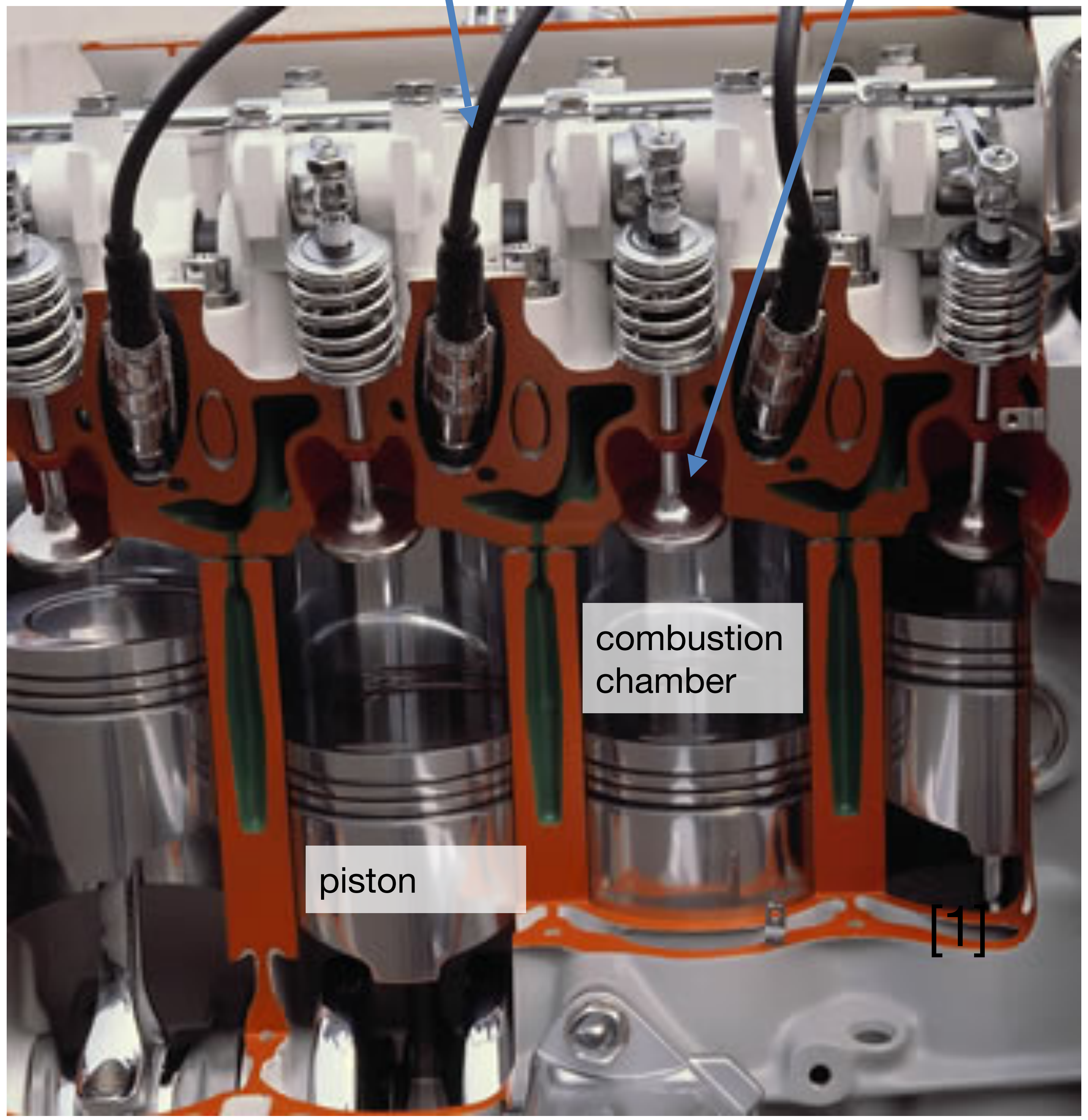
http://bmwmcmag.com/2013/01/bmw-i3-electric-car-to-get-bmw-motorcycle-engine-option/: Range extender: liquid cooled, inline, two cylinder from a C650GT scooter.
https://en.wikipedia.org/wiki/Fuel_injection#/media/File:PetrolDirectInjectionBMW.JPG

Compression-ignition engines



compressor-
expander unit

Compression-ignition
- Fuel: ignites easily
- Non-premixed to partially premixed lean
- Turbocharged
- Efficiency: 40-50%
- Key emissions: NOx, soot
- Mid power density
- High torque at low speeds

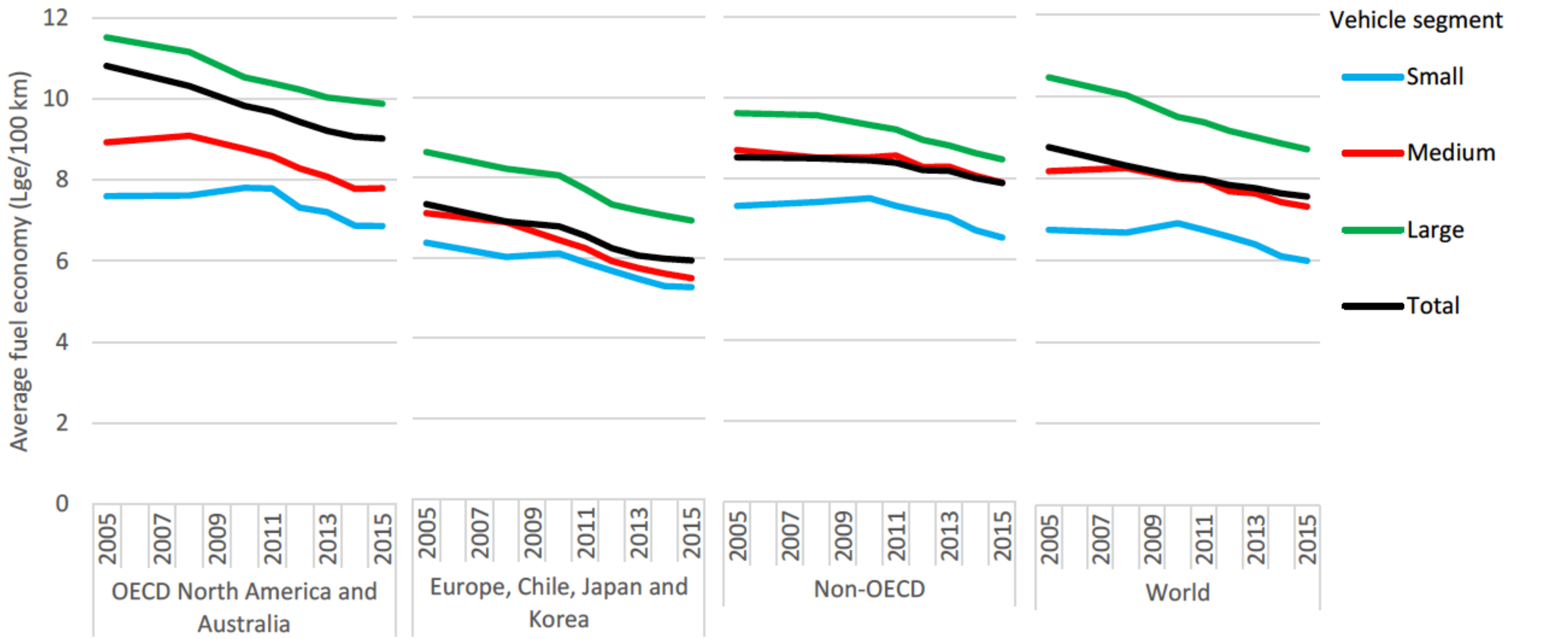


Spark-Ignition vs Compression-Ignition

	SI	CI
Ignition mode	spark	autoignition
Fuel	resistant to autoignition	autoignites easily
Charge	(mostly) premixed	(mostly) non-premixed
Load control	throttle	fuel injection
Turbocharging	seldom	always
Peak efficiency (%)	25-30	40-50
Compression ratio	6-11	12-24
Air/fuel ratio	Stoichiometric (ϕ = 1.0) (catalytic converter operation)	Lean (ϕ = 0.3-0.7) (soot limited)
Power density (kW/l)	20-60	5-26
Maximum bmep (bar)	7-10	5-20
Key emissions	NOx	NOx, PM

Average fuel consumption over the years

Figure 9 • Average fuel economy by segment, 2005-15

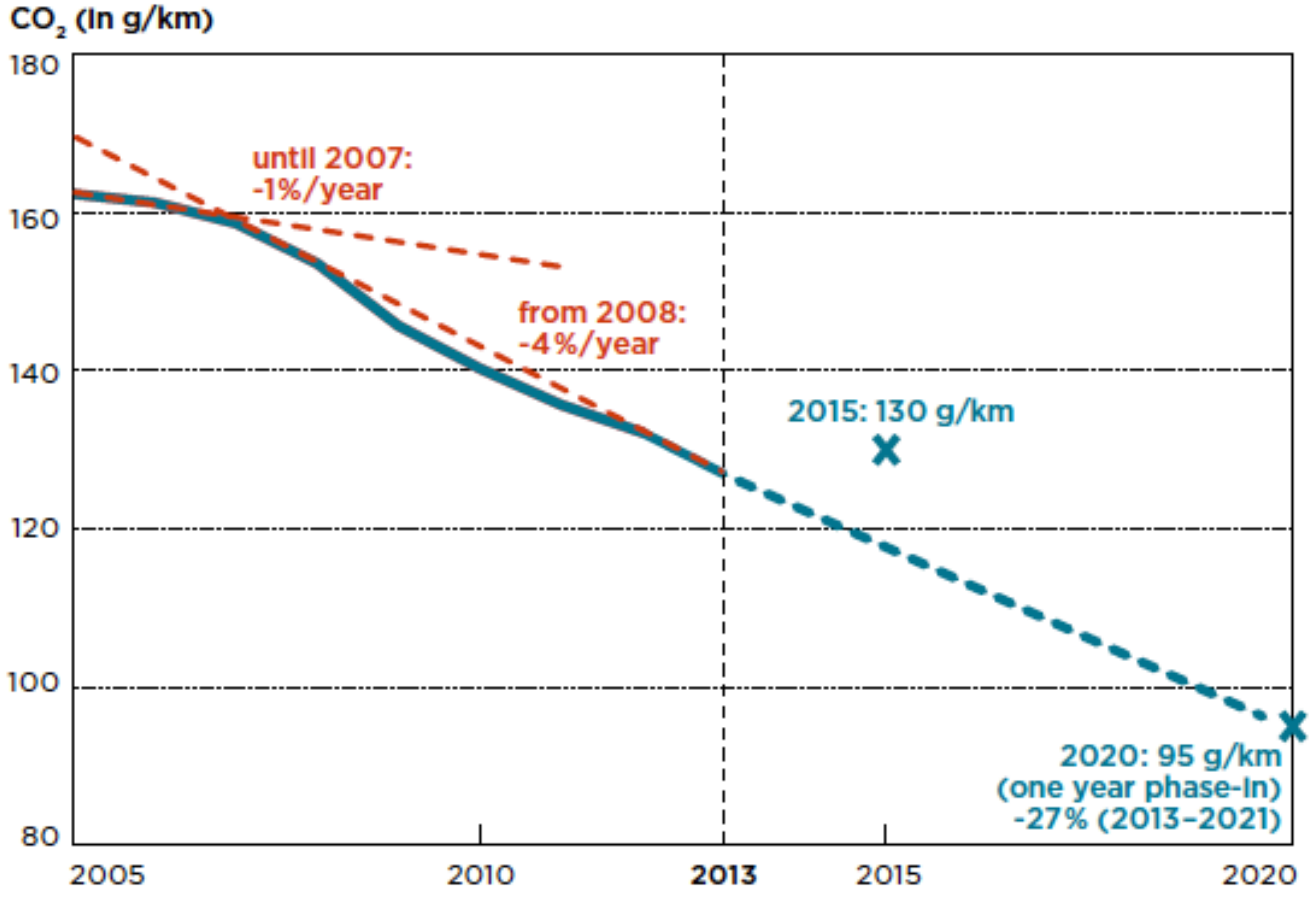


Source: IEA elaboration and enhancement for broader coverage of IHS Markit database.

Key point • Fuel consumption per km is lower in Europe, Chile, Japan and Korea than in all other clusters, even for similar market segments.

INTERNATIONAL COMPARISON OF LIGHT-DUTY VEHICLE FUEL ECONOMY 2005-2015, Working Paper 15, IEA, 2016

Evolution in vehicle fuel consumption efficiency



Europe

Mean fleet efficiency improving owing to regulation

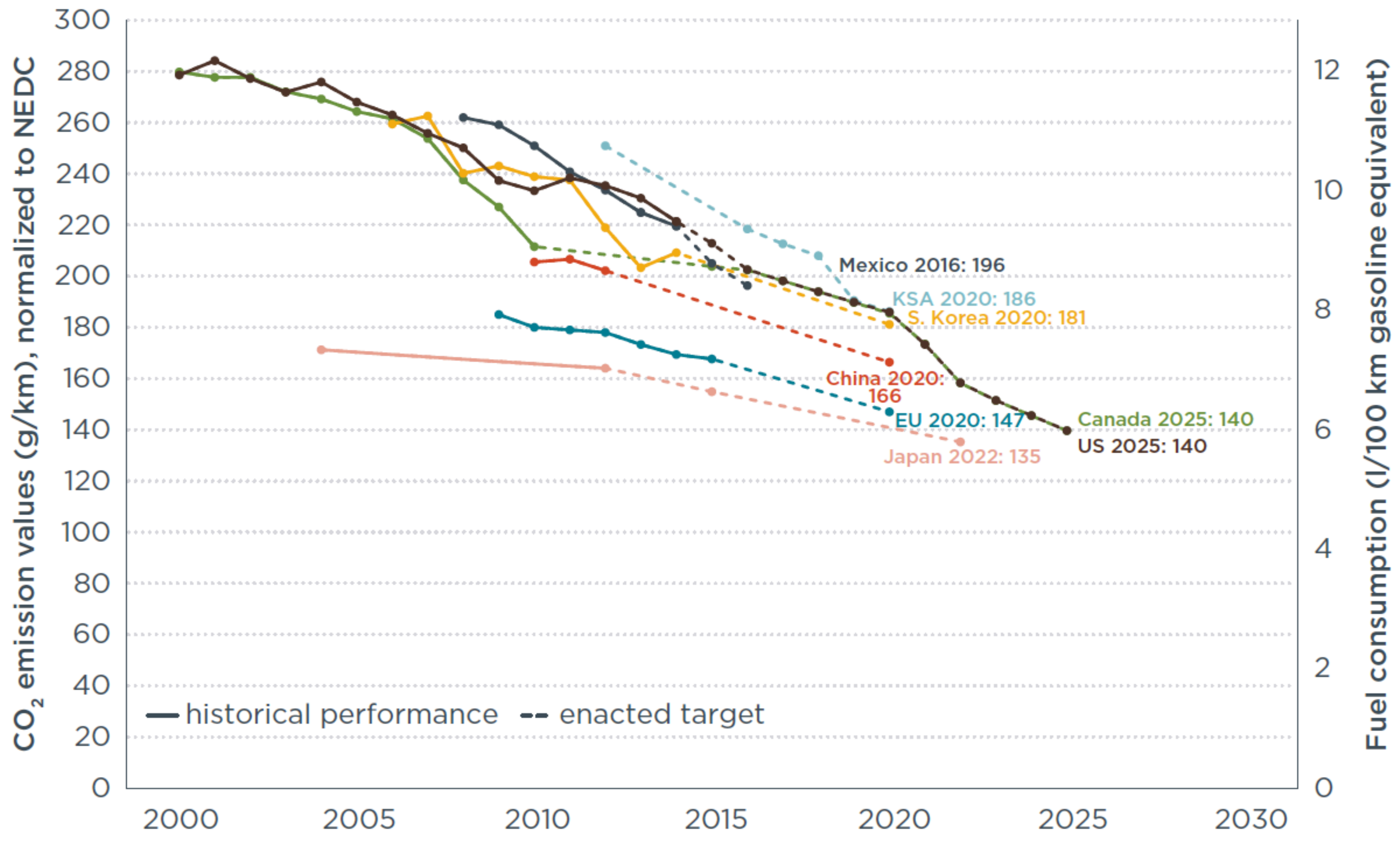
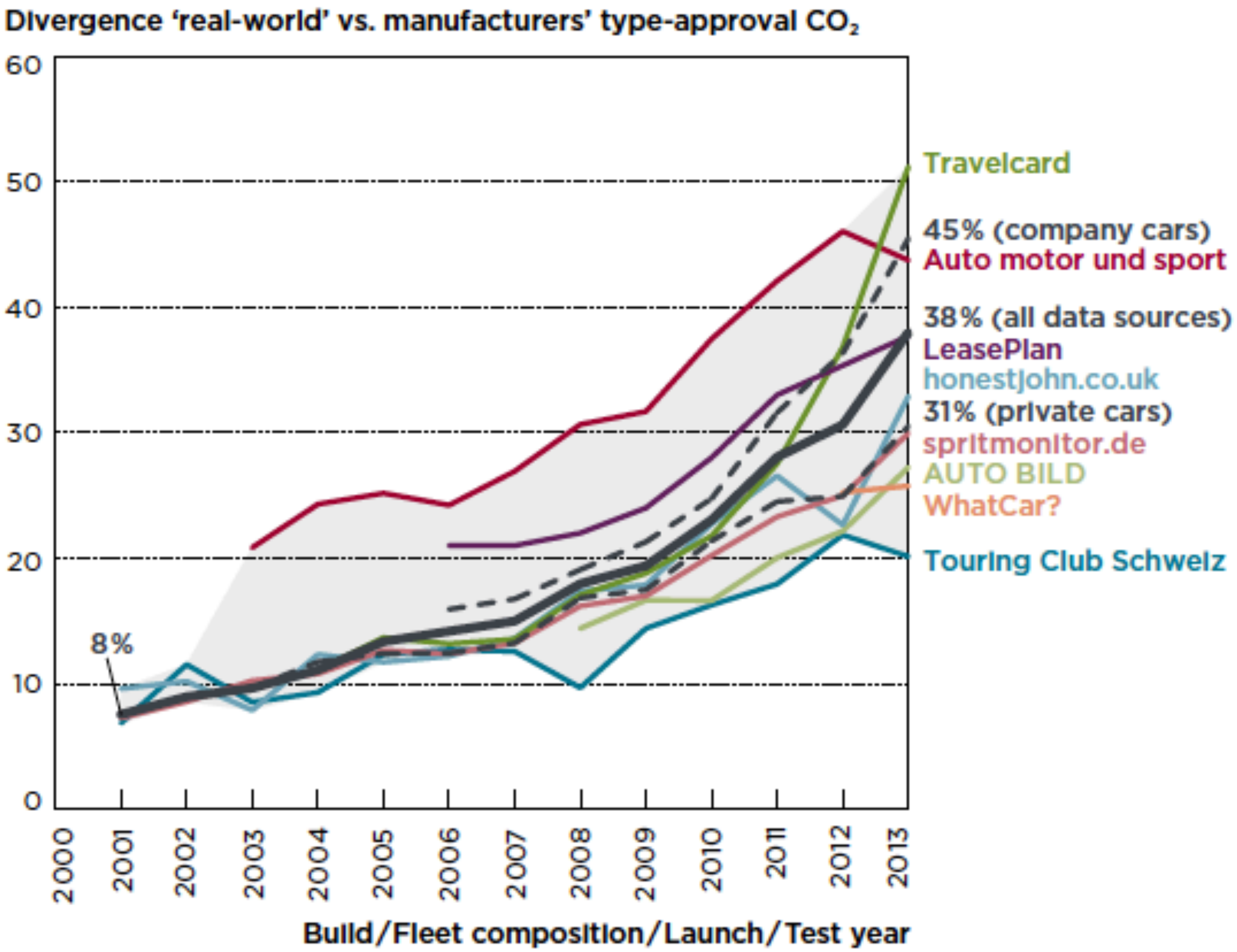


Figure 3. Historical fleet CO_2 emissions performance and current standards (gCO_2/km normalized to NEDC) for LCVs

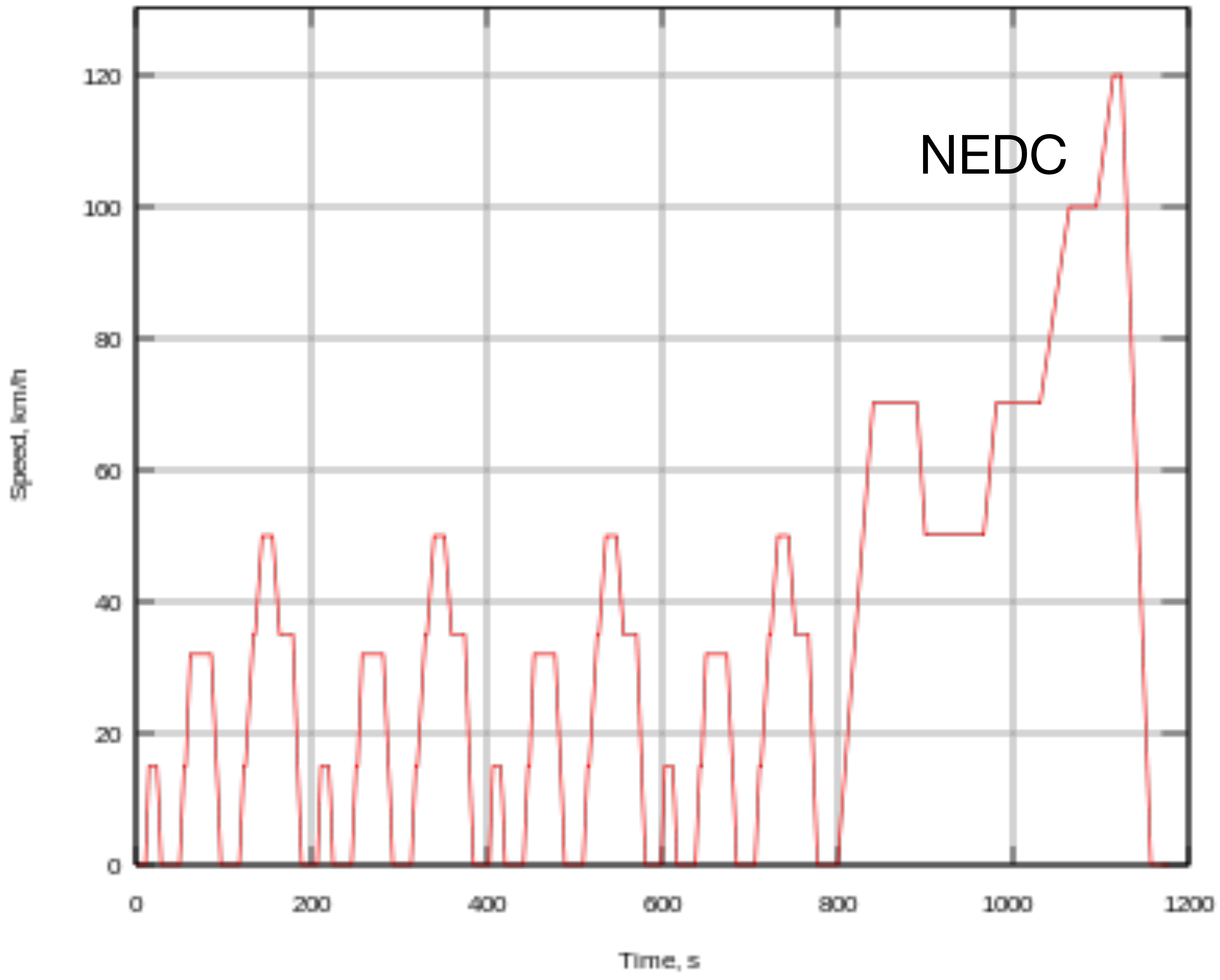
Source: International Council on Clean Transportation, 2015
2017 Global update: LIGHT-DUTY VEHICLE GREENHOUSE GAS AND FUEL ECONOMY STANDARDS
http://theicct.org

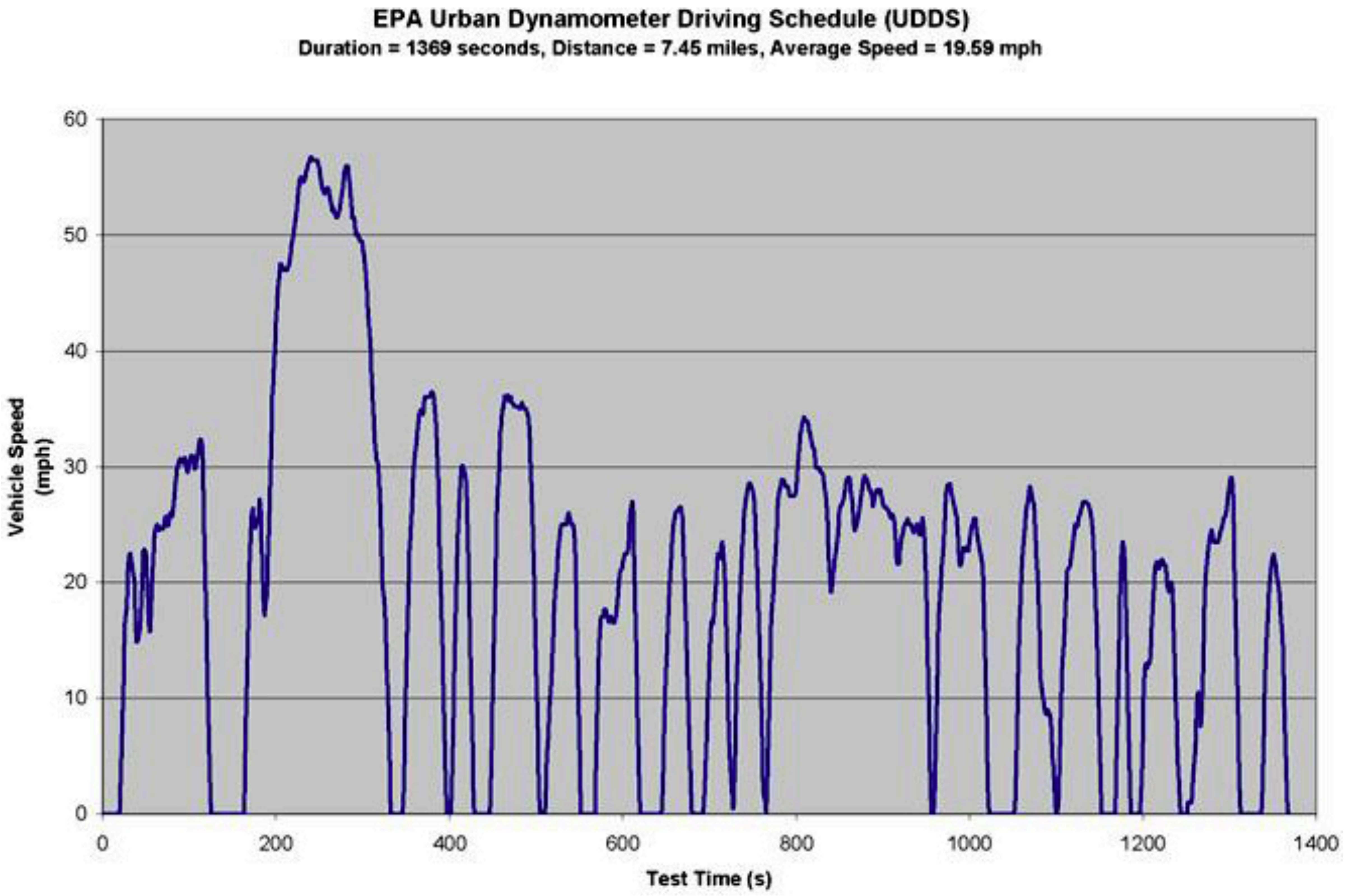
Efficiency in practice …



Source: International Council on Clean Transportation, 2015
http://theicct.org

Emissions Certification and Standard Driving Cycles





Used for certification: emissions & fuel economy

>2017: Real Driving Emission (RDE) to be used: RDE<2.1 x standard tests

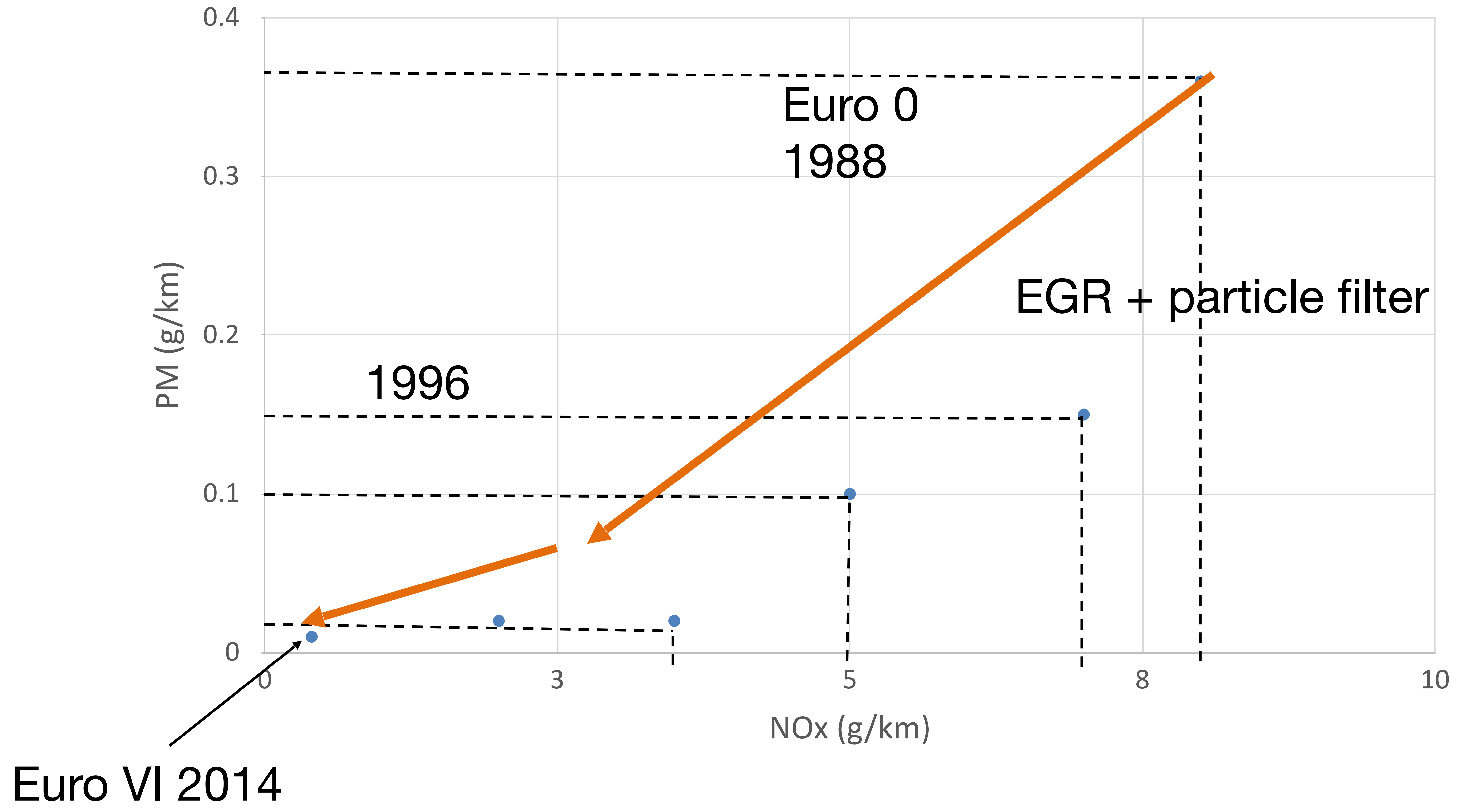
https://en.wikipedia.org/wiki/New_European_Driving_Cycle

https://www.epa.gov/sites/production/files/2015-12/emission-reference-guide-udds.jpg

Criteria emissions and testing in Europe

	Euro IV/V	Euro VI (current)	Euro 6 (current)	Euro 6 (WLTP/RDE)	
Test type	Engine dyno	Engine dyno	Chassis dyno	Chassis dyno	PEMS
Duty cycle	European SS, transient	World Harmonized SS (hot start), transient (cold+hot)	NEDC (transient, cold start)	WLTC (transient, cold start)	RDE test cycle on the road
Idling time (%)	6	17	23.7	12.6	6-30 (urban)
Average speed (km/h)	N/A (load 31%)	N/A (load 17%)	33.6	46.5	Urban (15-40), rural (60-90), motorway (>90)
Cold start test	No	Yes (14%)	Yes	Yes	Proposed
Off-cycle test	No	Yes (<0.6 g/KWh Nox)	No	No	Possible

EU PM and NO_x Emission Targets



Cooled EGR
High pressure, multiple injection
Variable geometry turbo
Selective catalytic reaction system

What about electric vehicles?

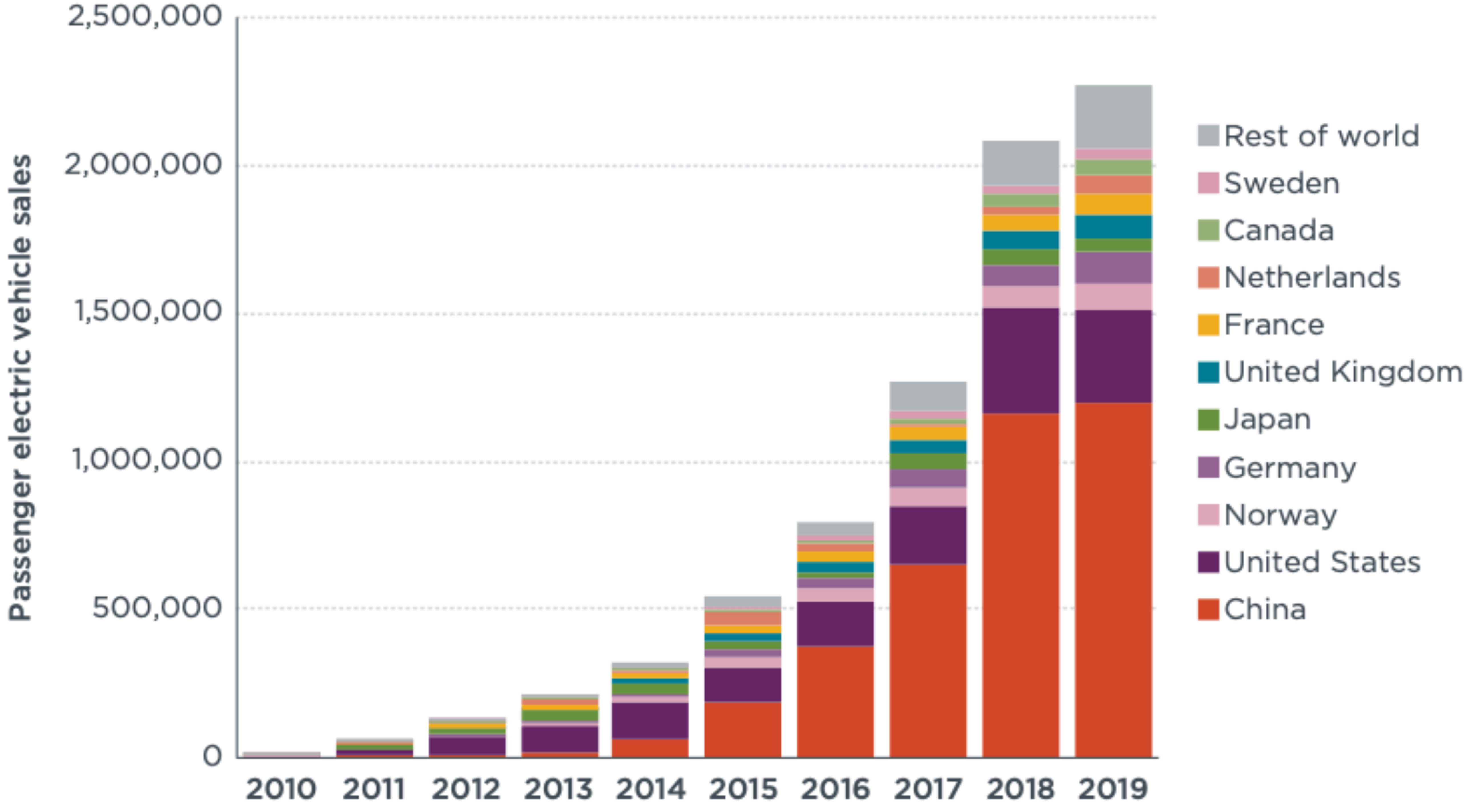


Figure 2. Annual passenger electric vehicle sales by markets from 2010 to 2019. Vehicle sales data from EV-volumes, 2019.

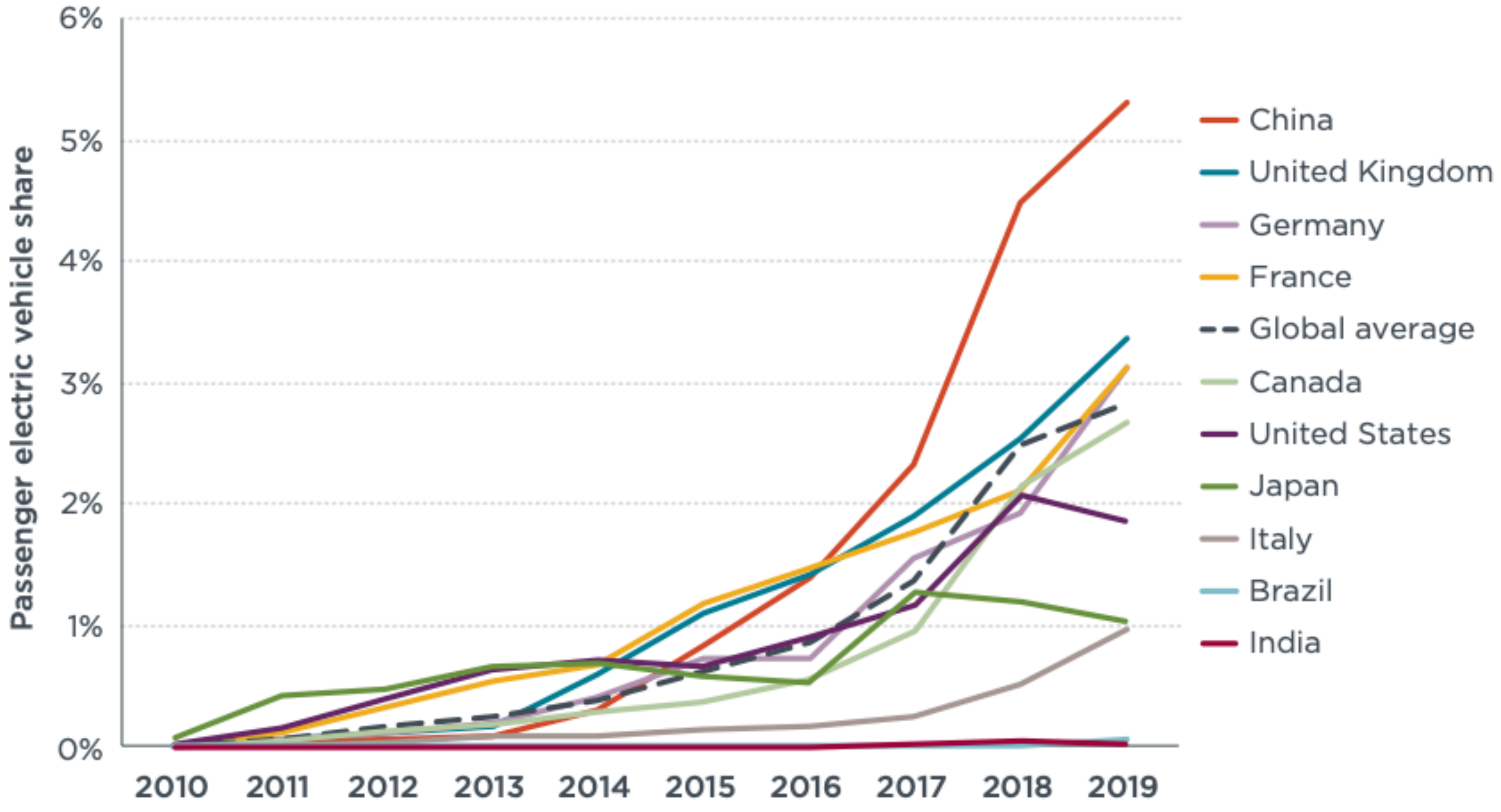
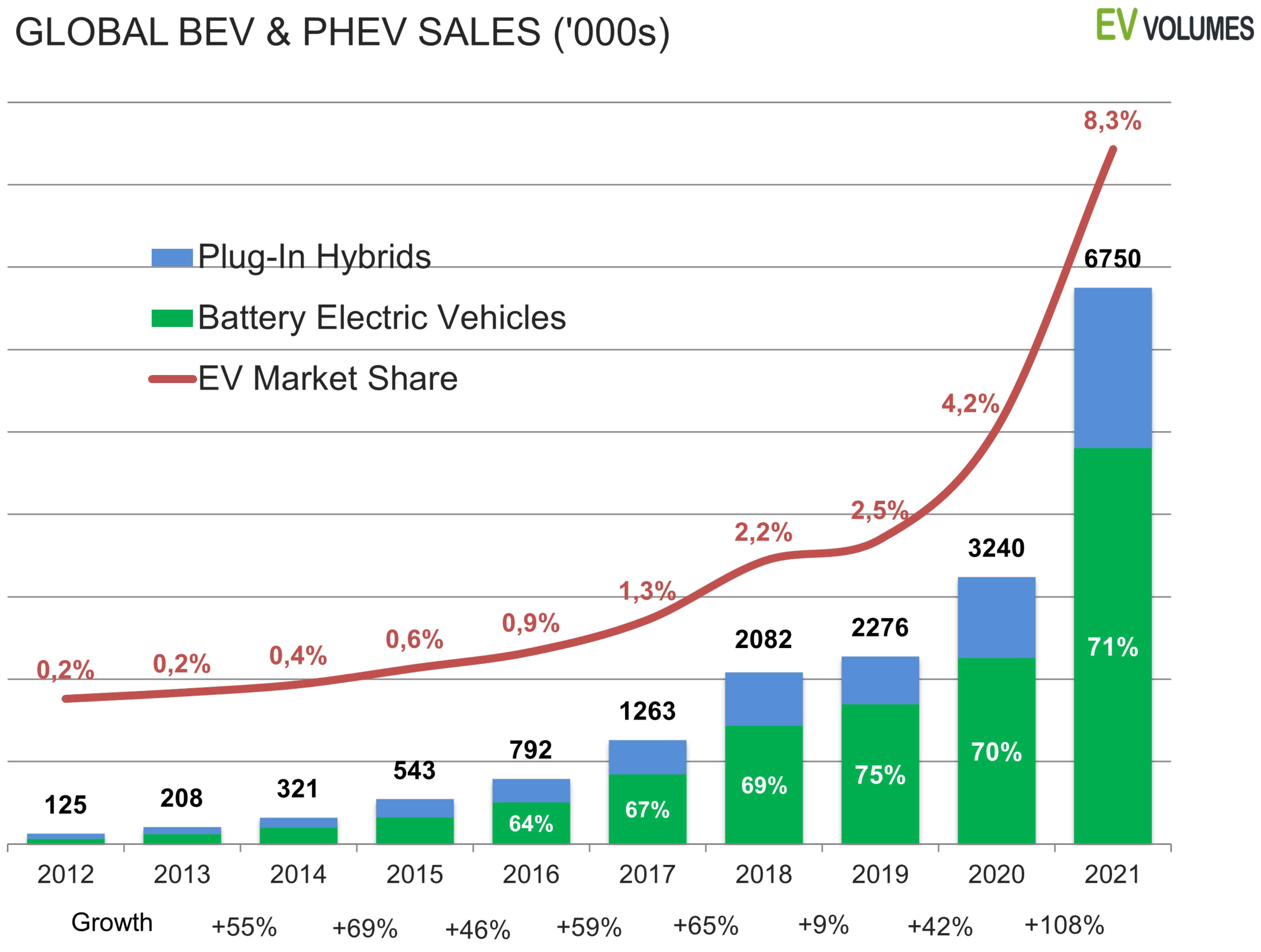


Figure 3. Electric vehicle shares of new passenger vehicle sales for largest markets. Vehicle sales data from EV-volumes, 2019.



https://www.ev-volumes.com/country/total-world-plug-in-vehicle-volumes/

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CO_2 emissions based on expected grid mix

Benefit of electrification significantly dependent on **decarbonisation of grid**

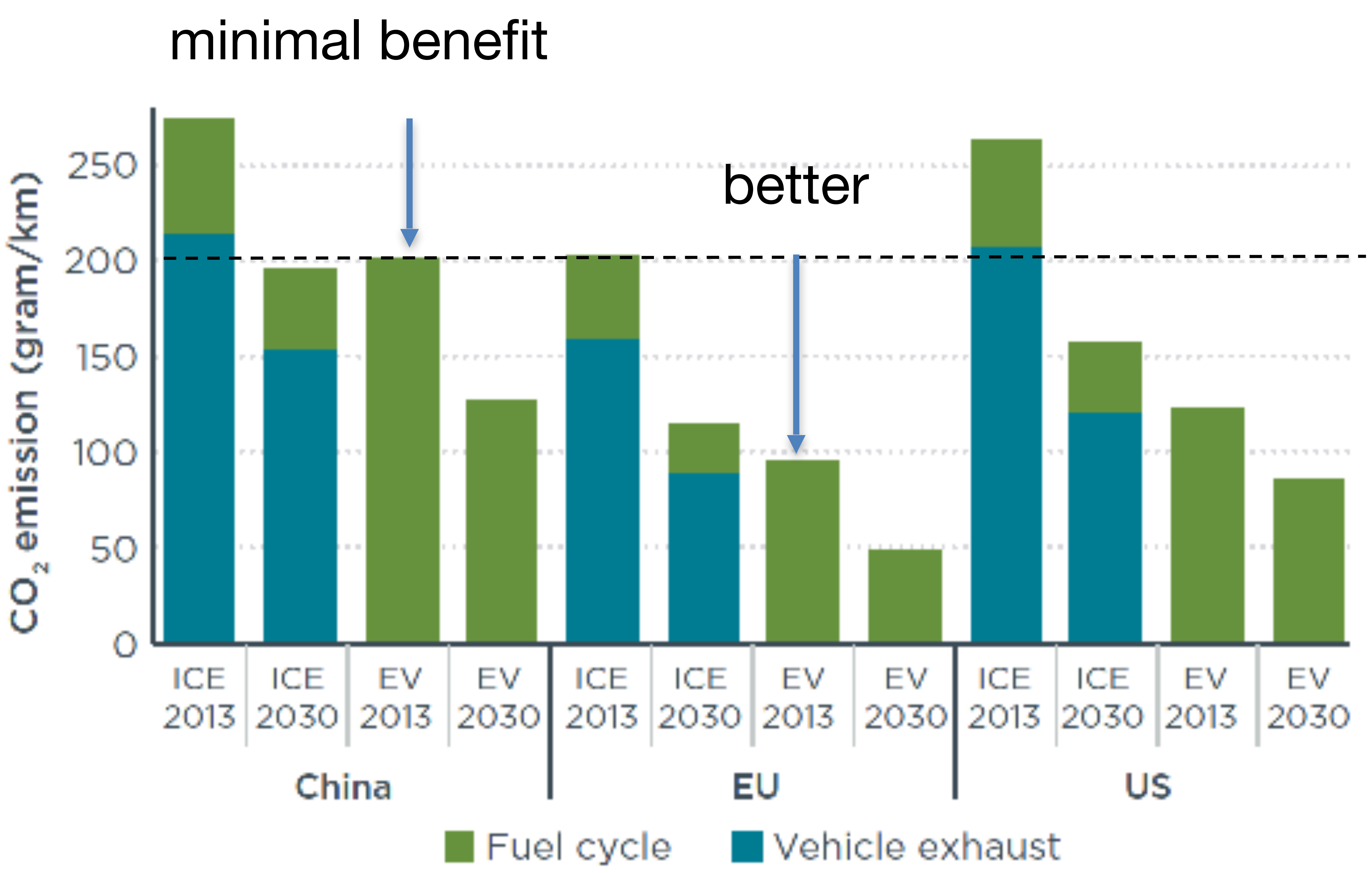

Figure 7. Vehicle exhaust and fuel-cycle emissions from conventional internal combustion engine and battery electric vehicles in select markets

http://www.theicct.org/sites/default/files/publications/ICCT_ghg-reduction-potential-evs_201512.pdf

Are IC engines disappearing by 2030?

Auto Express

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2030 petrol and diesel ban: what is it and which cars are affected?

New conventional petrol and diesel cars and vans will be banned from sale in the UK from 2030

by: Hugo Griffiths 11 Dec 2020

All new conventional petrol and diesel cars and vans are set to be banned from sale in 2030. New hybrids will be given a stay of execution until 2035, on the condition they are capable of covering a "significant distance" in zero-emission mode - a term which the Government has yet to define.

New plug-in hybrids will remain in showrooms for another five years, before being outlawed in 2035. The Government has also confirmed it will allow conventional hybrids, such as the Toyota Prius, to remain on sale until 2035, as long as they are capable of achieving the "significant" zero-emission distance.

Race is on as carmakers shut, switch or sell combustion engine factories

Manufacturers' share prices will be dependent on their ability to avoid losses on 'stranded assets', says analyst

▲ The production line of Volkswagen's ID.4 electric sport utility vehicle in Zwickau, Germany. Photograph: Jens Schlueter/Getty

- most of the to-be announced legislation bans petrol-only engines; hybrids likely to continue
- significant investments by vehicle manufacturers, especially on batteries could change landscape

Quiz

https://www.vle.cam.ac.uk/mod/quiz/view.php?id=11738932

Summary

- Transportation represents 1/3 of total energy consumption and GHG emissions
- IC engines responsible for 80-90% CO_2/fuel needs in transportation
- Potential for improvement in powertrain and emissions still pushing boundaries, at a cost (topic of this paper)
  - Modified cycles
  - Hybridisation
- EV/hybridisation clearly beneficial, at a cost: key CO_2 benefits depend on grid decarbonization