Thermoelectric heat recovery in automotive applications: is it feasible?

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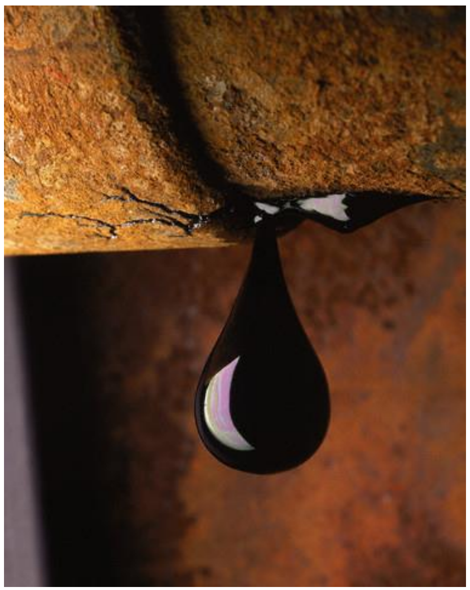
Drivers for sustainable road transport

Economic crisis

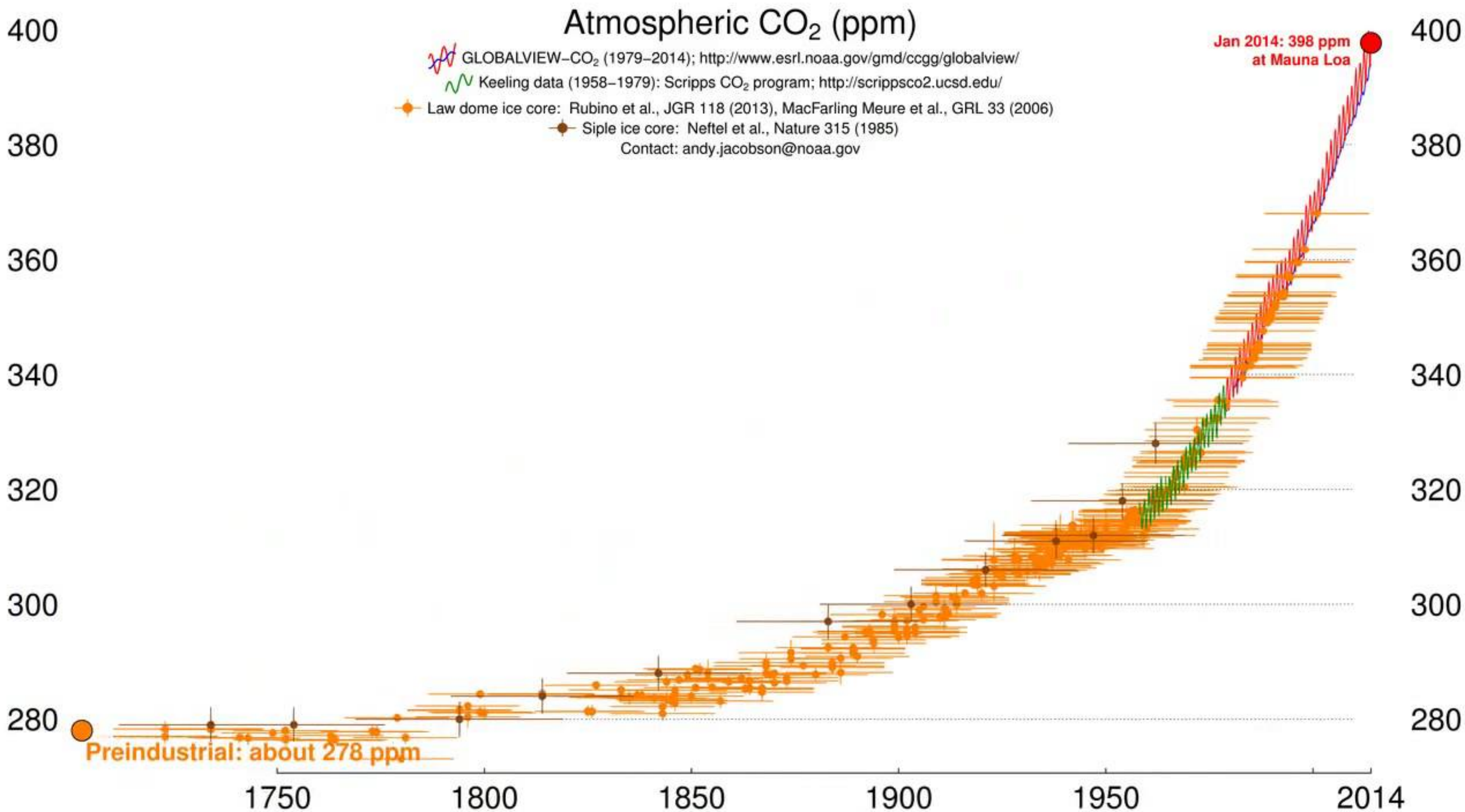


Resources

Climate change

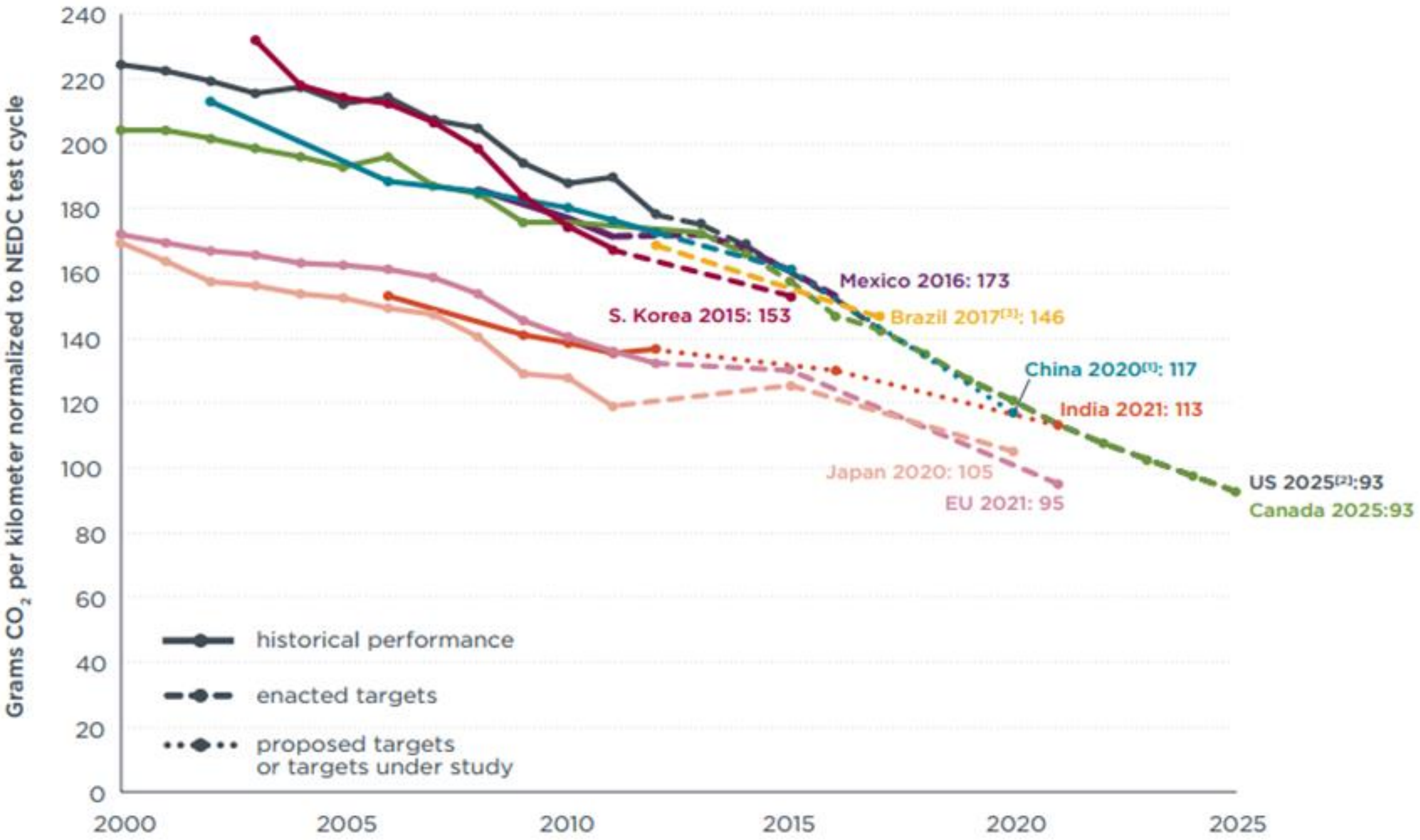
Noxious emissions

Reduction of CO_2 emissions



The concentration of CO_2 in the atmosphere is constantly growing from the beginning of the industrial era. The reduction of CO_2 emissions is mandatory for reducing the global warming and the related climatic changes.

Reduction of CO_2 emissions



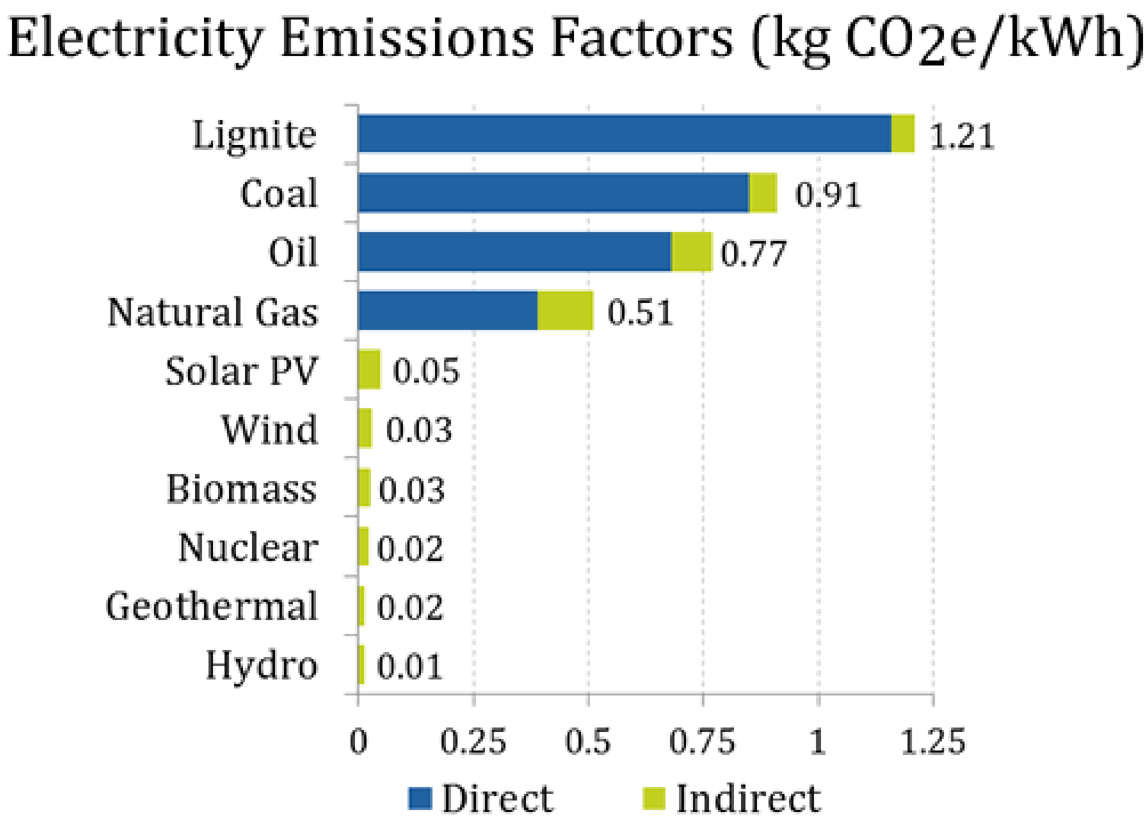
CO_2 emissions from passenger cars in Europe have to be reduced to **95 g/km by 2021** (**OEMS will pay €95** per exceeding gram of CO_2)

Is electrification a solution to reduce CO_2 emissions?

1. Carbon footprint of electricity production

2. Use of raw materials

Carbon Footprint of production of electricity

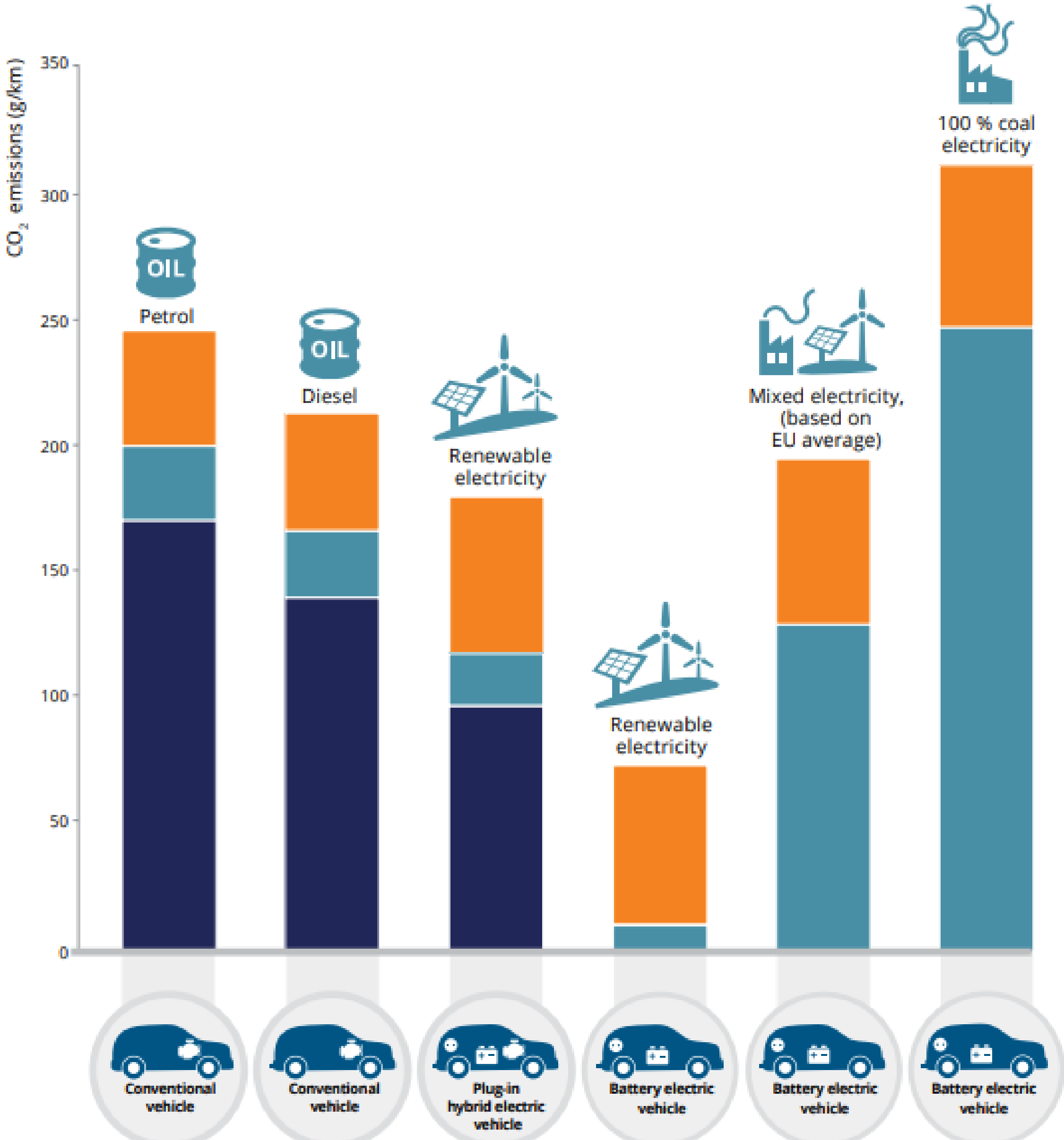


Note: Direct emissions are from fuel combustion, indirect emissions are from plant manufacturing and fuel supply processes. The biomass estimates assume the neutrality of combustion emissions over the carbon cycle.

Sources: World Energy Council - Comparison of Energy Sytems Using Life Cyle Assessment 2004

The **carbon footprint** of electric vehicles strongly depends on how the electric energy is produced

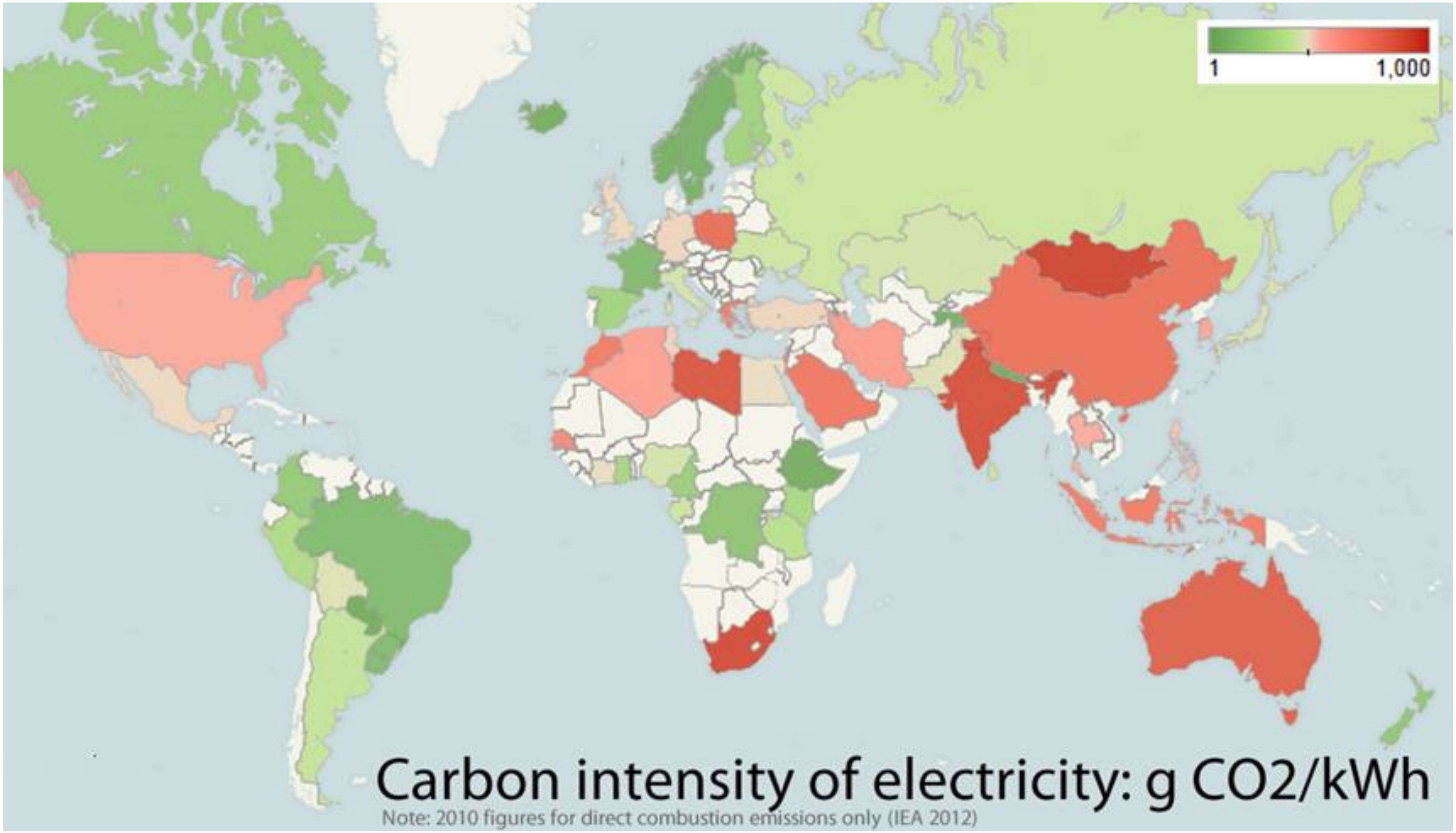
Carbon Footprint of vehicles



Source TNO (2015)

The values are estimated for an average mid-class vehicle, based on 220 000 km.

Carbon Footprint of production of electricity



In some countries electrification would worsen the current situation!

Noxious emissions

Electric vehicles don't emit **noxious emissions** (ZEV, Zero Emission Vehicles) and would mitigate the pollution in urban areas.

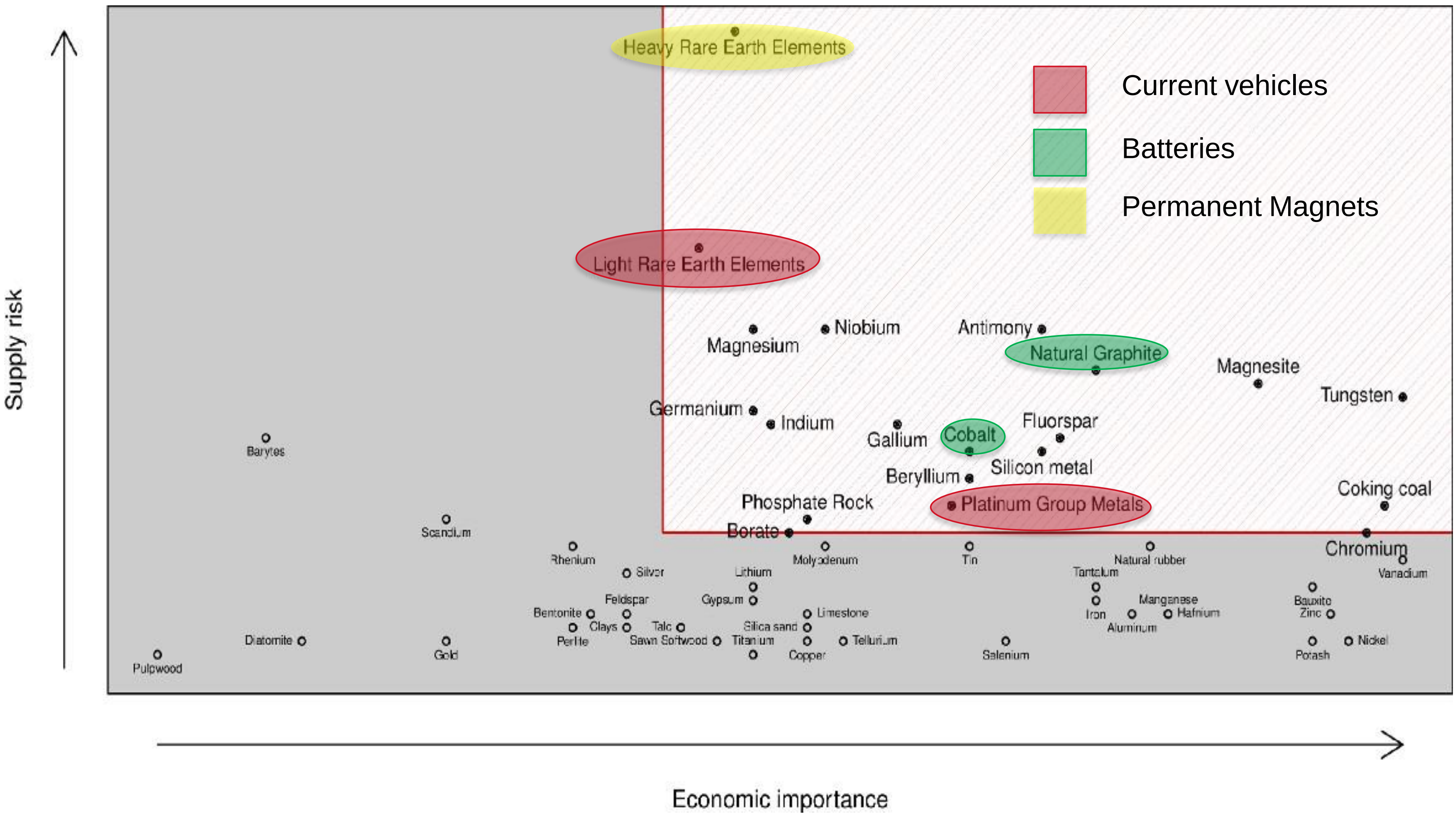
Critical raw materials

Environmental impact of **battery production** → Li-ion batteries require the use of **critical raw materials** (cobalt and graphite).

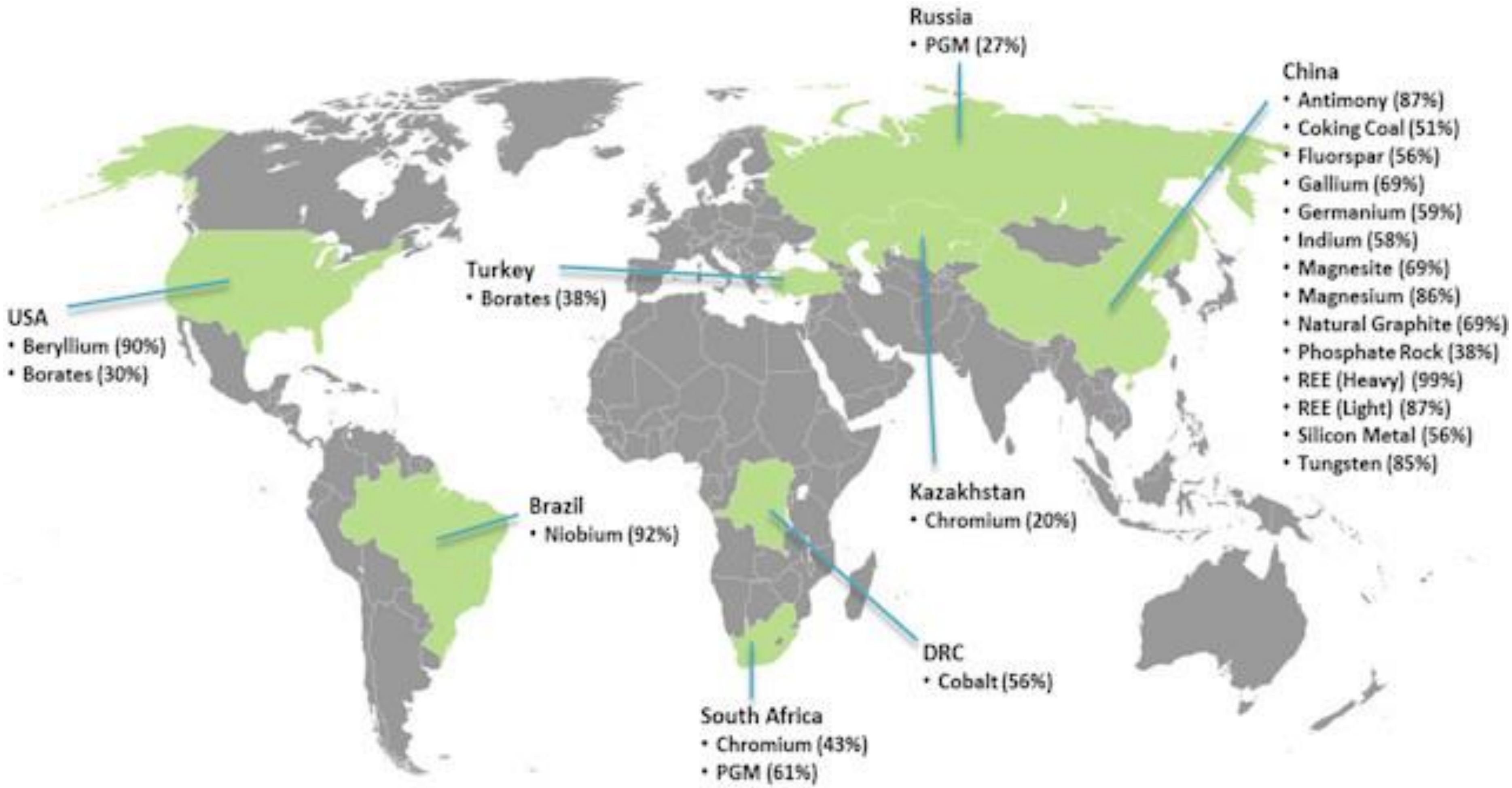
Critical Raw Materials (CRMs) are economically and strategically important raw materials for the European economy but characterized by a high risk associated with their supply. These raw materials are not just critical for industrial sectors and new technologies, but also for a sustainable future of the European economy. The European Commission has drawn up a list of CRMs based on the following criteria:

1. **High economic importance** for **key sectors** of the European economy (transport, electronics, defence, health)
2. **High supply risk**: very high dependence on extra-EU imports and high concentration of reserves in particular countries
3. **Lack of valid substitutes**: peculiar non-replaceable properties (eg precious metals PGM for catalysis)

Critical Raw Materials

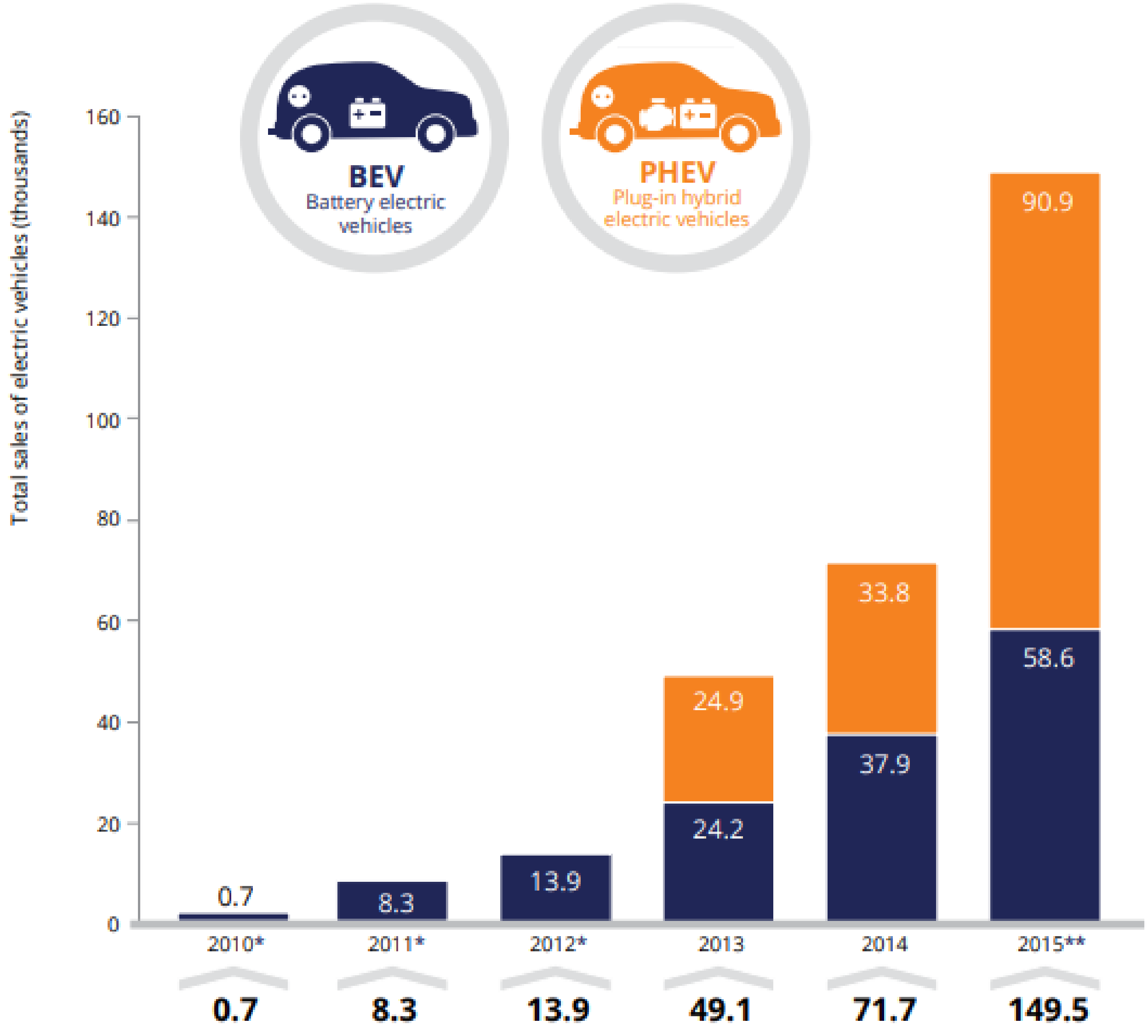


Critical Raw Materials



Cobalt is mined in the Democratic Republic of the Congo in not ethical conditions
→ «**conflict mineral**»

Total sales of electric vehicles in the EU-28



Source: EEA (2016).

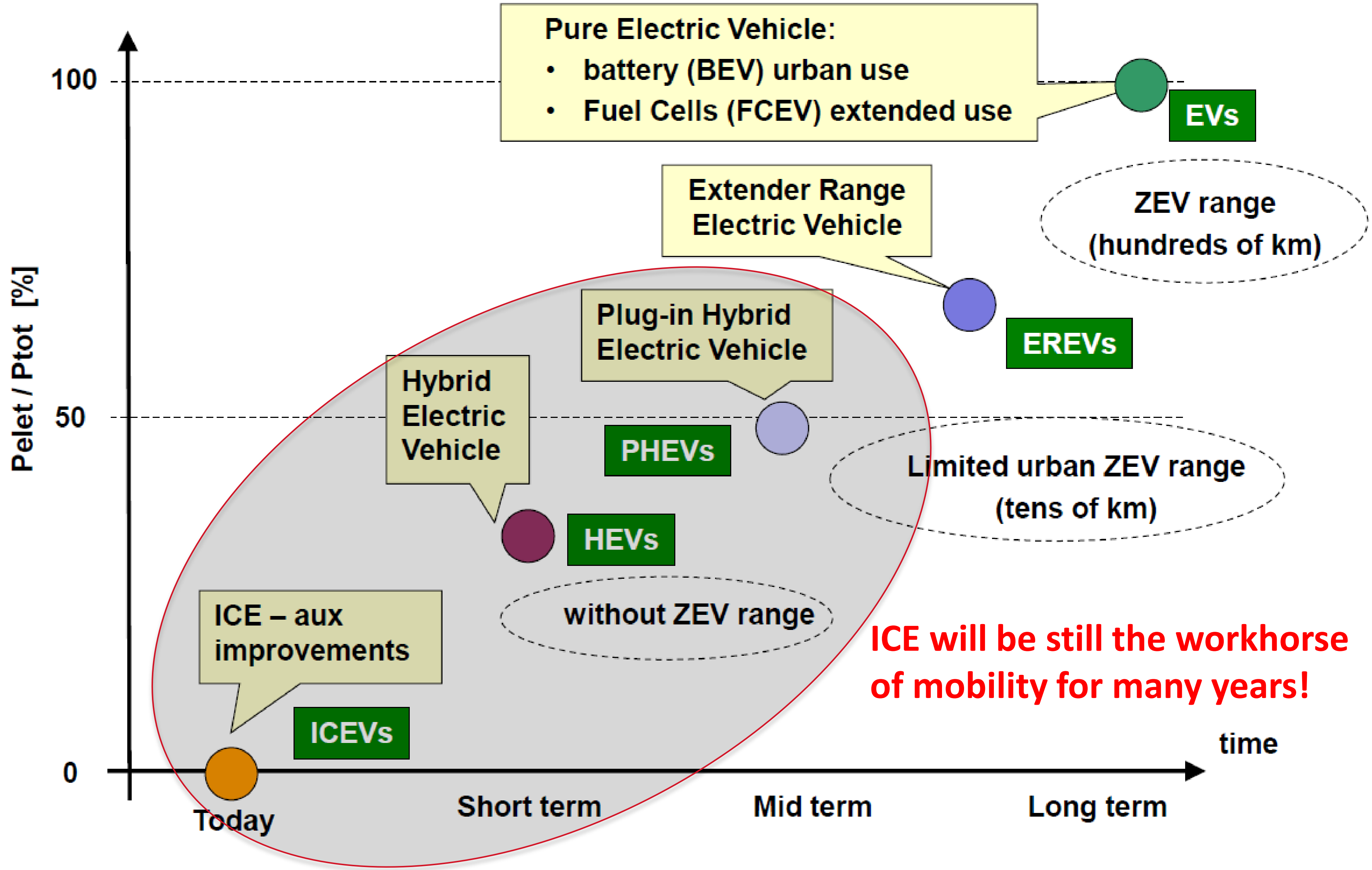
Sales of APV in the EU-28

Source: ACEA (2018).

Heat recovery from ICE?

Does it **still** make sense?

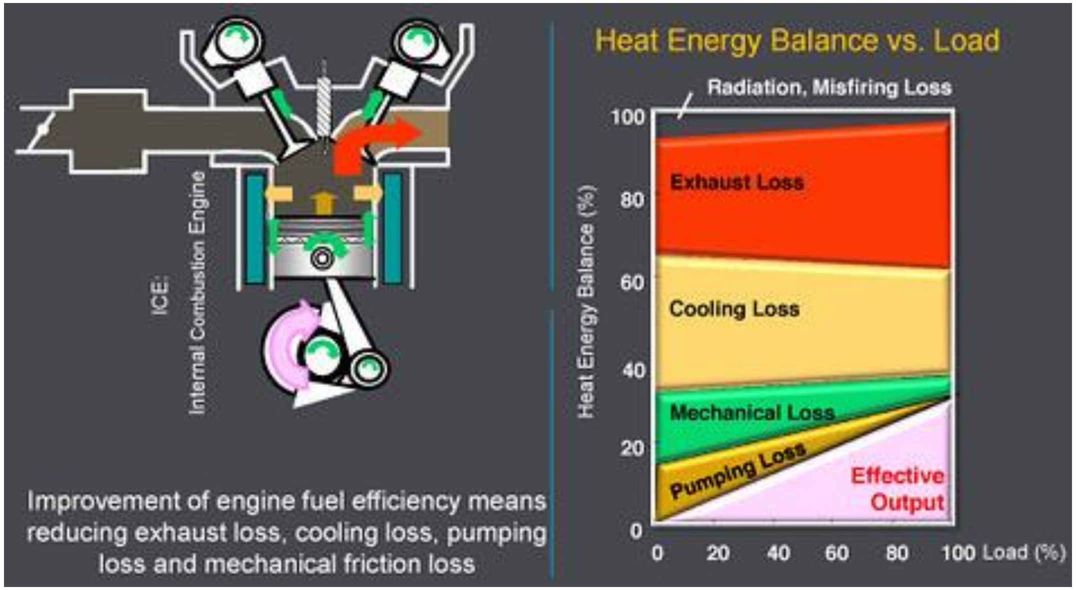
Roadmap for the electrification of vehicles



ICE will be still the workhorse of mobility for many years!

Internal combustion engine: energetic analysis

Energetic analysis of Internal Combustion Engine (ICE) vehicles



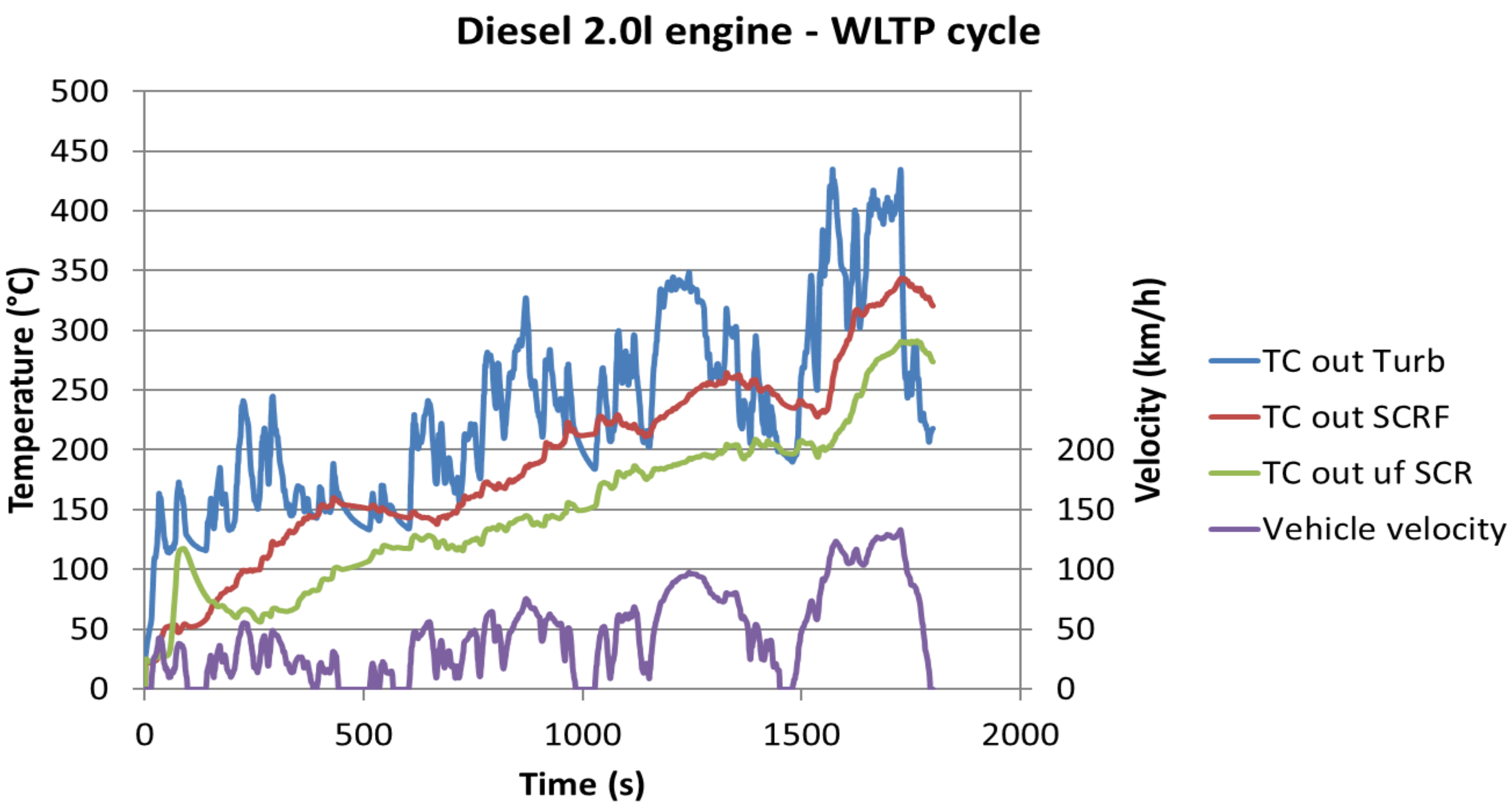
Source **Mazda**

- About **25-30% of fuel energy is lost as heat in exhaust gases**
- For an engine with a nominal 100kW power, about 30 kW of heat are dissipated in the exhaust gases
- The temperature of exhaust gases has a medium value of 500°C with peaks at 700°C, so it is an high temperature source that can be used to feed thermodynamic cycles

Automotive requirements

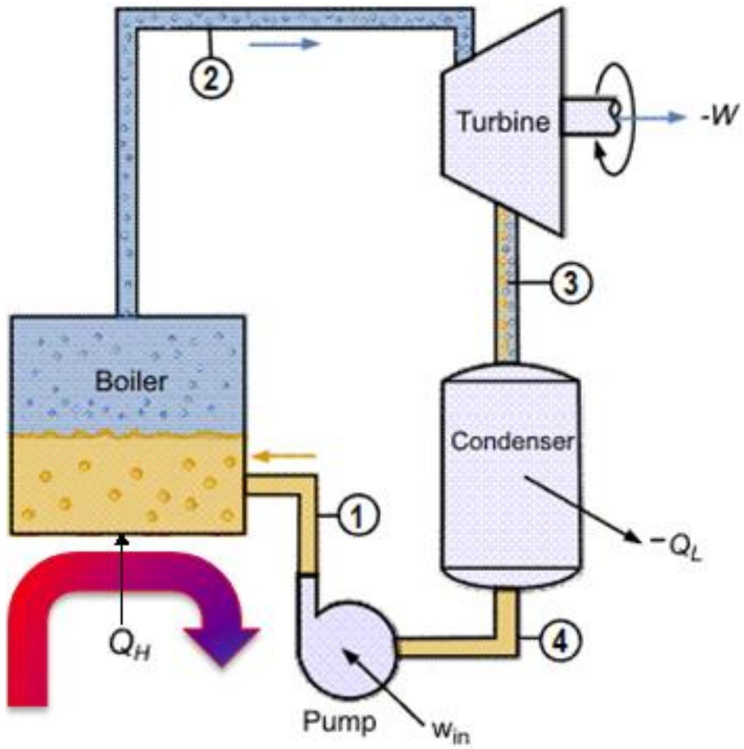
- **Low cost**
- **Limited space** to install added equipment
- Resistance to **shock and vibration**
- Environment **temperature range**: −40°C to 50°C
- **Thermal shock**: Exhaust gases steps from 20 to 400-500°C in less than 2 min at vehicle start-up
- **Thermal cycling**—Average 1500 cycles per year for at least 10 years, more cycles for frequent short trip driving or hybrid vehicles
- **Long life**
  - Minimum design life 10 years or 150000 Km
  - Target 20 year life and 220000 Km
- **Exposure** to a wide variety of fluids (water, coolant, exhaust gases, oil, etc.) either internally or externally. Example, hot units splashed with cold salt water during winter driving

Exahust gases temperature



The available peak thermal power for is about 23 kW. **And it is completely lost!**

Heat recovery with Rankine cycles



1) The working fluid is pumped into a boiler where it takes the heat $\mathbf{Q_H}$ by **exhaust gases** to become vapour. Since the fluid is pumped as a liquid, little input energy W_{in} is required.

2) The vapour is sent to a turbine where it expands generating power **W** and decreasing its temperature and pressure.

3) The liquid/vapour mixed phase is condensed to liquid in a condenser dissipating the heat Q_L
.

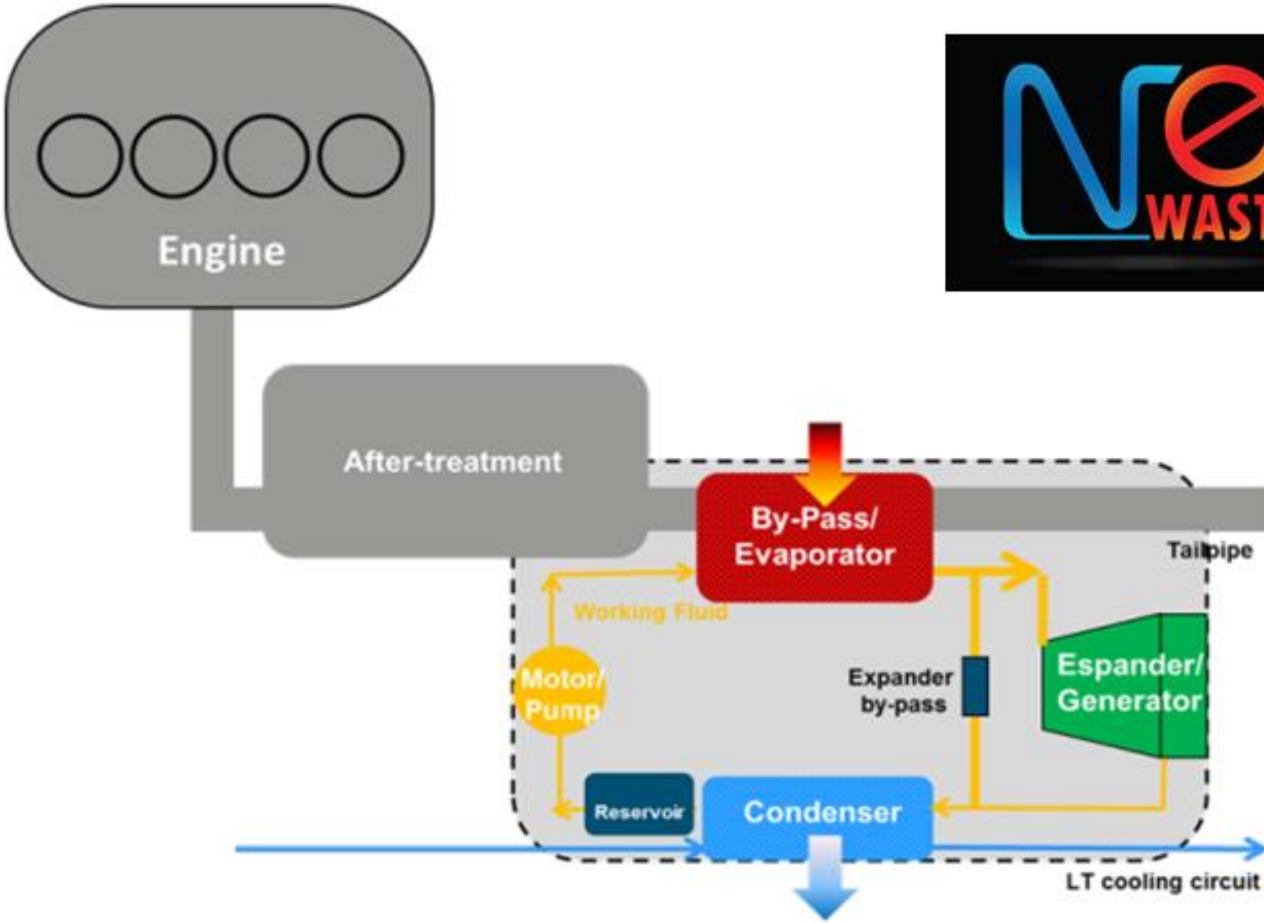
4) The liquid is sent back to the pump.

Rankine cycles on vehicles (*):
- BMW obtained 10% additional power at highway speeds on a conventional ICE
- Honda improved the thermal efficiency of hybrid vehicles by 3.8%

Drawbacks:
- High volume and weight
- Reduced reliability (moving parts: turbine, pump)

(*) J. Ringler, M. Seifert, V. Guyotot and W. Hübner. (2009) Rankine Cycle for Waste Heat Recovery of IC Engines (SAE 2009-01-0174)

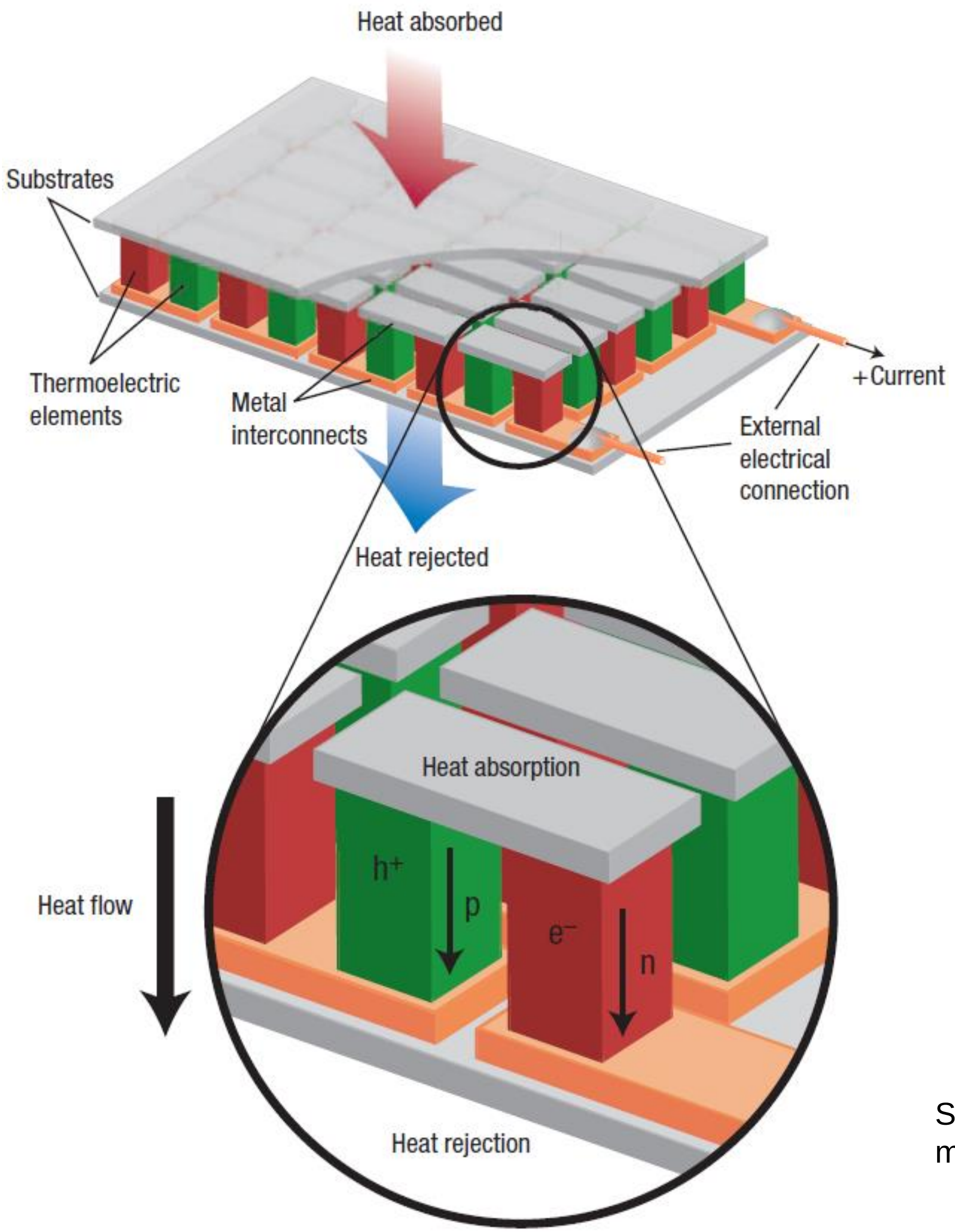
Heat recovery with Rankine cycles



In the No-Waste project CRF developed a waste heat recovery system based on an **Organic Rankine Cycle (ORC)** designed for commercial vehicle application. The system delivered an electric power output of ~2 kW with an efficiency between 2.4 and 3.8% depending on the engine load.

(*) "NoWaste: waste heat re-use for greener truck", Perosino et al., Proceedings of 6th Transport Research Arena, 2016, Warsaw, Poland.

Thermoelectric heat recovery

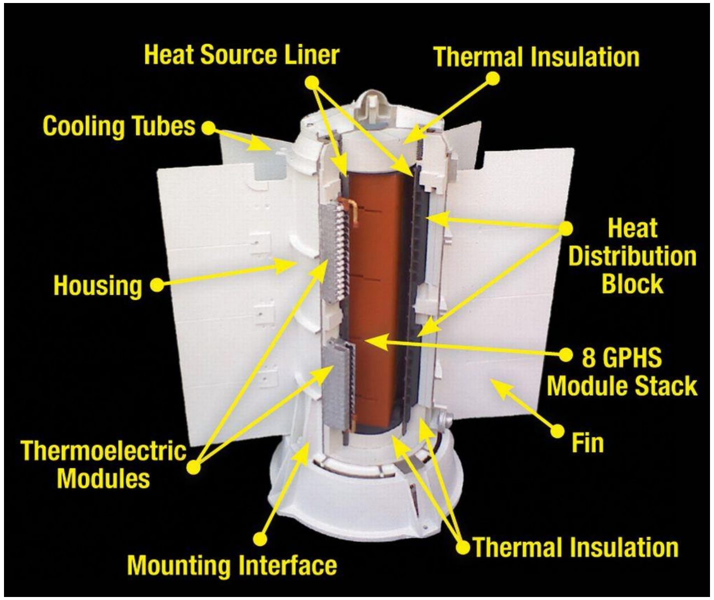


With TE modules it is possible to realize a **thermodynamic cycle** converting heat into electrical energy with **no moving parts**. Maximum theoretical efficiency is limited by **Carnot's efficiency**.

Snyder GJ, Toberer ES. Complex thermoelectric materials. Nature Materials, 2008;7:105-14.

Radioisotope thermoelectric generators

A radioisotope thermoelectric generator (**RTG**) is an electrical generator that uses an array of thermoelectric elements to convert the heat released by the decay of a suitable **radioactive material** into electricity.



Source **NASA**

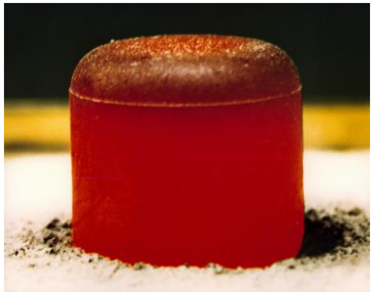
RTGs are the ideal solution for systems that are:

- **Unable to be** continually **maintained** and serviced for **long time**
- **Incapable** of generating **solar energy** efficiently

- **Solar radiation** is around 1375 W/m^2 on the Earth and falls to 1 W/m^2 around Pluto

Space missions: Voyager, Apollo, Viking, Galileo, Cassini, Pioneer

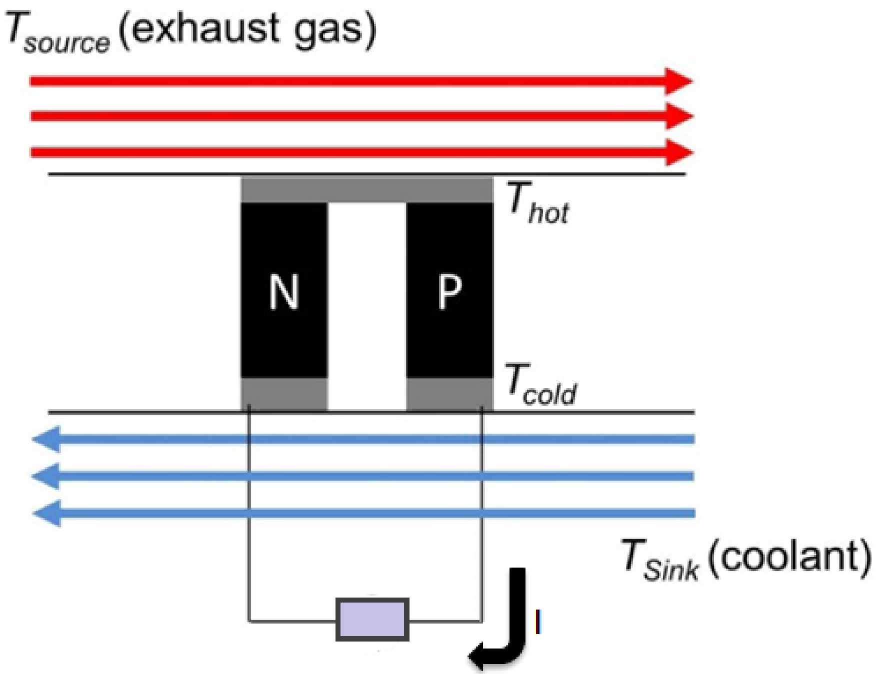
- **Tc** is very low (-240°C around Pluto)



^{238}Pu pellet

Radioactive sources: ^{238}Pu, ^{90}Sm, ^{241}Am, ^{210}Po

Heat recovery with Thermoelectric Generator (TEG)



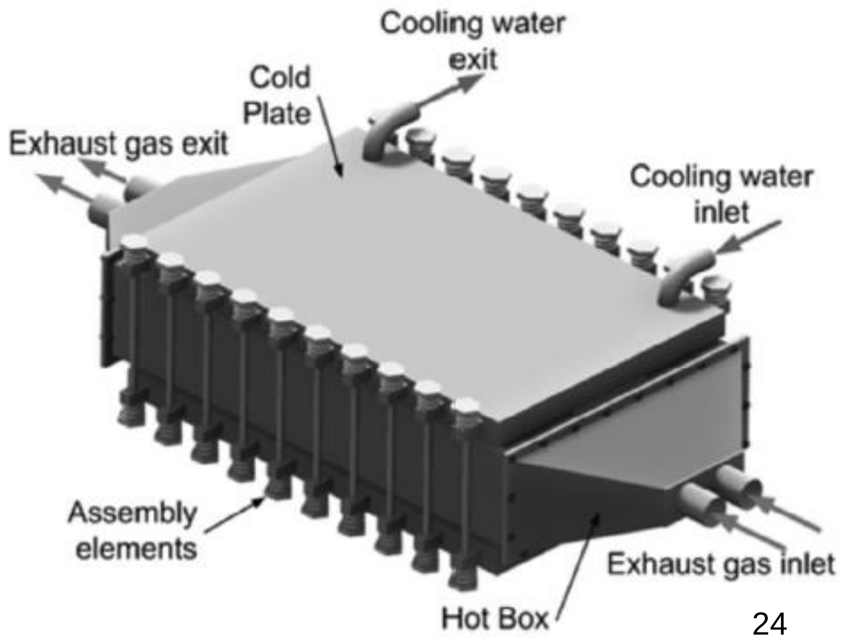
Advantages:

- No moving parts
- Absence of noise
- Durability/reliability
- Reduce maintenance
- Compactness

Drawbacks:

- Low efficiency (3% or less)
- Cost

Renalt prototype - EU RENOTER project



TEG efficiency

$$\eta_{TEmax} = \frac{W_{elec}}{Q_H} = \frac{\Delta T}{T_H} \cdot \frac{\sqrt{1+ZT}-1}{\sqrt{1+ZT}+\frac{T_C}{T_H}} \quad \text{with}$$

$$Z = \frac{(\alpha_p - \alpha_n)^2}{\left((\lambda_p.\rho_p)^{1/2} + (\lambda_n.\rho_n)^{1/2}\right)^2}$$

$$T = (T_H - T_C)/2$$

$$\Delta T = T_H - T_C$$

W_{elec} electric energy produced

Q_h thermal energy entering the hot side

T_H (T_C) temperature of the hot (cold) side of the TE modules

ZT is the **dimensionless figure of merit** of the TE materials

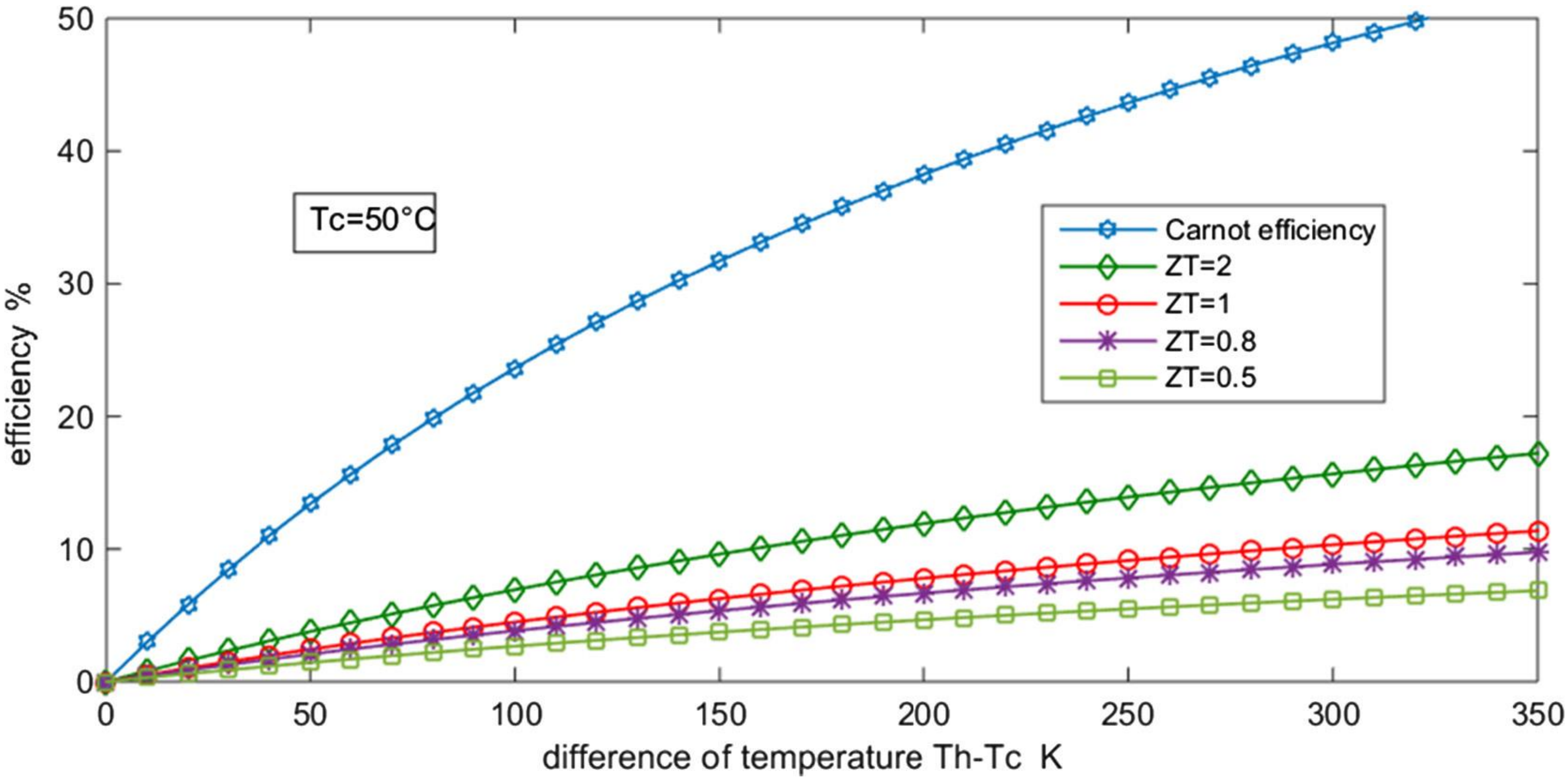
ρ_p and ρ_n electrical resistivities

λ_p and λ_n thermal conductivities

α_p and α_n Seebeck coefficients

Min G. In: Rowe DM, editor. Thermoelectrics Handbook Macro to Nano. CRC Press; 2006.

TEG efficiency



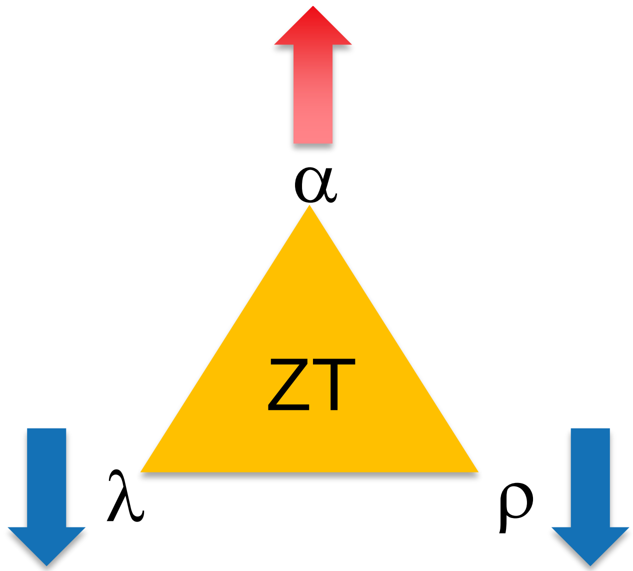
- Efficiency increase with ZT and ΔT
- Usually TC is ambient temperature → **materials working at high T are required**

Figure source: Thermoelectric generators: A review of applications, Daniel Champier, Energy Conversion and Management 140 (2017) 167–181

TEG efficiency

But Nature conspires against thermoelectric generation….

Pisarenko's relation $$\alpha = \frac{8\pi^2 k_B^2}{3eh^2} m^* T \left(\frac{\pi}{3n}\right)^{2/3}$$



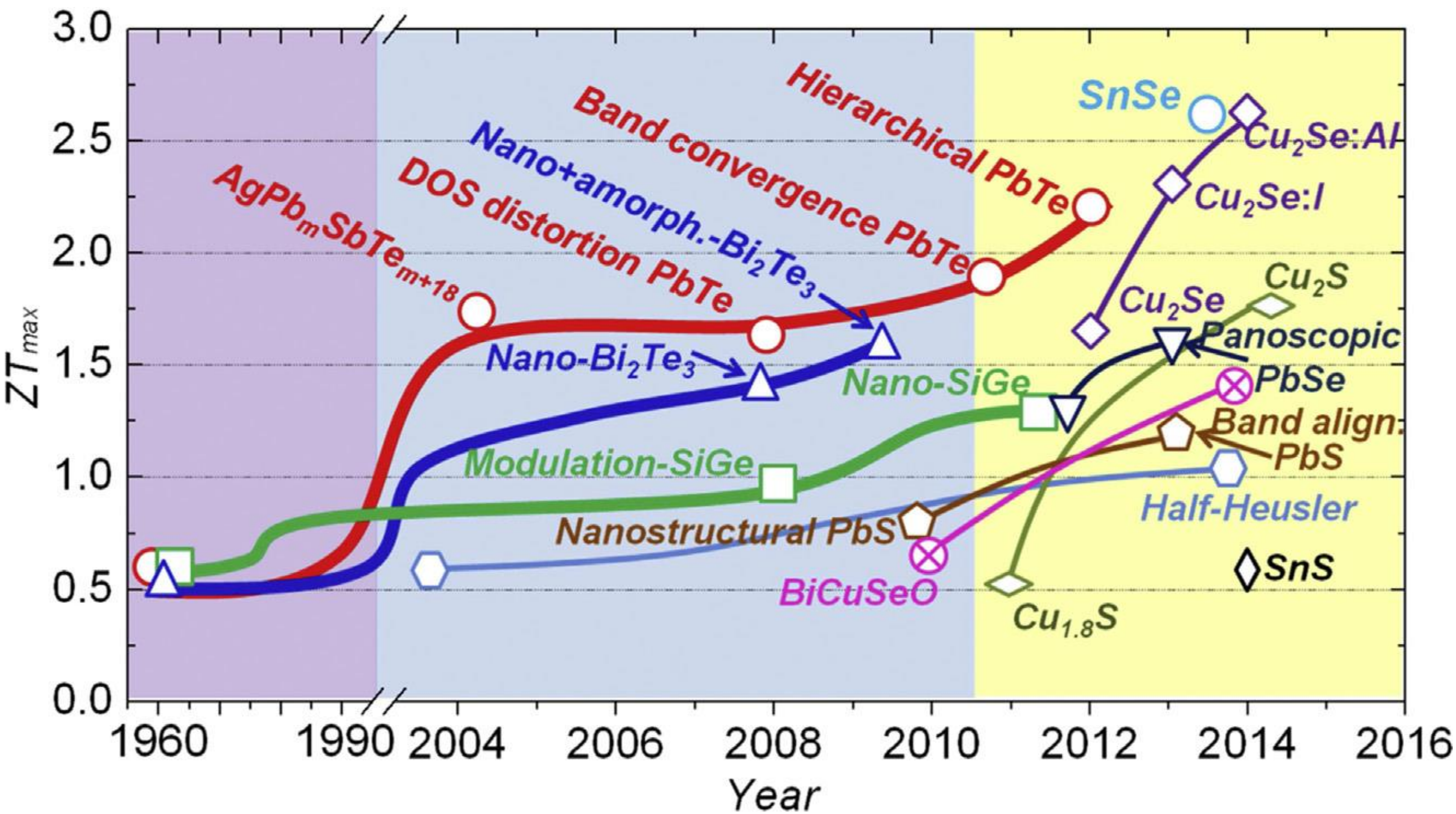
$\lambda_{tot} = \lambda_{ph} + \lambda_{el} = \lambda_{ph} + L\sigma T$

$1/\rho = \sigma = ne\mu$

Wiedemann-Franz law

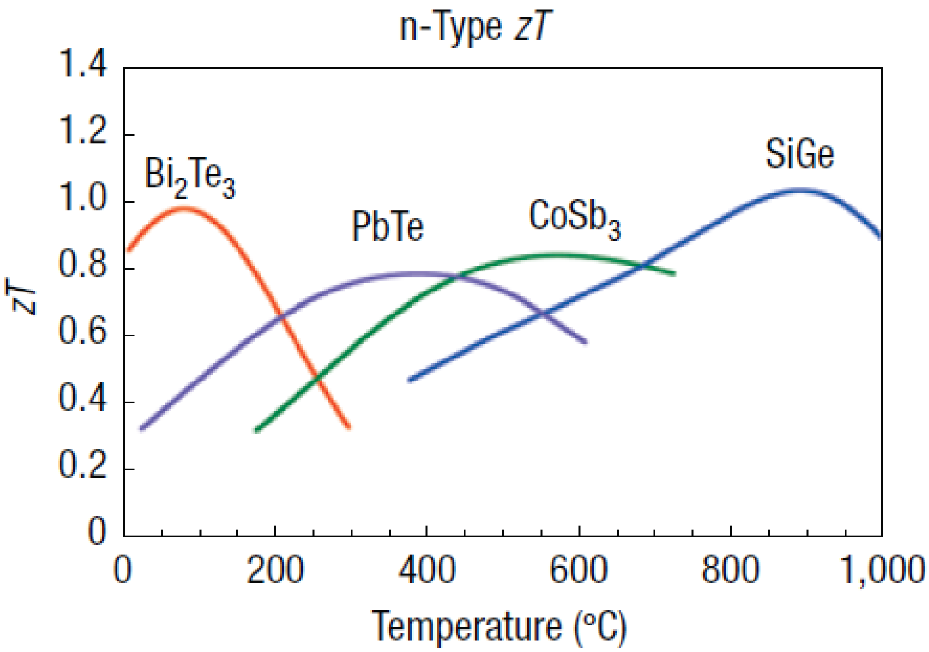
Snyder GJ, Toberer ES. Complex thermoelectric materials. Nature Materials, 2008;7:105-14.

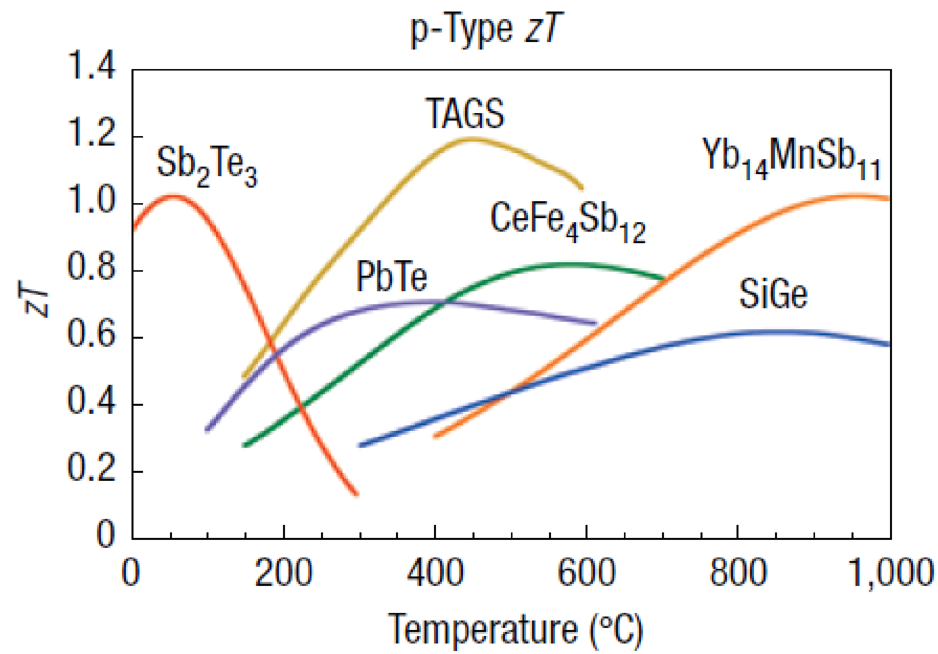
Thermoelectric materials



Thermoelectric materials: Energy conversion between heat and electricity, Xiao Zhang, Li-Dong Zhao, Journal of Materiomics 1 (2015) 92-105

Thermoelectric materials





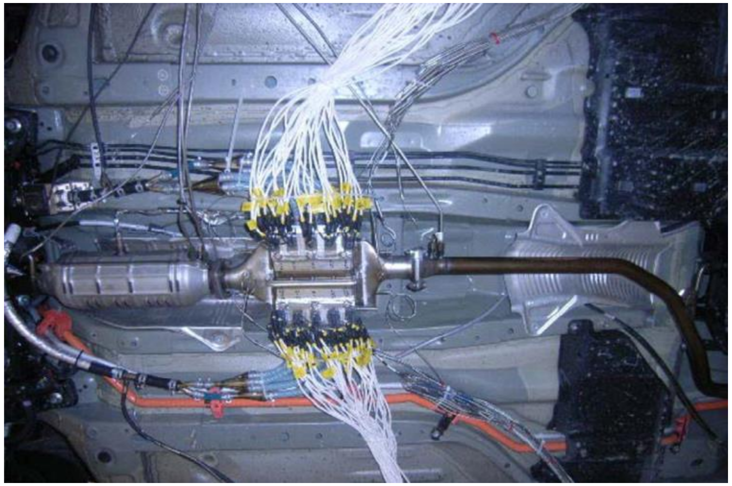
Automotive exhaust heat recovery requirements:

- **high operating temperature**
- **low cost**
- **non-toxic** and **available raw materials**

Si-Ge alloys are promising materials for automotive applications

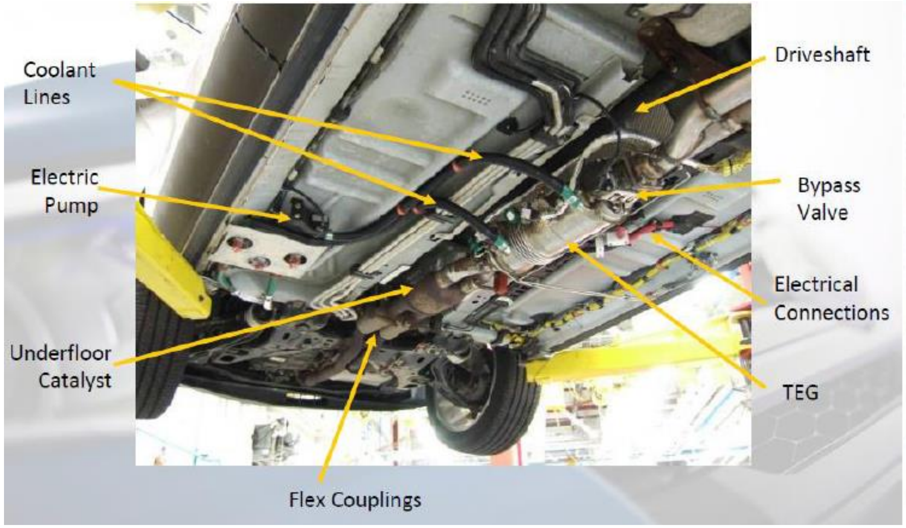
Snyder GJ, Toberer ES. Complex thermoelectric materials. Nature Materials, 2008;7:105-14.

Automotive TEG prototypes



Honda

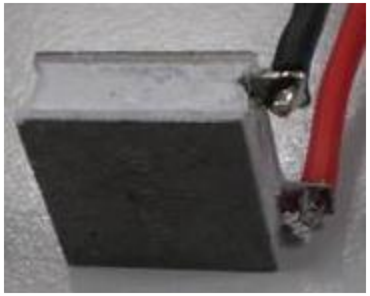
GM

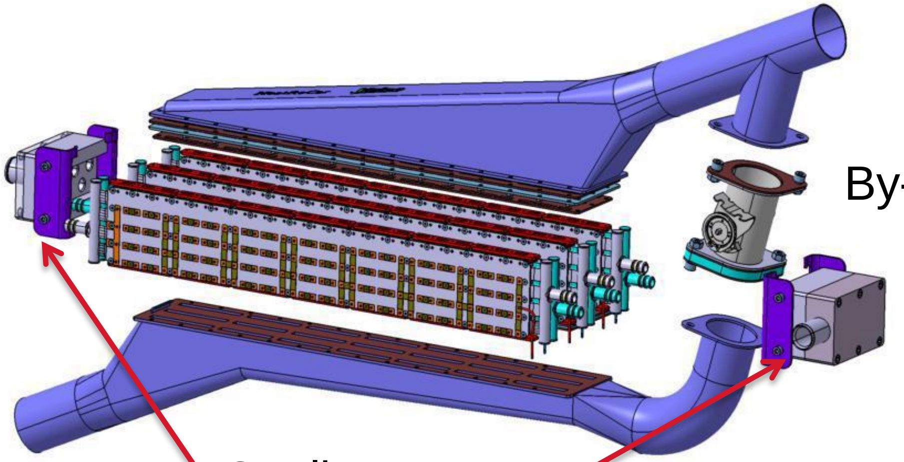


Ford

BMW

HEATRECAR Project





- Commercial Bi_2Te_3 modules were integrated in an heat exchanger designed to maximize the heat transfer and reduce the pressure drop on the exhaust line
- A bypass valve was used to maintain the temperature of the hot side below 270°C to avoid damages on the TE materials at high engine regimes

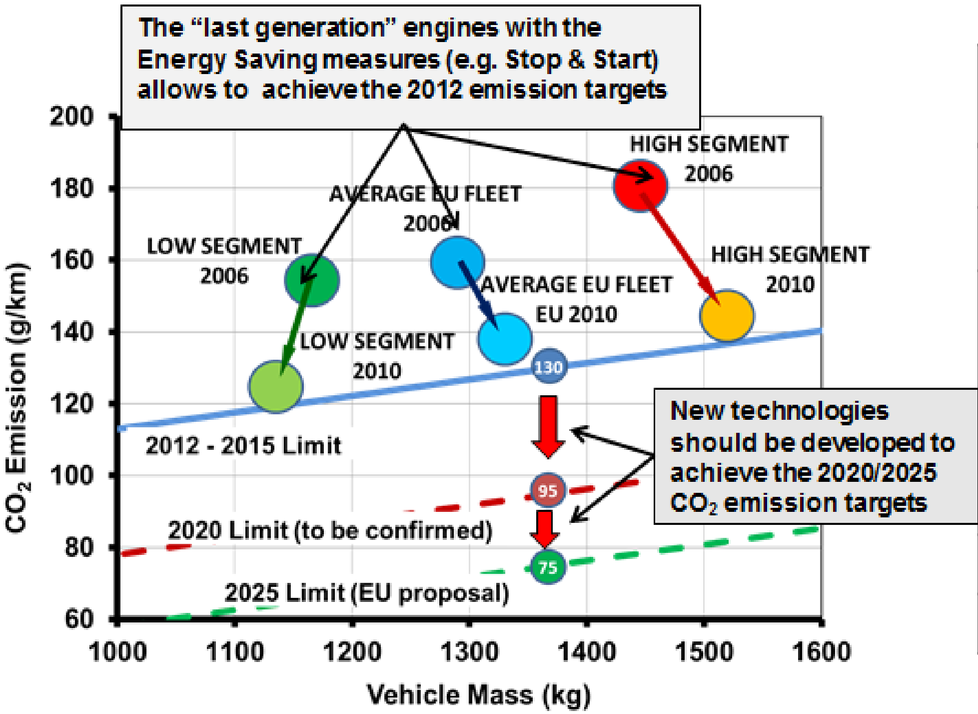
D. Magneto 3rd International Conference Thermal Management for EV/HEV Darmstadt 24-26 June 2013

HEATRECAR Project

- The TEG was integrated on a IVECO Daily commercial light duty vehicle
- On the homologation WLTP cycle, the system reached a peak of 220 W
- In the last part of WLTC, corresponding to **highway conditions** TEG power is sufficient to provide the on-board electric needs, completely replacing the alternator
- **4% fuel economy** improvement over the WLTC cycle has been achieved corresponding to a reduction of CO_2 emissions of 9.6 g/km

D. Magneto 3rd International Conference Thermal Management for EV/HEV Darmstadt 24-26 June 2013

Economic analysis

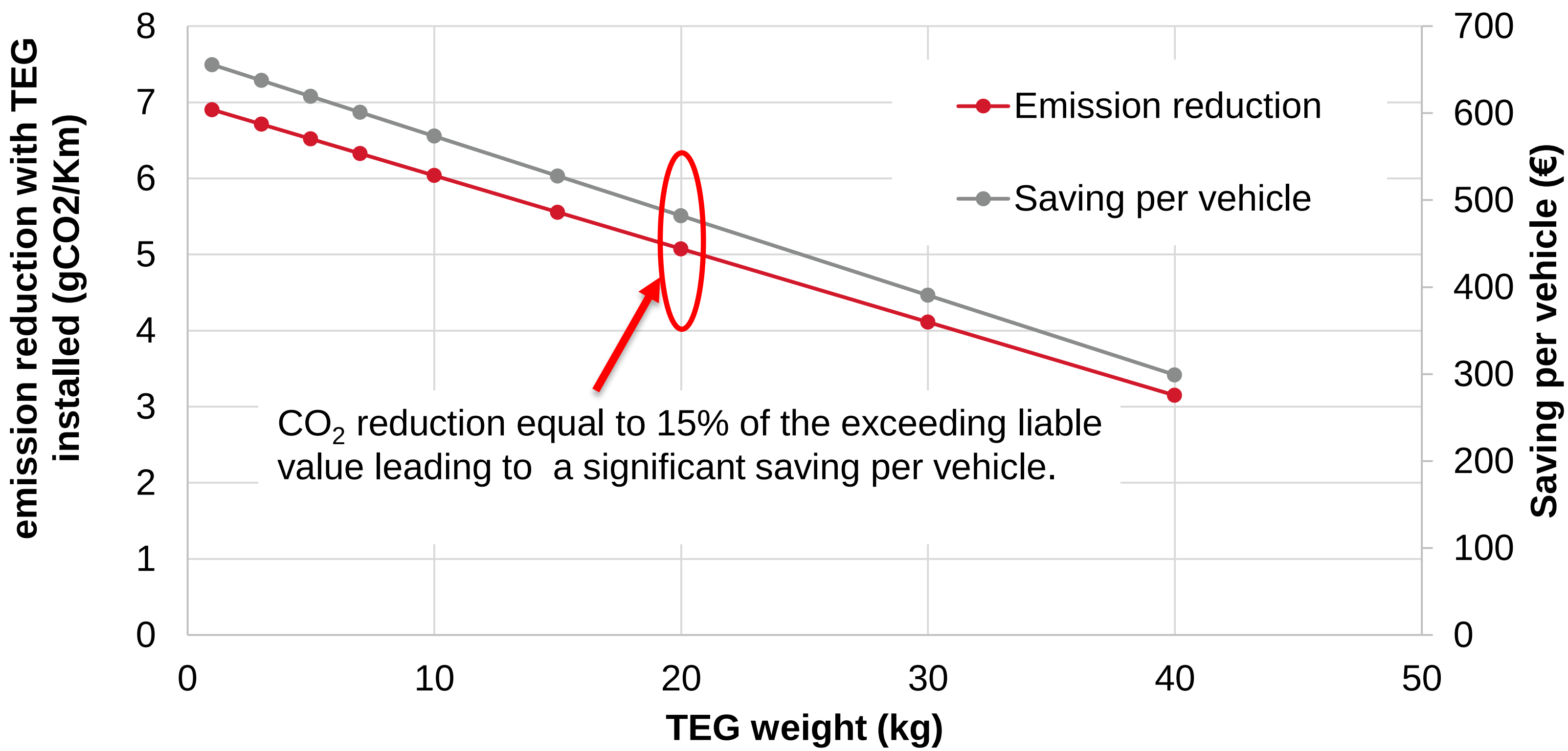


Average EU fleet	
CO_2 emission (gCO_2/Km)	130
weight (kg)	1350
estimated reduction of emission with TEG generating 500 W (gCO_2/Km)	7
emission limit 2020 (gCO_2/Km)	95
emission limit 2025 (gCO_2/Km)	75
fine for exceeding gCO_2/Km (€)	95

- CO_2 emissions set by the European Commission for passenger vehicles stood at 130 g/km in 2012 and are to be reduced to 95 g/km by 2021
- Car manufacturers will have to pay **heavy fines** for vehicles exceeding the CO_2 limits (95 € per exceeding gram from 2021)

Economic analysis

CO_2 emission reduction by employing a TEG with 2% efficiency and power output 500W installed on an "European average vehicle" and its impact on fuel economy, and fine reduction. The analysis assumes a reasonable TEG weight that depend on ZT and system design.



15% of overall fines for FCA is approximately equal to 0,5 billion €/y

Accepted cost: as a function of the weight: from 0.6 to 1.3 €/W.

Conclusions and perspectives

- Exhaust heat recovery with TEG is being developed by several automotive OEMs
- Commercial TE modules have 1<ZT<1.5 and operating temperature up to 600°C, allowing to reach a 5% conversion efficiency
- The electric power output of current prototypes is about 500W
- A reduction of CO_2 emissions of 4-5% is already possible on ICE vehicles
- TEG generators can be effectively integrated in hybrid vehicles since the produced electric power can be used to recharge the battery pack.
- Low cost TE modules based on easily available non-toxic materials are required to make the technology available on large scale

THANK YOU FOR YOUR ATTENTION!