Thermoelectric Network Meeting
Engineering Challenges and the Thermoelectric Roadmap

Market Applications and Future Activities

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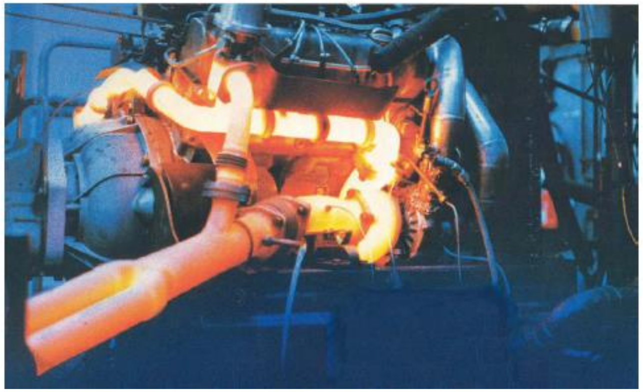
Content

- **Key market applications**
- Potential research activities

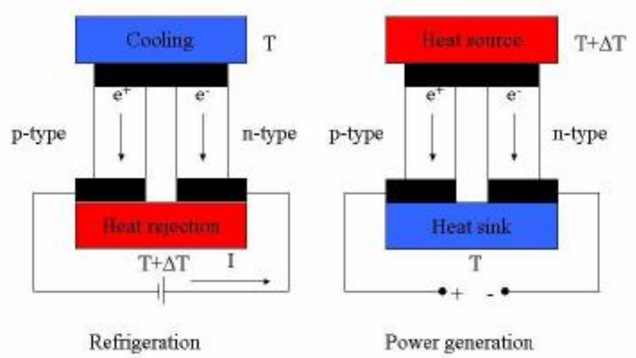
Key market applications – focus on Internal Combustion Engines

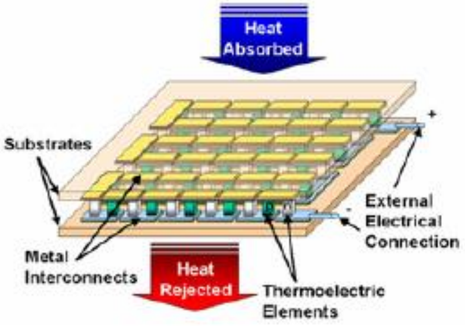
- Seebeck effect – Heat to Electrical Power for reduction of fuel consumption and CO_2 emissions:
  - Internal Combustion Engines:
    - **Passenger car – Diesel, gasoline engines ~ 0.5-1 kW**
    - **Heavy Duty Vehicles – Diesel, natural engines ~ 2-5 kW**
    - **Stationary engines – Diesel, Natural gas > 5-100kW**
    - **Combined Heat and Power - Diesel, Natural gas**
  - Industrial plants, furnaces
  - Autonomous sensors

- Peltier effect – Electrical Power to Heat / Cold for thermal comfort, cooling of electronics
  - Transport applications: cabin thermal comfort (steering wheel, seat), battery cooling/heating, power electronics cooling
  - Buildings – heating and cooling

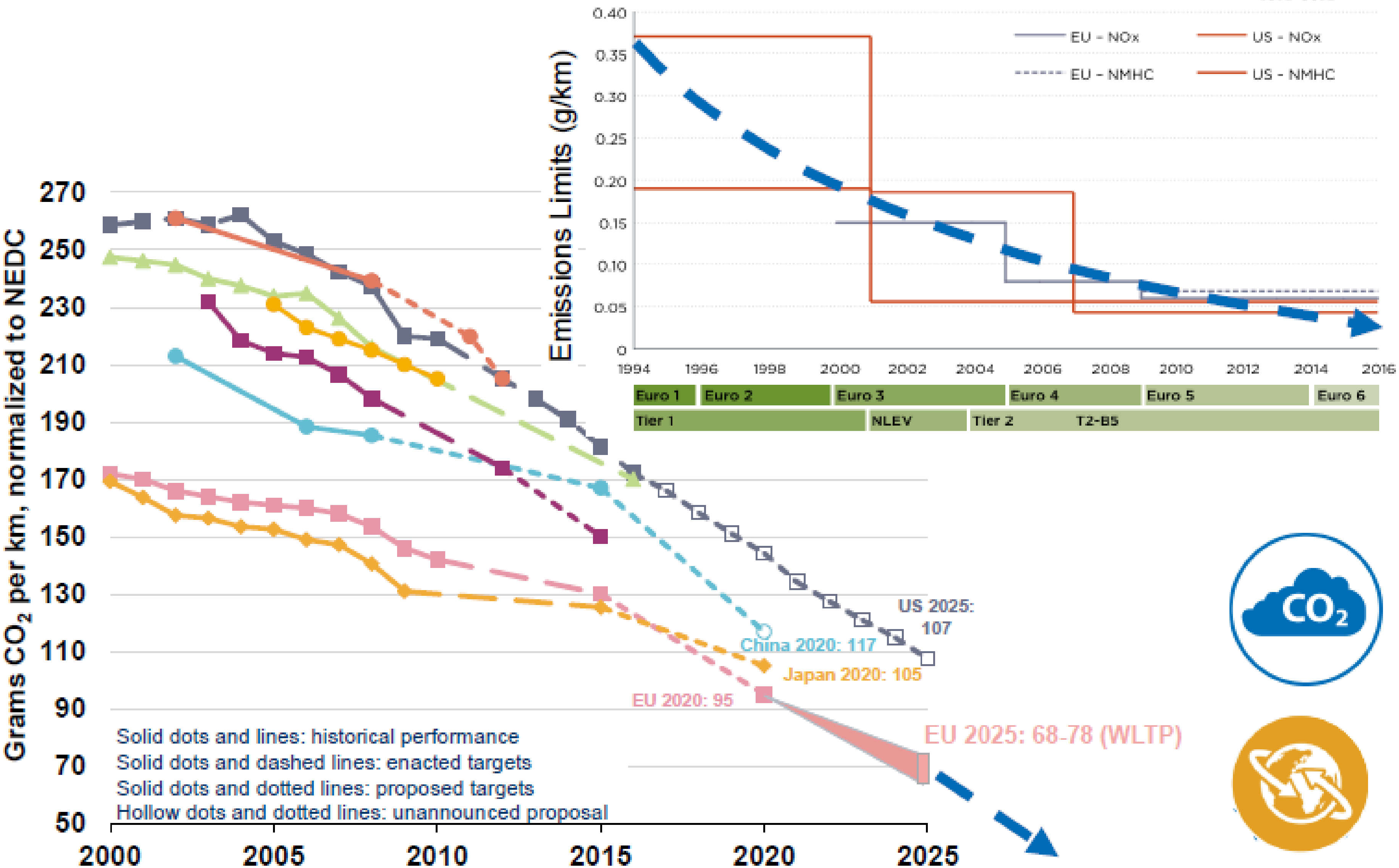


Source: DEER, Fairbanks





Passenger car – Electrification trend
Legislative drivers will continue to demand ever lower CO2 emissions and with zero air quality impact



Electrification is here to stay but no "one size fits all" solution – Micro/48 volt systems for volume and PHEV for premium

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1915-2015

Increasing degree of vehicle electrification

Micro Hybrid → Mild Hybrid → Full Hybrid → Plug –in Hybrid → Range Extended EV → Pure EV

Ricardo developing customer applications/demonstrators in all categories

Micro/Mild: Solution for the "Average Car"

- **Ricardo HyBoost** ~ 95 g/km in "C" class car
- **Ricardo ADEPT** ~ 70 g/km in family car
- **Micro-hybrid** 48v architecture under development since 2011
- Below 60v "hazardous" threshold

Full Hybrid: Niche or High Performance

- **Prius** best-selling hybrid - But, at **89g/km** cost/benefit eroded
- **New cycles** place more weight on highway driving where hybrids have less benefit
- **KERS** systems make sense in supercars

Plugged In: The Future? – From Premium to Volume

- **Favourable treatment in legislative cycles** makes technology attractive in larger premium vehicles
- **BMW i3** – EV with optional range extender
- **Tesla** – shows that it is possible to make money with a premium "eco" product

Advanced combustion engines & electrification of the powertrain are key to future of light duty vehicles

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SHORT TERM: ~2015

- Boosting & downsizing
  - Turbocharging
  - Supercharging
- Low speed torque enhancements
- Friction reduction
- Advanced thermal systems
- Stop/Start & low cost Micro Hybrid technology
- Niche Hybrid, PHEV's & Electric Vehicles
- Weight reduction (5-10%)

MEDIUM TERM: ~2025

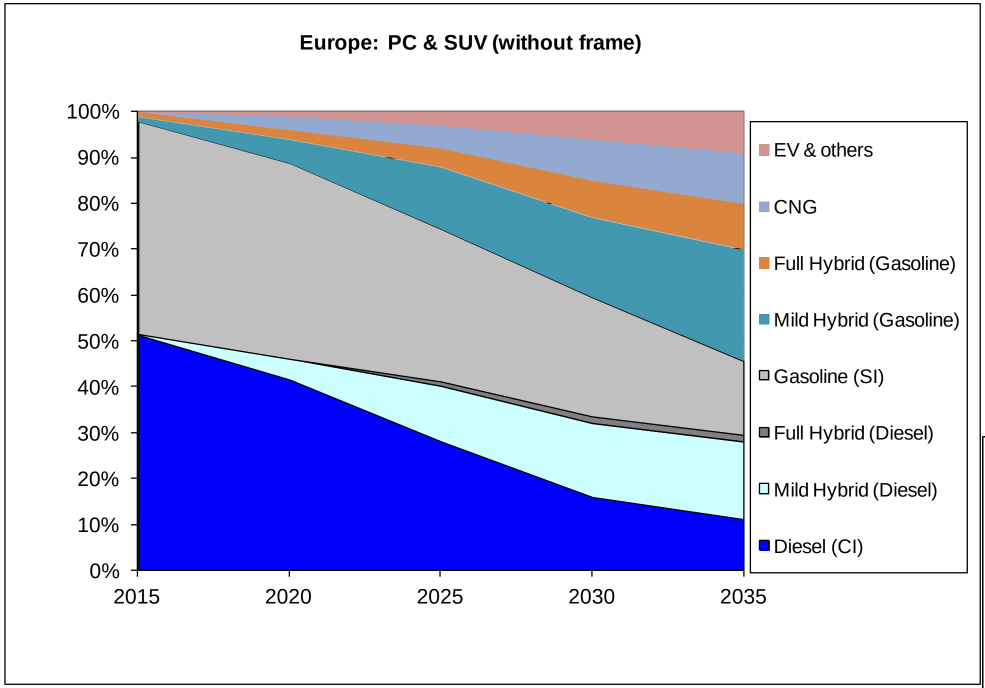
- Extreme downsizing with 2 & 3 cylinder engines
- Combined turbo/ supercharging systems
- Advance 48 volt micro hybrid systems dominate
- PHEV's in premium & performance products
- EV's for city vehicles
- Significant weight reduction
- High Efficiency Lean Stratified Gasoline
- Advanced low carbon fuel formulations

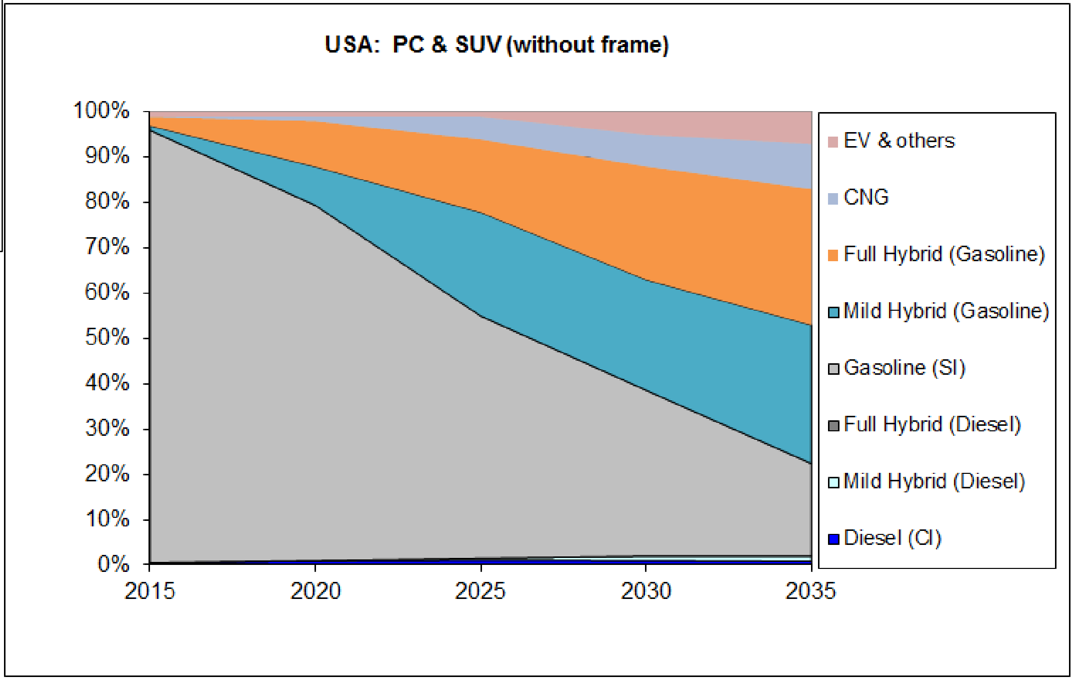
LONG TERM: ~2050

- Plug-in/Hybrid electric systems dominate
  - Very high specific power ICE's/Fuel Cells
- 50% lower weight
- Range of application specific low carbon fuels
- Exhaust & Coolant energy recovery
- Advanced thermodynamic Cycles
  - Split Cycle?
  - Heat Pumps?

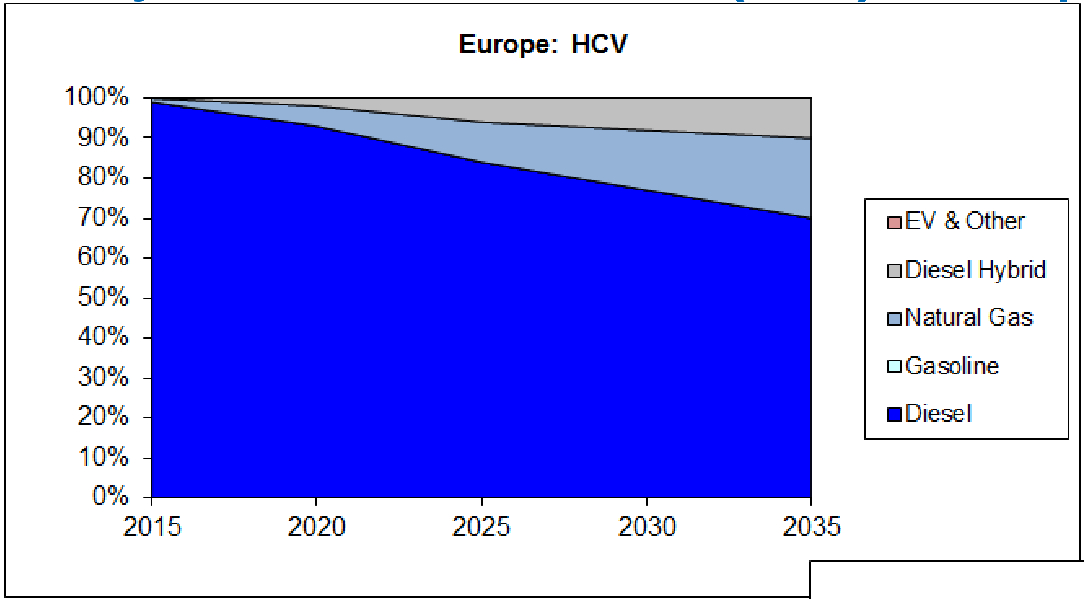
Increasing Importance of Electrification

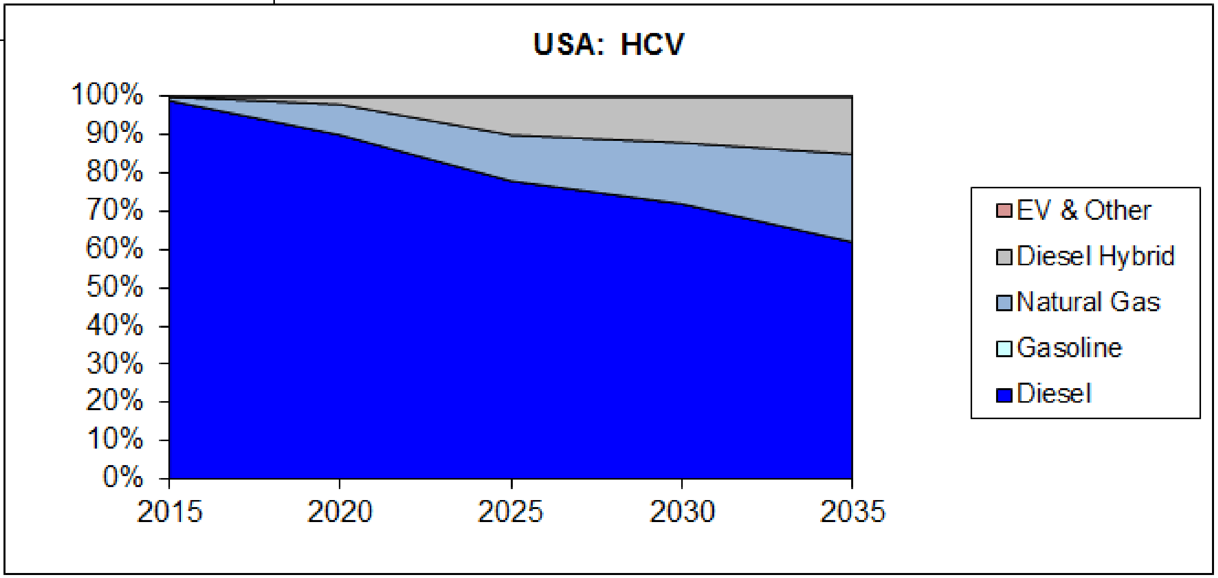
Passenger car – Electrification trend
Estimates of Market Penetration of Diesel/gasoline Engines: Passenger Cars & SUVs without chassis frames – Europe & US





Commercial Vehicles - Electrification trend
Estimates of Market Penetration of Diesel/gasoline Engines: Heavy Commercial Vehicles (HCV) – Europe & US

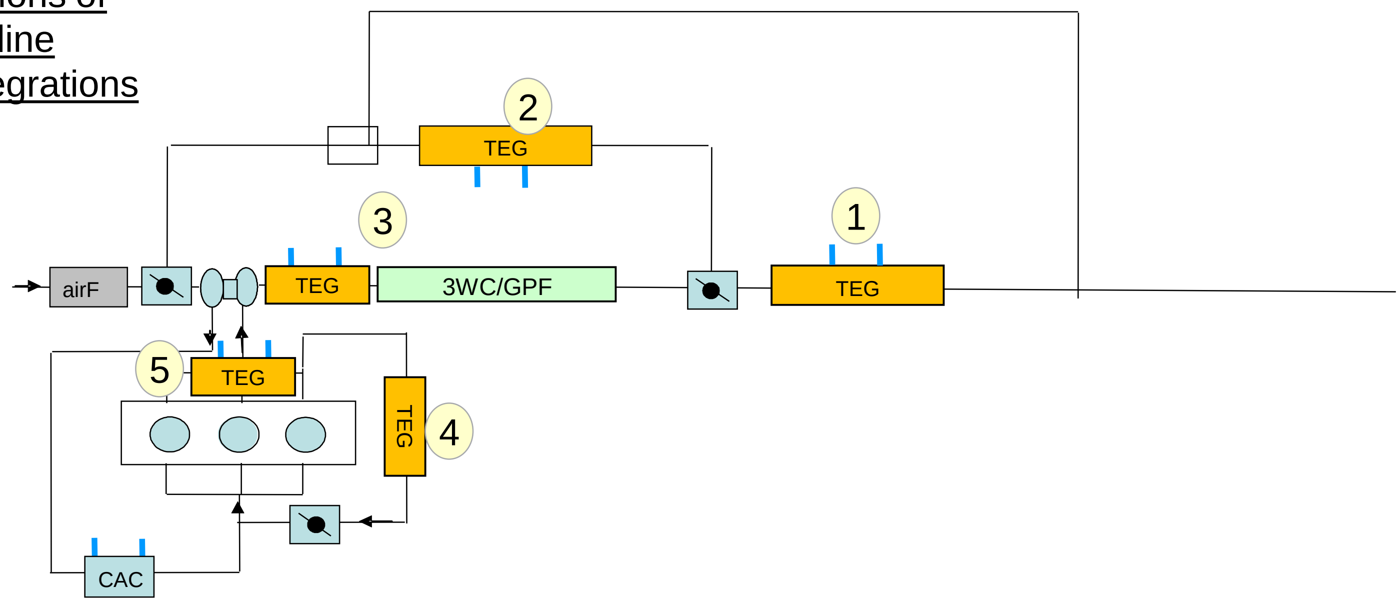




Possible integration of thermoelectric generator (TEG) on engines (Diesel, gasoline, Natural gas)

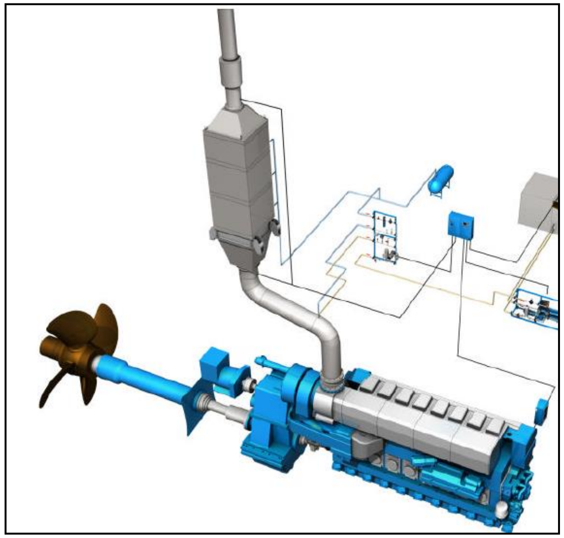
- Example: Application on 3 cylinder downsized gasoline engine wit or without EGR (HP or LP)
- Thermoelectric Generator can be installed after Exhaust After Treatment or as EGR cooler (HP or LP) and cooled by engine coolant and/or engine lubricating oil
- **Objectives:**
  - Recover exhaust / EGR heat and convert it into electricity using thermoelectric effect (Seebeck materials)
  - Recover exhaust/EGR heat and transfer it to engine coolant and/or engine lubricating oil
  - Improve engine coolant and/or engine oil warm-up
  - Fuel Consumption benefit over NEDC: 3-5%, WLTC: 2-4%

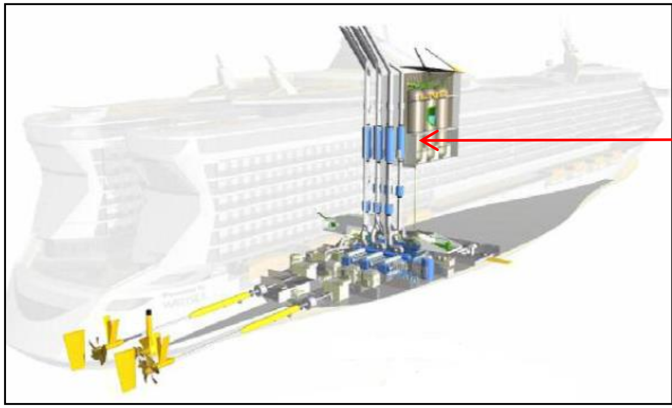
Example of different installations of TEG on EGR or exhaust line (including IEM): 5 possible integrations



Marine – Large Diesel engines

- Example of installation of TEG





Source: Wartsila, example of heat exchanger for WHR (ORC here)

Installation TEG in chimney

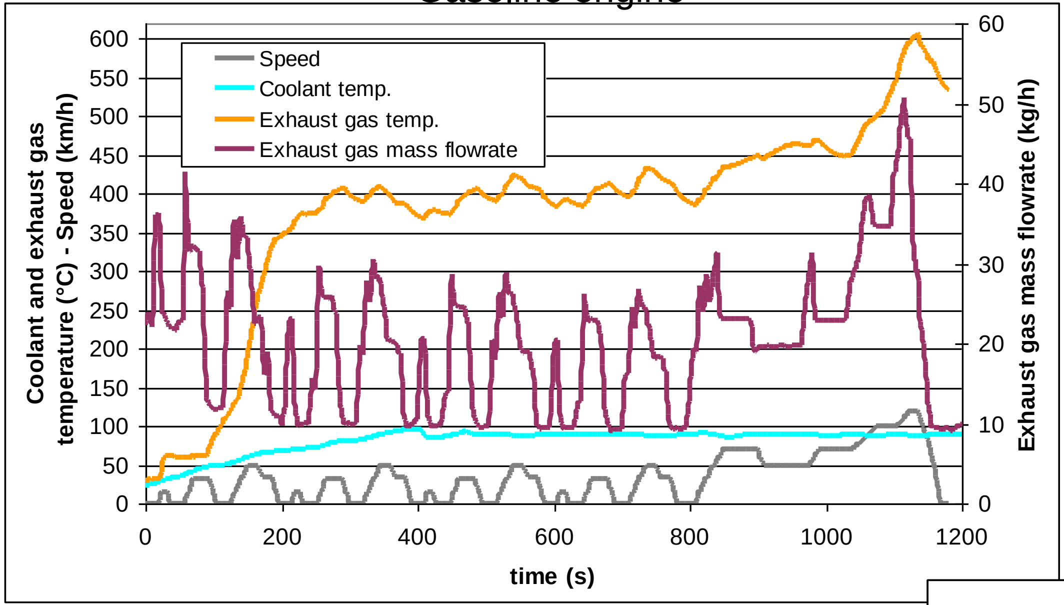
Boundary conditions – hot / cold for transport applications

	Passenger car – gasoline engine	Passenger car – Diesel engine	Heavy Duty Diesel vehicle	Large Engine (Marine) - Diesel
Exhaust gas temperature *	300 - 800ºC	150 - 650ºC	300 - 450ºC	300 - 350ºC
EGR temperature	400 - 900ºC	250 - 700ºC	350 – 650ºC	N/A
Cold source temperature	40 - 100ºC (engine or Low temperature circuit coolant)	40 - 100ºC (engine or Low temperature circuit coolant)	40 - 100ºC (engine or Low temperature circuit coolant)	< 45ºC (sea)

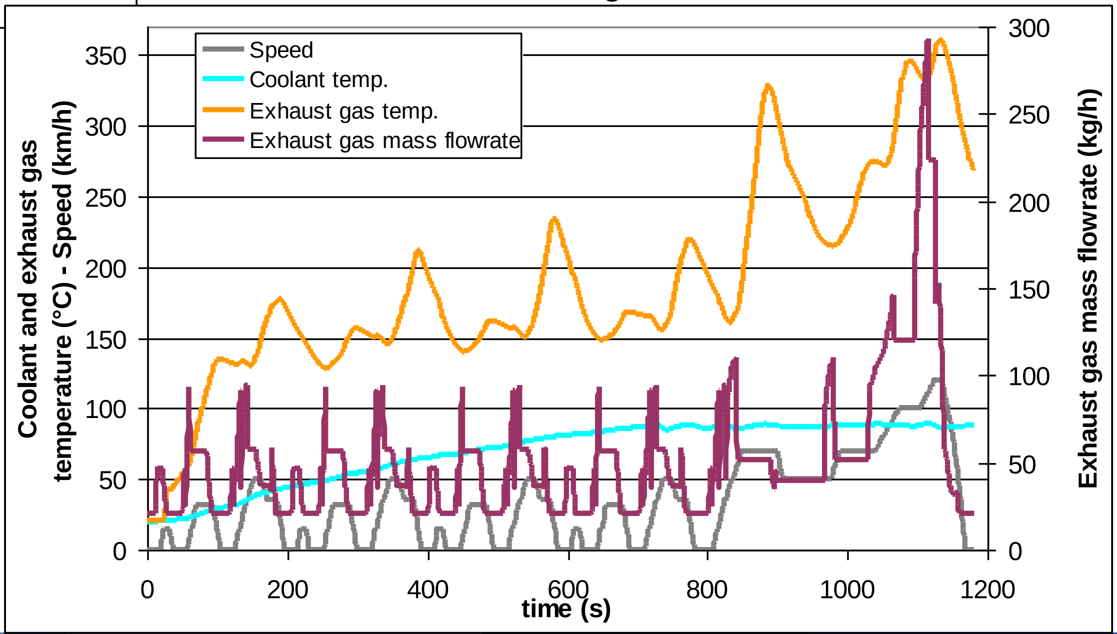
* Temperature after after-treatment system

Hot/cold sources – Gasoline & Diesel engines - NEDC

Gasoline engine



Diesel engine



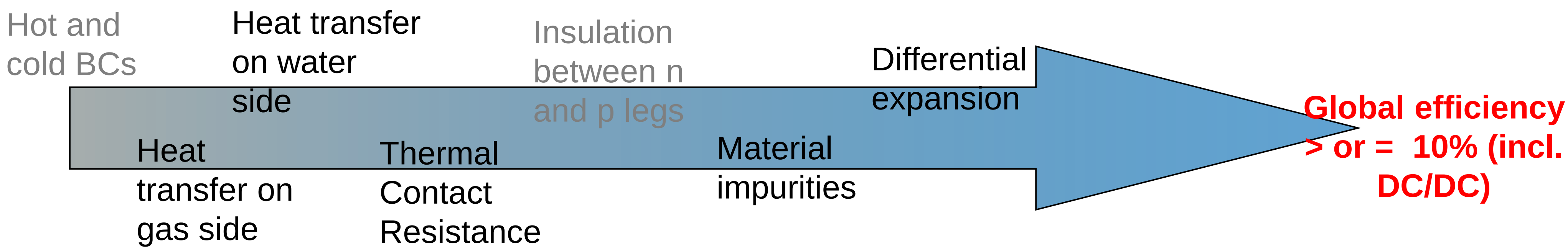
Content

- Key market applications
- **Potential research activities**

Thermoelectric generator challenges – to reach 10% efficiency thermoelectric generator

- Several activities are still needed; simulations, specifications, tests, FMEA, risk & hazard analysis
- **Thermoelectric components :**
  - Shape of thermoelectric elements/generator (annular or flat plate)
  - Assembly process / High T° brazing and differential expansion
  - Insulation for reducing thermal losses between p and n joints (aerogel)
  - Improvement merit coefficient ZT (now 0.4 to 0.8 – objective 1.5-2)
    - Interest of the segmentation for materials for optimising ZT / T°
  - Thermomechanical behaviour / reliability / durability
  - Reduce the number of material layers between hot and cold sources in order to reduce thermal resistance
- Efficient heat transfer on exhaust line without increasing the pressure drop (usually: + 100 mbar on exhaust line => -1 to -4 kW on the engine crankshaft)
- Electric production strategies (HW / SW) : electric auxiliaries / strategy / DC/DC – MPP Tracker – with high efficiency
- Cost / benefit ratio – competitive with other Waste Heat Recovery Solutions

Interface risks: control of « global efficiency » (holistic approach)



BC: Boundary Condition

Exhaust heat energy recovery can yield significant efficiency gains for the IC engine

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- Variety of exhaust energy recovery approaches to improve engine efficiency

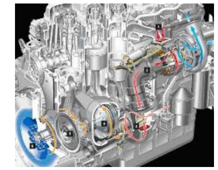
30-50% of energy is wasted in the exhaust

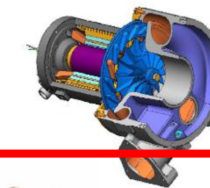
Coolant, Friction, Radiation

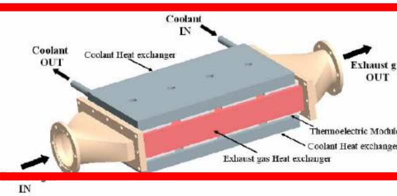
Exhaust heat

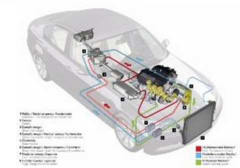
Usable Engine Energy

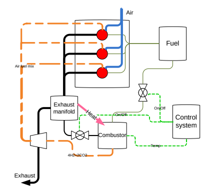
Turbo-compounding *	• Mechanical systems applied to long-haul trucks – Electrical systems also offered by suppliers
Thermo-electric (Seebeck)	• Potential simple solution with no moving parts – Research to develop improved materials
Bottoming cycle (Rankine, Brayton) *	• Commonly used for power generation – Packaging and irregular thermal load issues require detailed systems development approach
Thermo-chemical *	• Ethanol reformation to increase calorific value – Has been demonstrated at laboratory level
Novel engine cycles	• Compression and combustion/expansion processes separated – Demonstrated at Ricardo for power generation











*Not presented here

Source: Scania, Bowman Power, MTZ, RWE Innogy

All WHR systems are costly relative to many application needs
Solutions in bold are being studied actively for HDD/passenger cars

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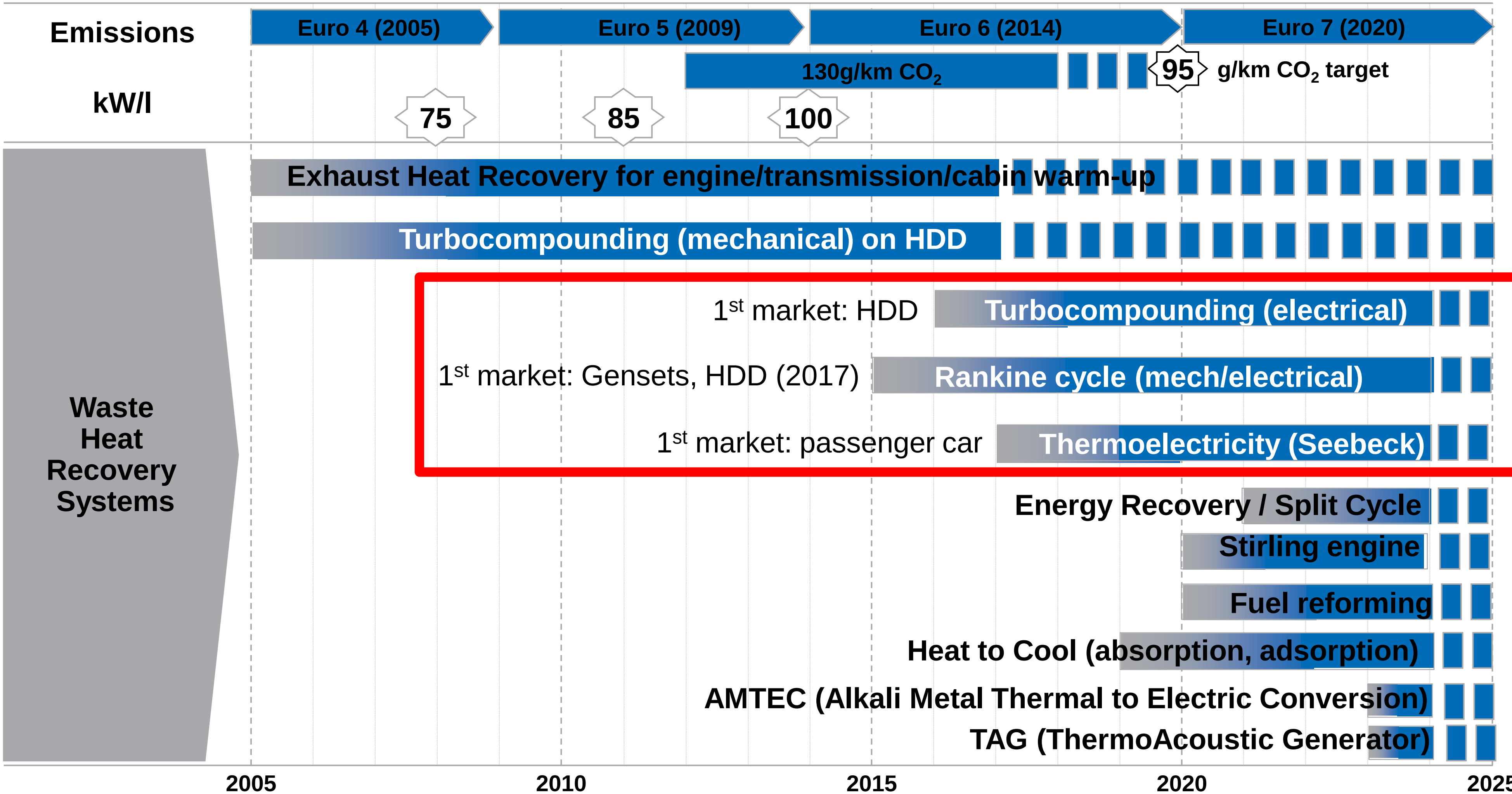
< 2020	Heat energy recovery	Typical FE gain	Applications	Issues	Transiency	Cost	Technology maturity
Turbo compounding (m)	5 %	3 - 5%	Heavy duty Truck, Off Highway, Marine, Rail & Power **Passenger car**	Mechanical losses at low load	+++	-	Commercialised in premium products
Turbo compounding (e)	**15%**	**3 -10%**		Need for electrical power consumer or motor	+++	- -	Commercially-ready systems available
Rankine cycle / ORC	**20%**	**3 -10%**		Condenser cooling, bulk and cost	++	- -	Working prototypes developed
Thermo electrics (Seebeck)	**10%**	**3 -5%**	**Passenger cars** Heavy duty diesel	Cost	+++	- -	Concept (Automotive) Comm'd (Space)
Fuel reforming		3-10%	Combustion improvement – any ICE	Reformate management, transients, Cost	+	- - -	Concepts and prototypes
AMTEC-Alkali Metal Thermal to Electric Converter	20-30%	3 - 10%	Passenger cars	High temperature operations Material (Na, K), BASE	++	--	Concepts and prototypes
Stirling engines	20%	3 - 12%	Micro CHP Marine engines	Requires precise matching, Cost	++	- - -	Commercialized as standalone devices
Split cycle engines	60%	36%	Power generation Automotive	Complexity, risk, Cost	++	- - -	Prototype (Power) Concept (Automotive)

> 2020

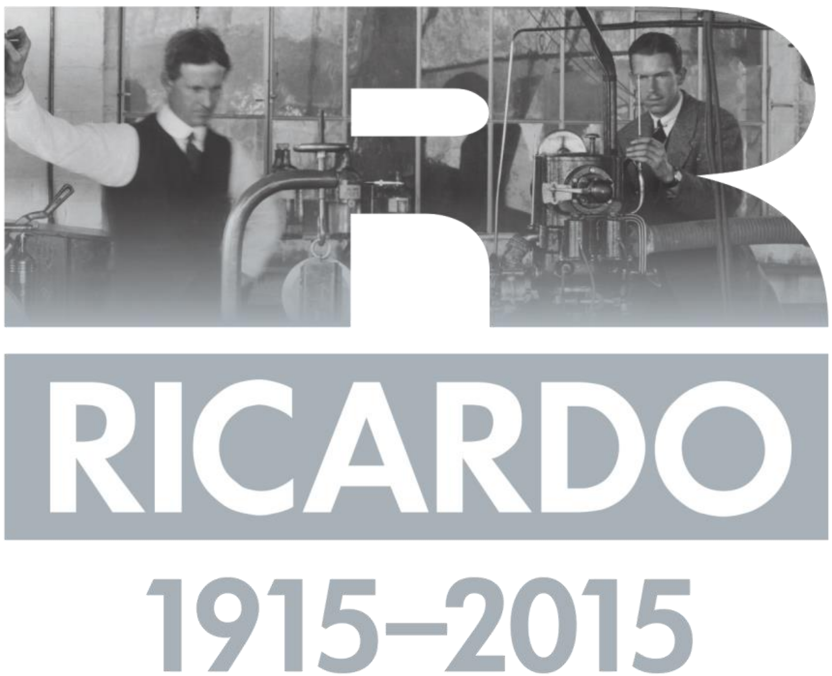
The high level technology roadmap for Waste Heat Recovery Systems, using exhaust gas and/or any other fluids available on gasoline / diesel vehicles (coolant, oil, EGR, charge air)

Europe: Technology Roadmap for Thermal Management gasoline/Diesel



Source: Ricardo Analysis

THANK YOU FOR YOUR ATTENTION
ANY QUESTIONS?



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