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Researcher Links UK-Russia Workshop / Scientific and technical grounds of future low-carbon propulsion

Waste Heat Recovery Systems

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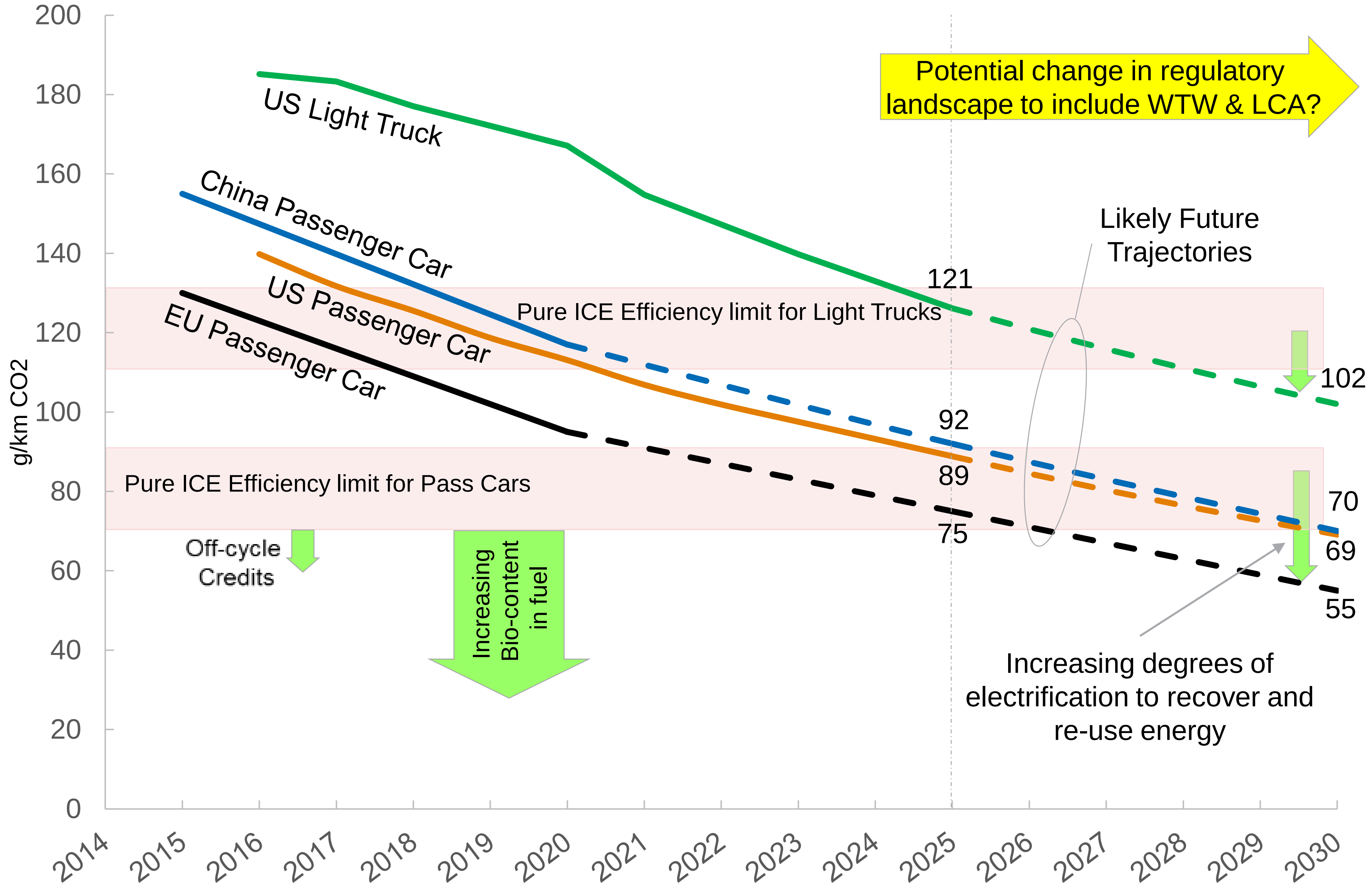
Content

- **Context**
- **Waste Heat Recovery Systems**
  - Energy Balance
  - WHRS comparison
- Focus on some Waste Heat Recovery Systems
  - Turbocompound
  - Seebeck thermogenerator
  - Organic Rankine Cycle
- Conclusion

GHG reductions beyond 2025 are not yet defined but must continue – 2030 targets defined on more holistic basis?



For the medium and longer term, powertrain electrification will play an increasing role alongside advanced combustion engines

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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
- **Advanced 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

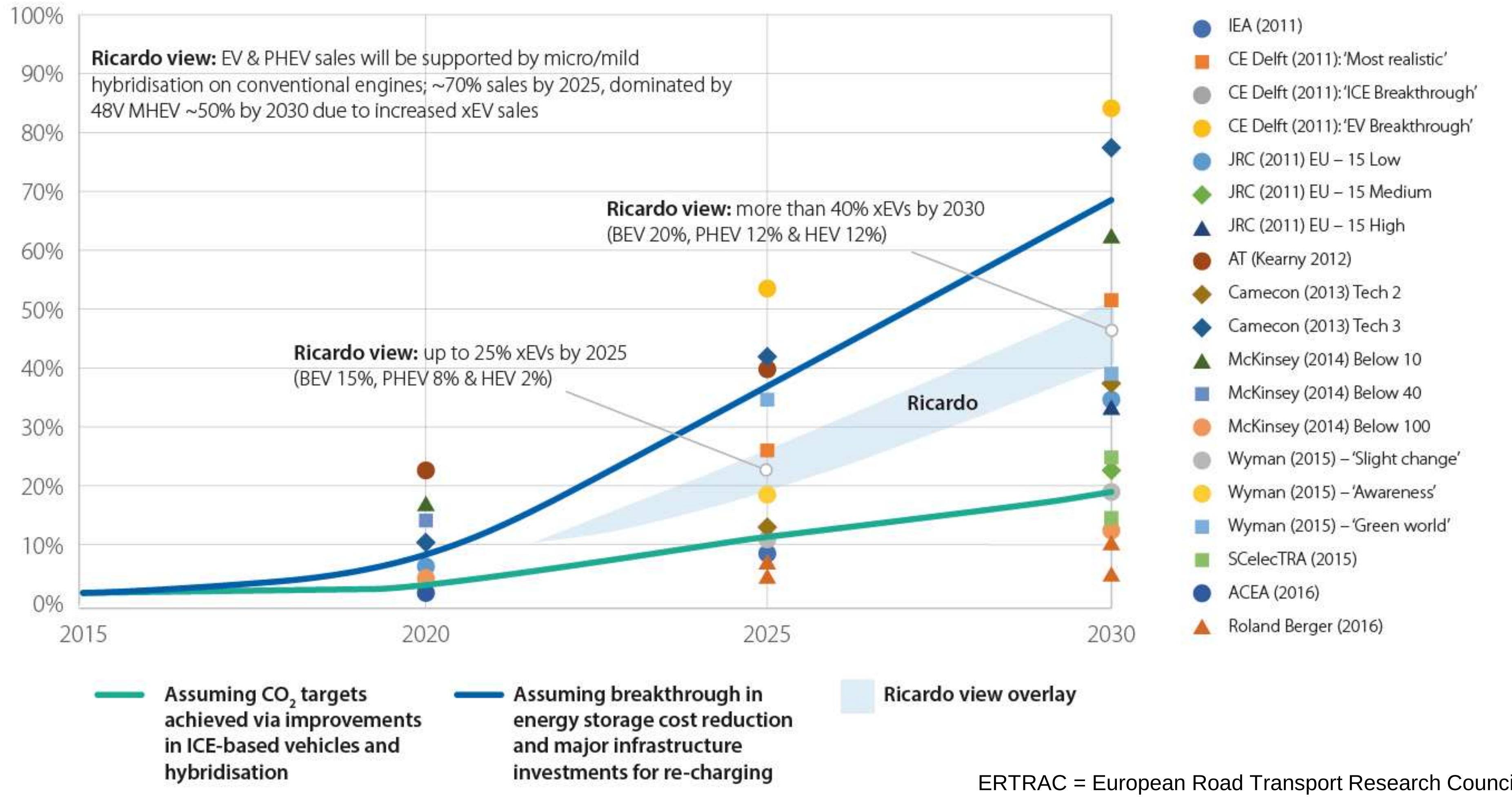
- Plug-in/Hybrid electric systems dominate
  - Very high specific power ICE's
- 50% lower weight
- Range of application specific low carbon fuels
- **Exhaust & Coolant energy recovery**
- **Advanced thermodynamic Cycles**
  - **Split Cycle?**
  - **Heat Pumps?**

Increasing Importance of Electrification

Source: Ricardo Technology Roadmaps, Ricardo Analysis

2017 ERTRAC electrification roadmap: BAU forecast <20% by 2030 but >60% if target cost reductions achieved – little agreement for published forecasts but definite upward trend

BEV, PHEV and HEV passenger car sales forecast 2020 – 2030



ERTRAC = European Road Transport Research Council

Source: ERTRAC, Ricardo analysis

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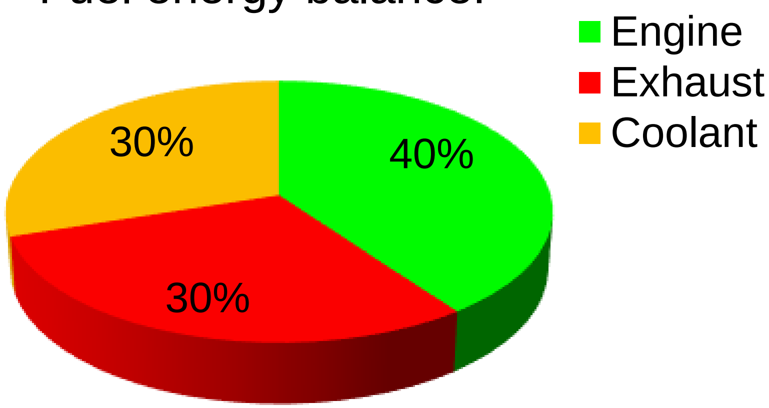
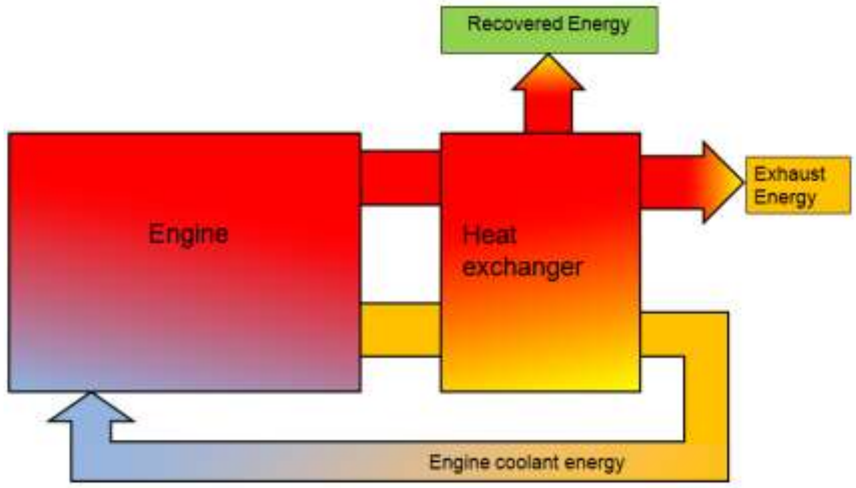
- Conclusion and next steps

Energy Balance – Waste Heat Recovery potential

- Great advances have been made in internal combustion engines in the recent years
  - Improved fuel consumption and reduced emissions
  - Current literature suggests that further improvements will not be so great
- WHR is now seen as a viable method of improving fuel consumption
- How it works
  - Heat is rejected by the engine
  - The waste heat recovery system converts this into useful power
- **Target: 10% fuel consumption improvement**
- Fuel energy balance:



Typical engine energy balance



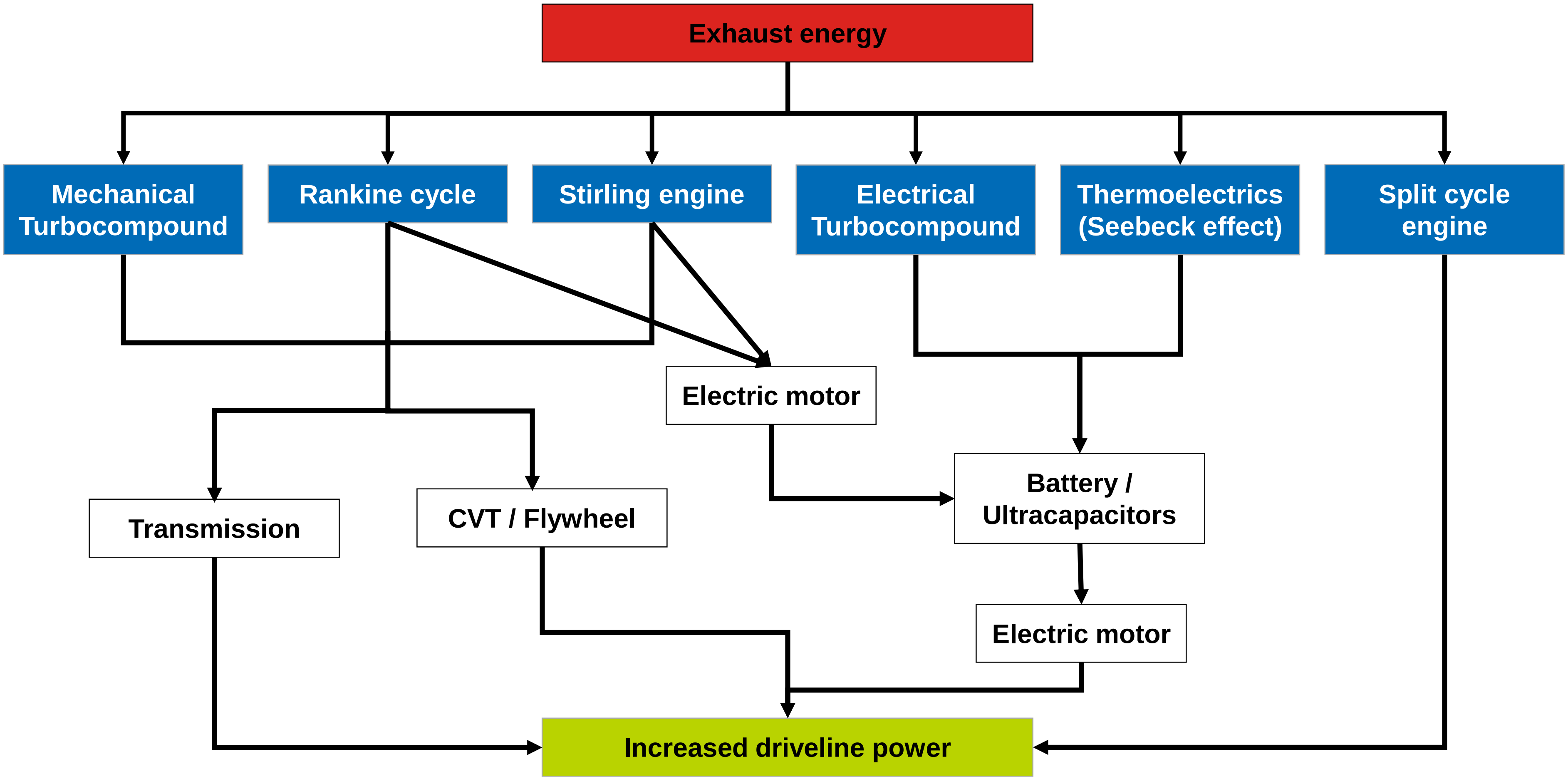
Typical WHR circuit

Several solutions are developed for Exhaust Heat Recovery
Solutions in bold are being studied actively for HDD/passenger cars

< 2025	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
ThermoAcoustic Generator	20-30%	3 - 10%	Passenger cars Heavy duty diesel, Marine, gensets	Packaging of resonance tube, low TRL	++	-	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)

> 2025

Coupling waste energy recovery and energy storage could lead to great fuel economy benefits



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)

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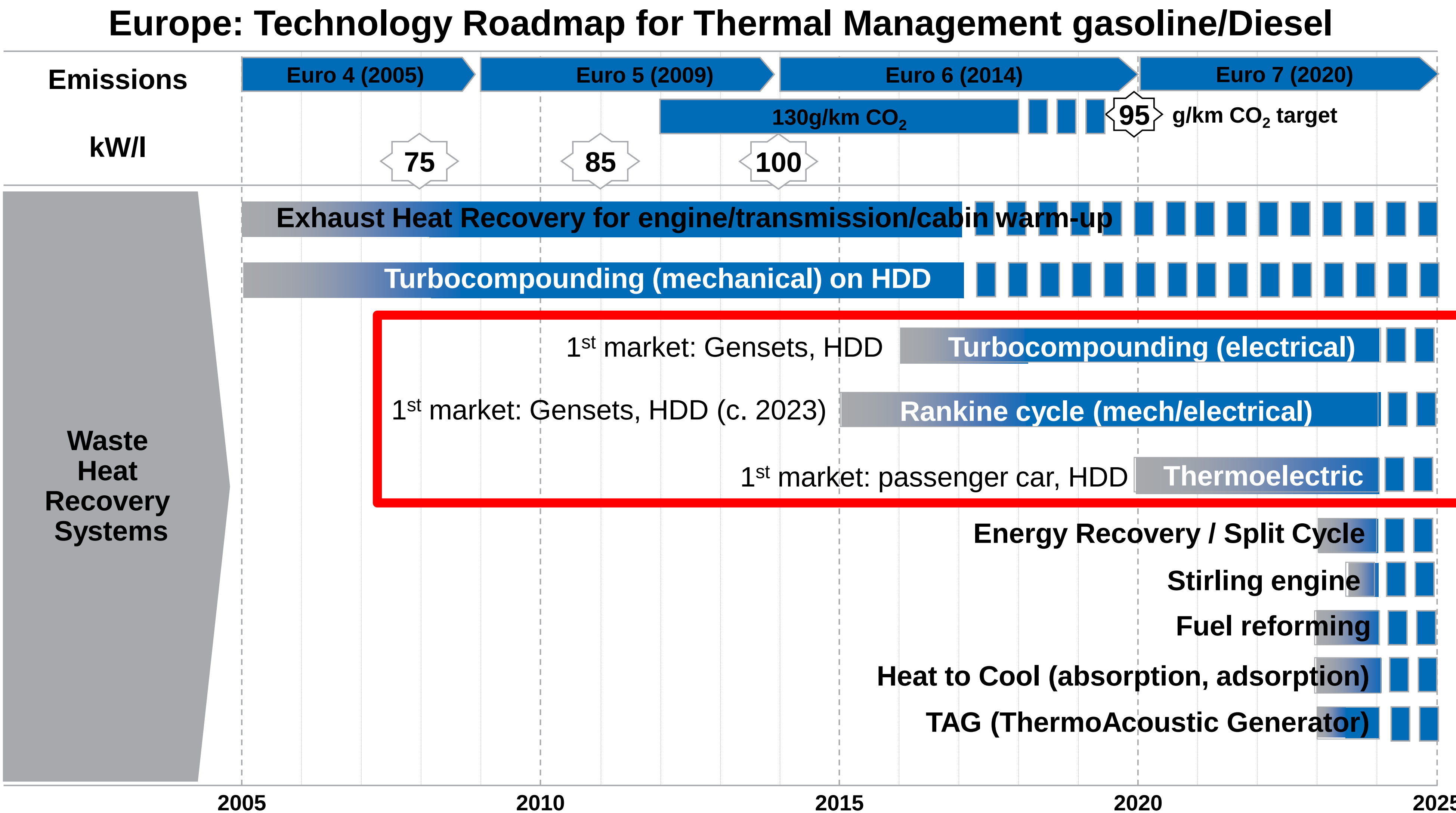
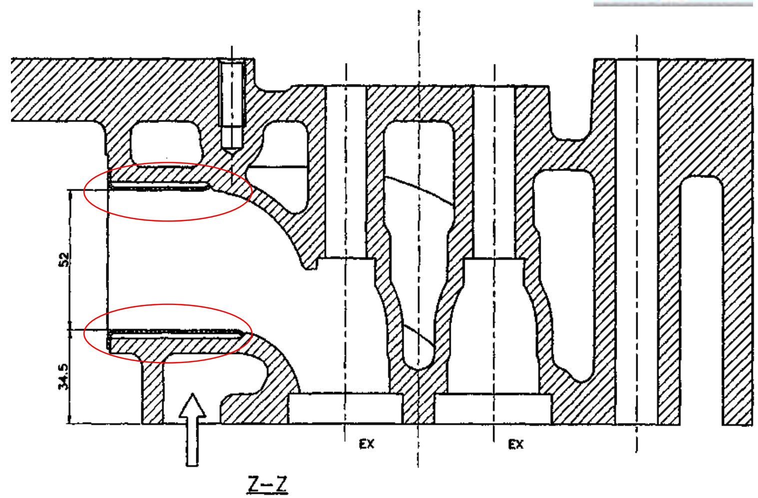


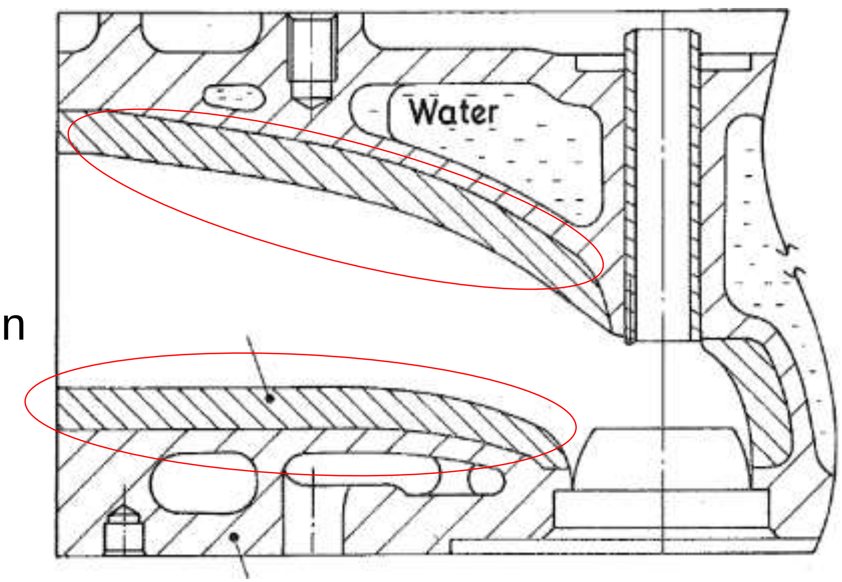
Source: Ricardo Analysis

WHR synergy with Low Heat Rejection engine (LHR), exhaust line insulation

- Ricardo has experienced different projects of **semi adiabatic engine** in the past involving following components:
  - Combustion chamber: piston flame face, cylinder head flame face, cylinder liner top section, intake and exhaust valves (ex.: silicon nitride, temperature swing materials from Toyota)
  - Exhaust port liner (ex.: aluminium titanate)

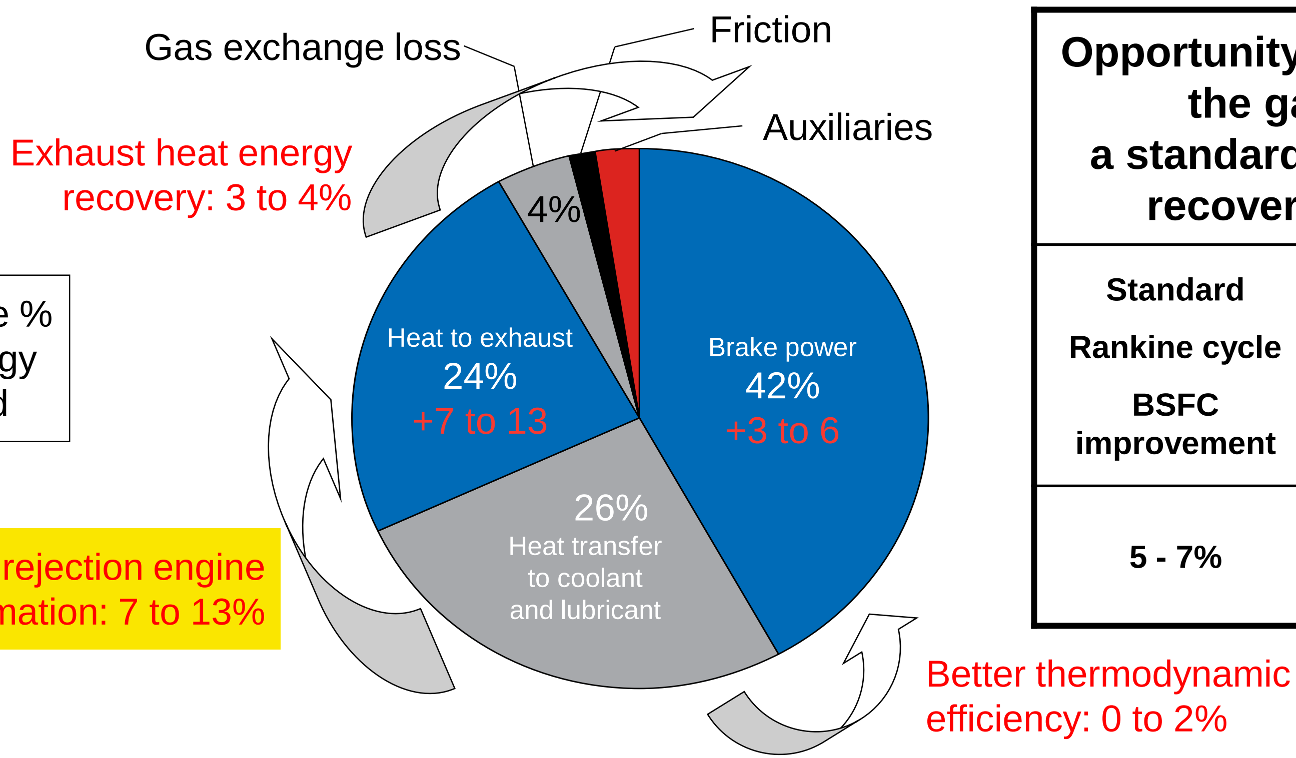
  With different ceramic materials:
  - Sprayed ceramic coatings (combustion chamber)
  - Ceramic inserts or air gap inserts (combustion chamber and exhaust port)
  - Cast or press-fit metal/air gap insulators (exhaust port)
- **Synergy with insulated exhaust line (specific coating)** for exhaust line thermal management for aftertreatment => will have benefits for WHR as well





Evolution on HDD/MDD/passcar (low heat rejection engine + WHRS): to increase the system efficiency we need to look at the source of the losses and their temperatures (example)

Numbers are % of fuel energy at full load



Low heat rejection engine transfer estimation: 7 to 13%

Opportunity to increment the gain from a standard heat energy recovery concept	
Standard Rankine cycle BSFC improvement	Rankine + low heat rejection engine BSFC improvement
5 - 7%	7 - 12%

Increased overall efficiency requires:

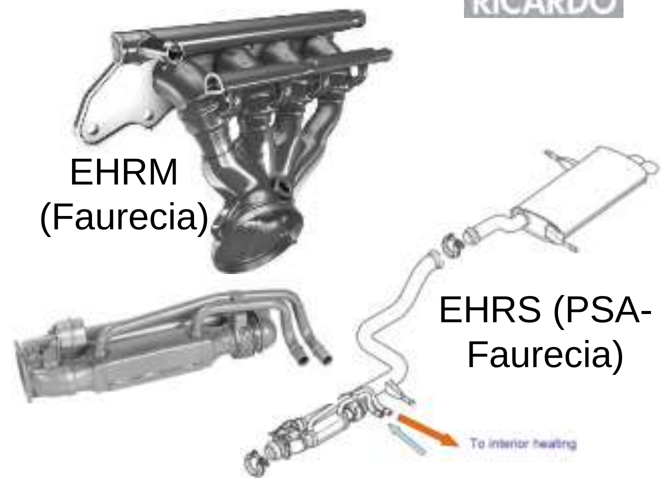
- ***Increasing the engine efficiency (ex: low heat rejection engine)***
- ***Recovering lost energy in exhaust (Rankine, Seebeck, Brayton, Turbocompound) and brakes (Hybrid, Flywheel)***

Exhaust Heat Recovery System EHRS – Heat to Coolant

On the market: PSA, Toyota, Ford, Honda, Hyundai

Technology Overview

- Objective
  - Accelerate warm-up by using adding heat to coolant within exhaust gas heat exchangers to heat coolant, thus accelerate engine warm up.
- Approach
  - System is installed after EATS (or Integrated Exhaust Manifold) and with coolant thermal mass, thus usually requires few hundred seconds to heat coolant sufficient to before system can aid in warm-up.
  - System continuously adds heat to cooling system, thus can maintain engine temperatures during cold ambient and helps with cabin heating
  - Control strategy must be implemented to allow the shut off of heat recovery once normal operating conditions achieved



Feature Summary		
System	Thermal Efficiency	
Proposal	**Exhaust Heat Recovery System**	
Concept	Reduce engine warm up time	
Potential Benefit Conditions	Warm Up	○
	Normal Operating Temperature	×
Potential CO_2 Impact	ECE	⇩
	EUDC	-
	NEDC	⇩0.5-1.5%
	Real World	⇩1%

Ricardo Assessment & Test results

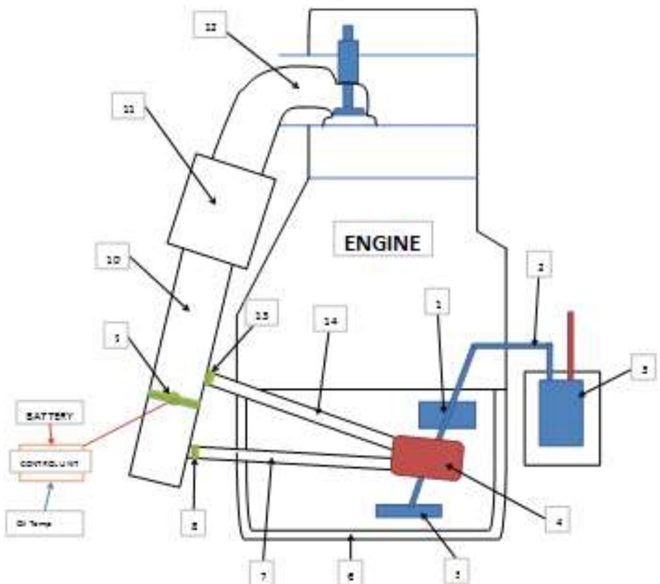
- Simulation data on coolant circuit (EHRS between gas and coolant) suggest that standard warm up efficiency can be improved by 0.5 to 1.5 %, however drive cycle must have a relatively long warm up period or start from a very low ambient to obtain fuel economy benefit

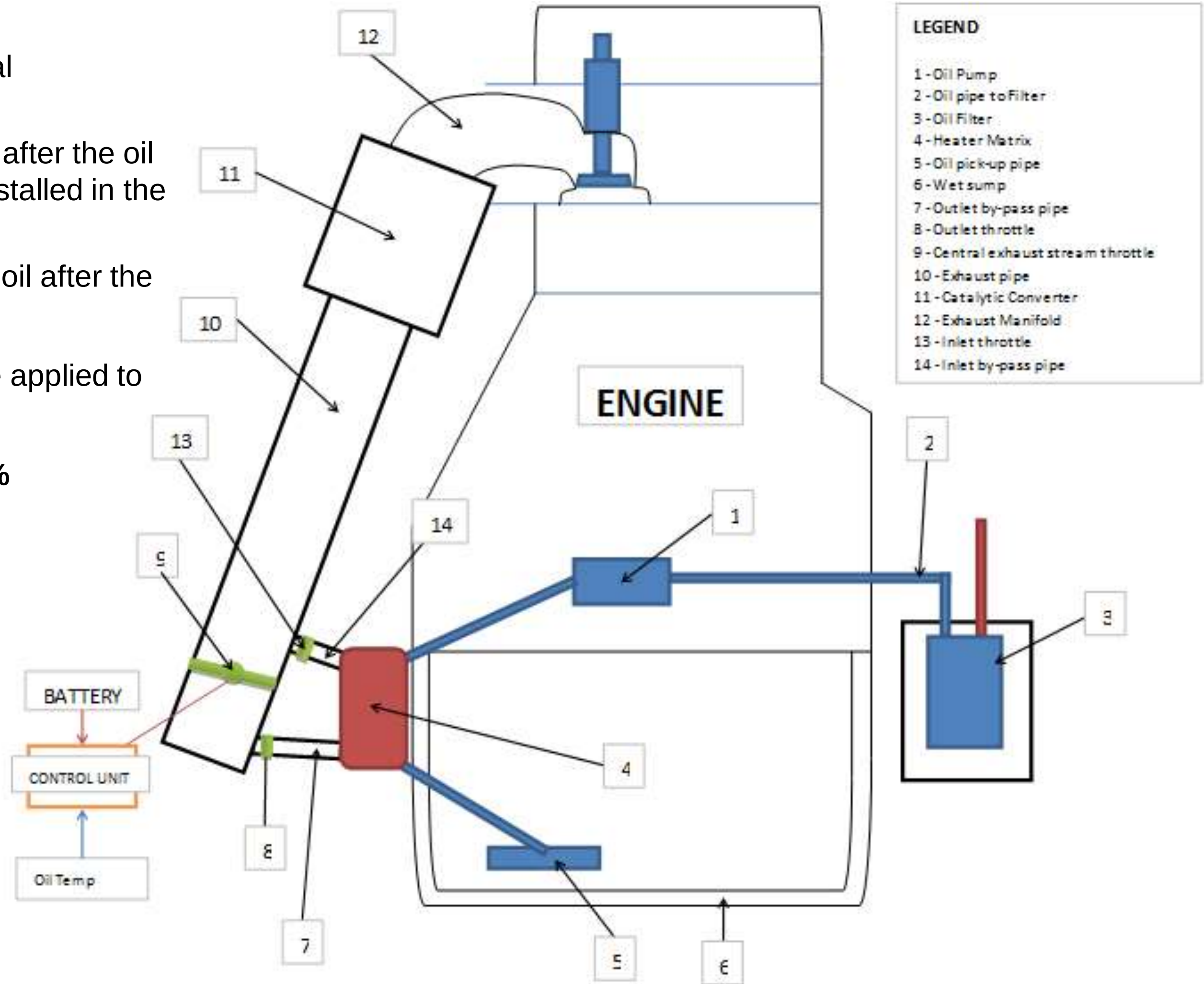
Toyota Prius 3 EHRS

Exhaust heat recovery systems are best suited to slower warm up engines / drive cycles where cabin heat assistance and very cold ambient fuel economy improvements are desired

Architectures for heating oil with exhaust heat: Heat to Oil

- Thermomanagement solutions are often applied to coolant circuit (improvement of combustion by reducing heat losses and indirectly friction) but improving oil warm-up helps **directly** reducing friction
- Ricardo has developed 2 concepts of thermal management focused on the oil circuit:
  - Use the exhaust heat to warm-up the oil after the oil pick-up pipe (exhaust heat exchanger installed in the sump or outside the sump)
  - Or use the exhaust heat to warm-up the oil after the oil pump
- The same concept (direct oil heating) can be applied to the transmission
- **Potential Fuel Consumption Benefit: 2-4%**





Ricardo proposes the same concept of direct oil heating for the transmission (automatic – eg with oil pump)

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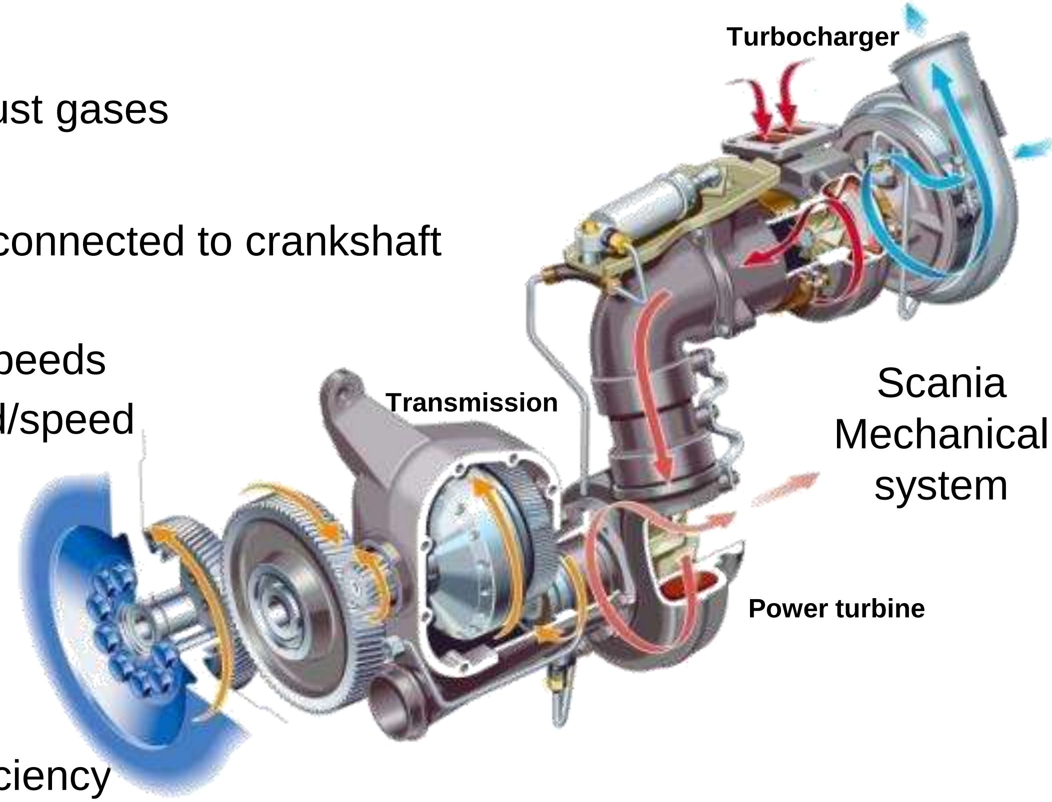
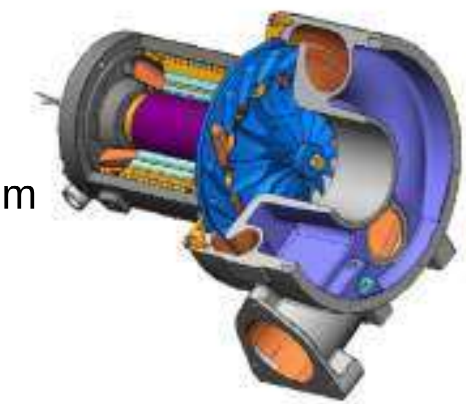
Turbo Compounding: turbine recovers energy from exhaust gas, can use energy directly (mechanical) or turn generator (electrical)

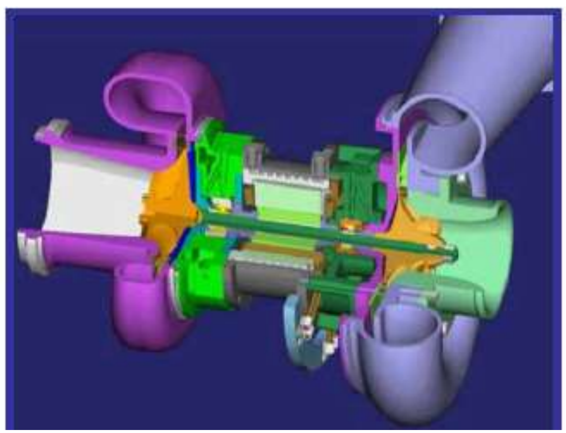
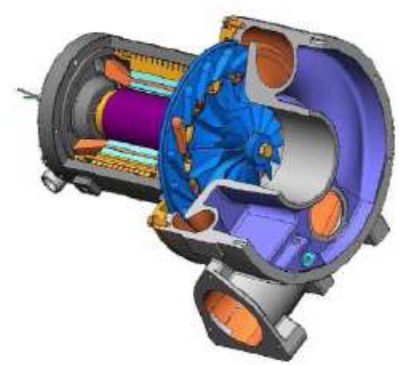
- Blowdown turbine recovers energy from exhaust gases
- System may be mechanical or electrical
  - **Mechanical** system: turbine mechanically connected to crankshaft
    - Contributes to crank work
    - Highest benefit at high loads and high speeds
    - Fuel economy may decrease at low load/speed
  - **Electrical** system: Turbine connected to electrical generator
    - Can charge battery
    - Can power auxiliary devices
    - Can operate at any load/speed
- Back pressure causes reduction in engine efficiency
  - Overall system gain is larger than loss
  - Back pressure acts as a type of internal EGR
  - NO_x benefits
- Increases engine power & pumping losses
- Particularly suited to heavy duty diesel



John Deere Electrical system

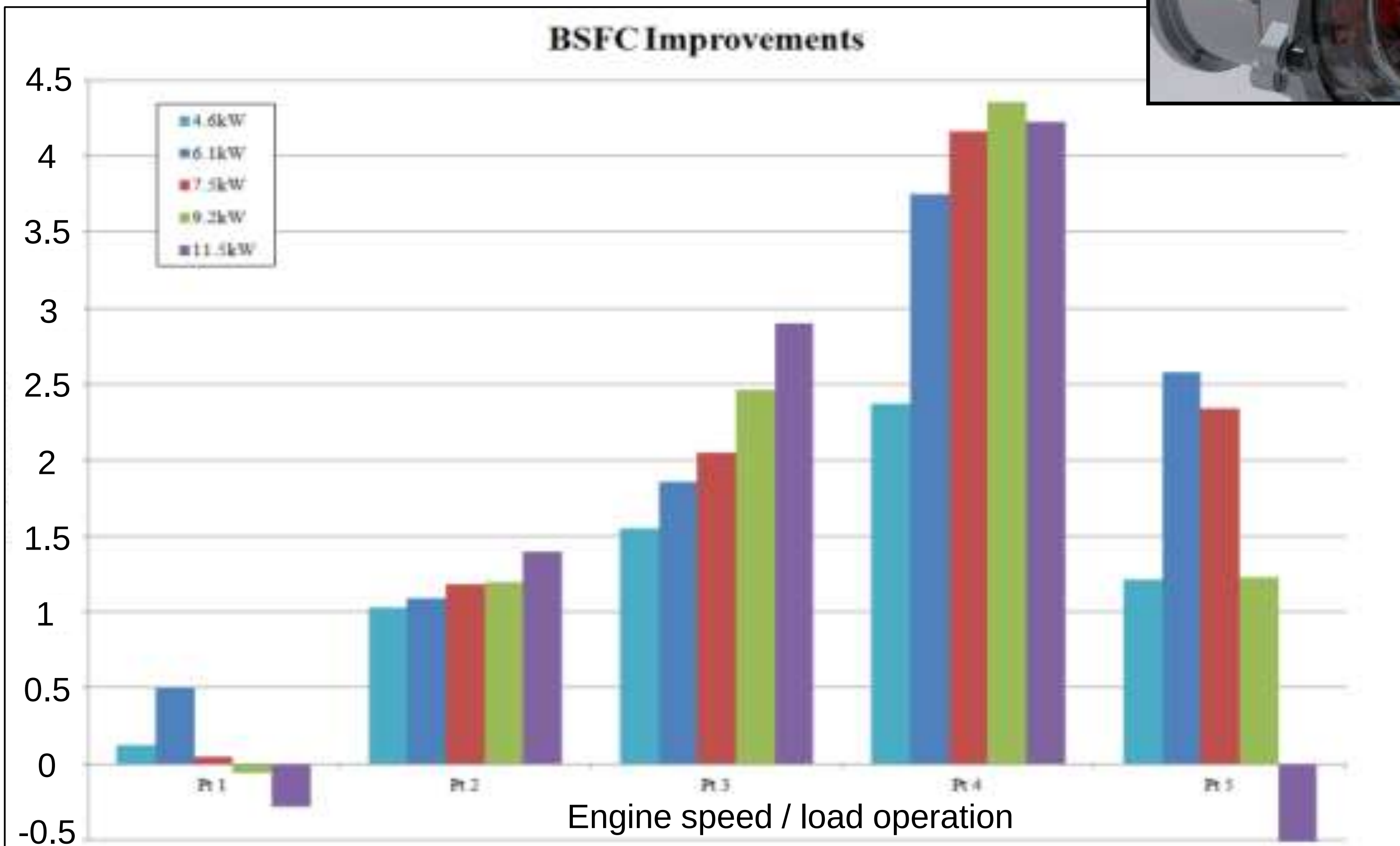


Electric turbogenerator (next step!) vs Electric turbine

	Electric turbogenerator	Electric turbine
Overview	• Generator inserted between Turbocharger	• Maintain existing Turbocharger and add separate turbine
Advantage	• Less complexity in term of vehicle/engine integration	• Freedom in electric motor shape and size • Possible to be reused in case of engine power change
Disadvantage	• Limitation to generator shape and size → Could limit power and cooling • New development needed for new engine	• Increase system complexity
Application examples	• Formula 1 (potentially other race applications) • BorgWarner	• CPT • Bowman • MHI •BorgWarner
Picture		

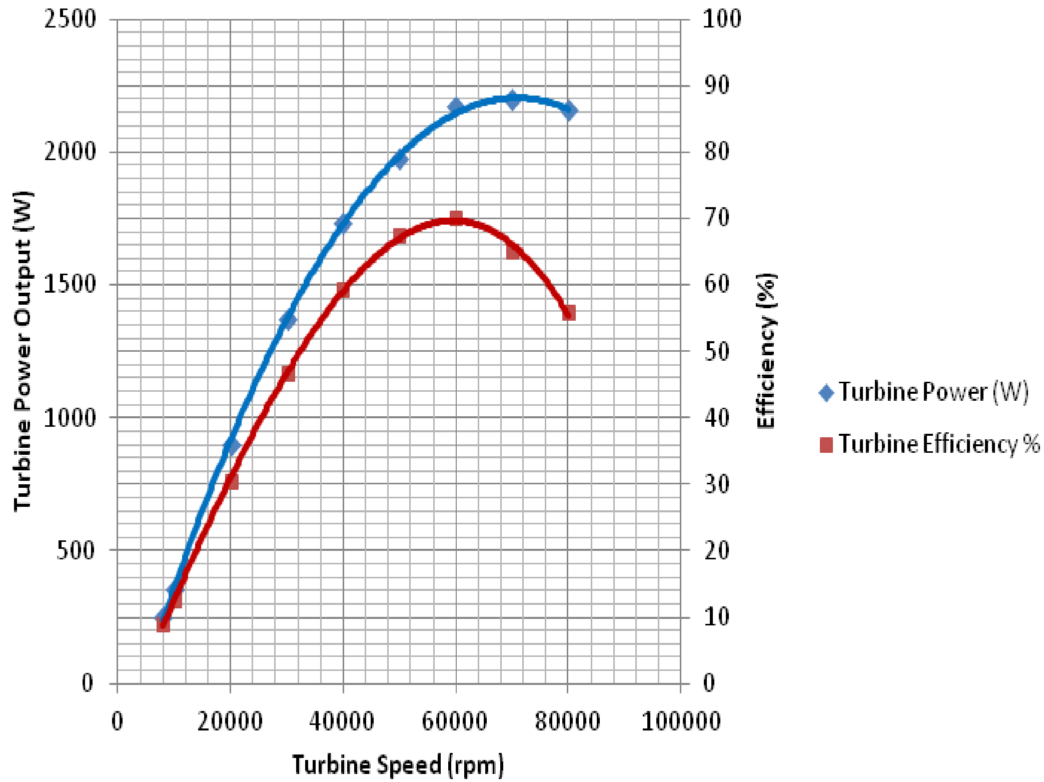
UK funded project - Thermal Energy Recovery System on Series hybrid bus - e-turbine Model Results (CPT, UK)

- **Results for the e-turbine have been produced at five key operating points**
  - An initial 4.5kW device produces a 2.4% improvement in BSFC at full engine load
  - A higher-power (9kW) device produces 4.3% improvement in BSFC
- **Increasing the power output of the e-turbine reduces this peak BSFC improvement**
  - Effect of backpressure is a critical consideration to the success of the system

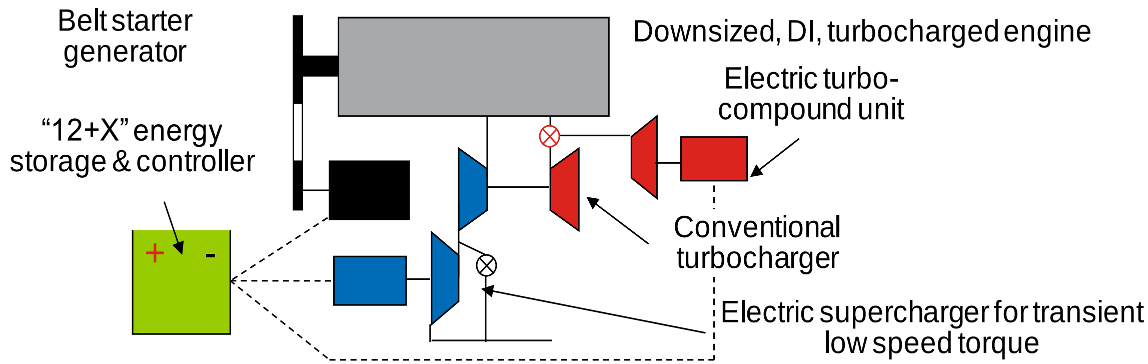


HyBoost (Innovate UK funded) - Low pressure ratio high performance turbine for e-turbine (CPT, UK)

- New turbine design developed to recover latent energy of discharged exhaust gases at low pressure ratio (1.05 - 1.3 bar) and to drive a small electric generator with continuous power output of 0.5 KW, max power output >2 kW
- The design operating conditions were fixed at 50000 RPM and 1.1 pressure ratio
- Commercially available turbines are not suitable for this purpose due to the very low efficiencies experienced when operating in these pressure ranges.



Requirement for the turbocompound unit:
- Operating speed: 50000 rpm
- Cont Power : 0.5 kW
- Peak Power: >2 kW
- PR : 1.05 – 1.3



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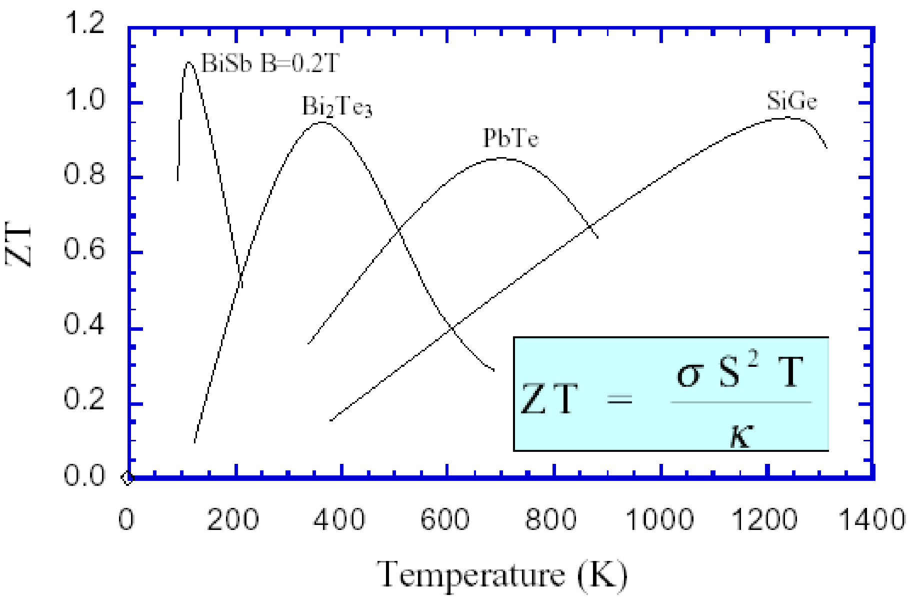
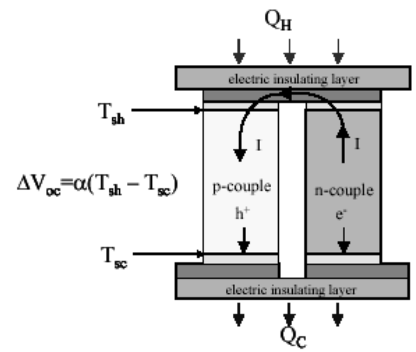
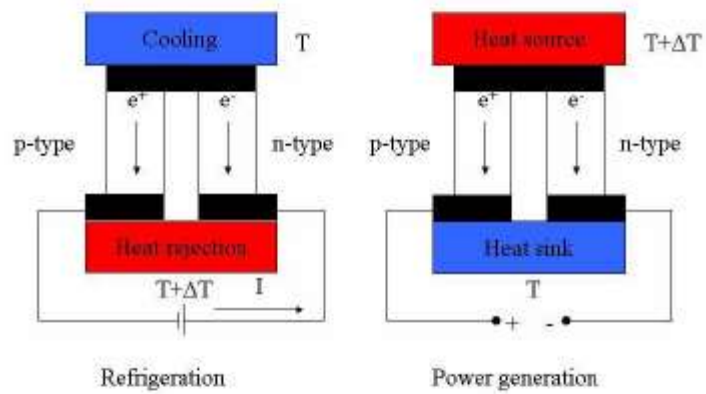
Waste Heat Recovery System: Seebeck thermogenerator

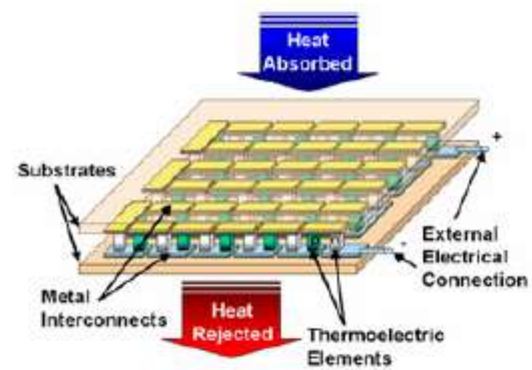
- ZT (merit coefficient) characterizes the energetic efficiency of materials
- System total efficiency depends on:
  - ✓ ThermoElectric material
  - ✓ Thermal contact resistance
  - ✓ Temperature of hot and cold sources
- <u>Objectives</u>: high **electric** conductivity, low **thermal** conductivity



T° difference (top-bottom) on TE material



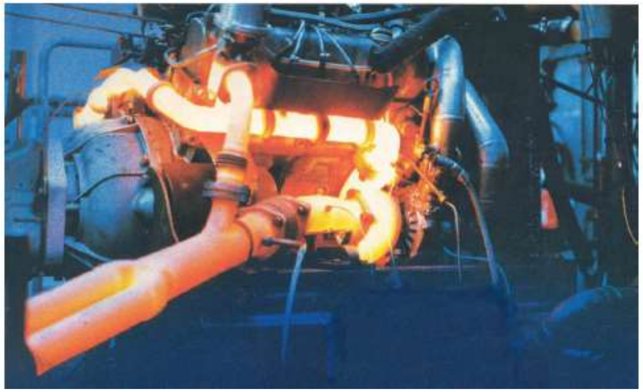




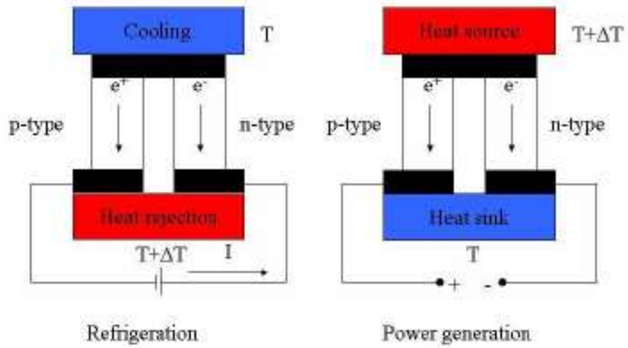
Key market applications – focus on Internal Combustion Engines

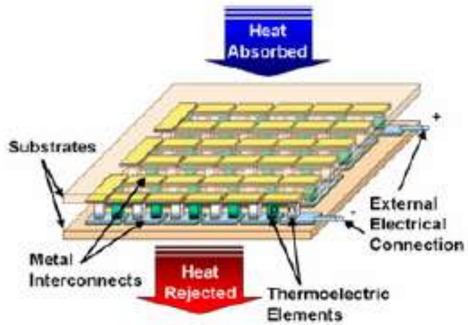
- Seebeck effect – Heat to Electrical Power for reduction of fuel consumption and CO2 emissions:
  - **Internal Combustion Engines:**
    - **Passenger car – Diesel, gasoline engines <u>~ 0.5-1 kW</u>**
    - **Heavy Duty Vehicles – Diesel, natural engines <u>~ 2-5 kW</u>**
    - **Stationary engines – Diesel, Natural gas <u>> 5-100kW</u>**
    - **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



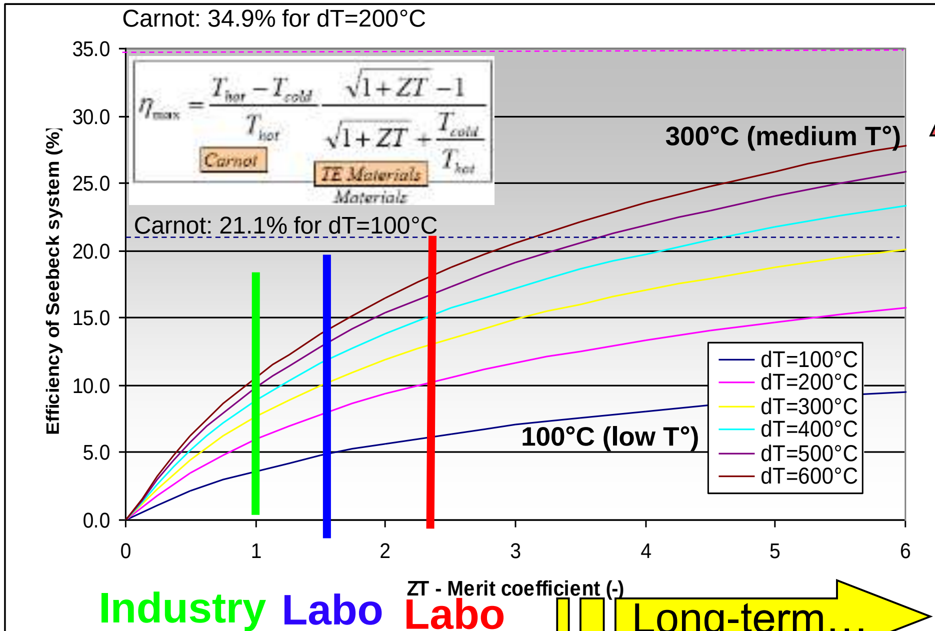


Evolution of ZT coefficient and thermogenerator efficiency

- Way of improving the thermogenerator efficiency = increasing ZT
  - Example of BiTe: **ZT doping with nanostructures**

Industry objective: ZT=1.5

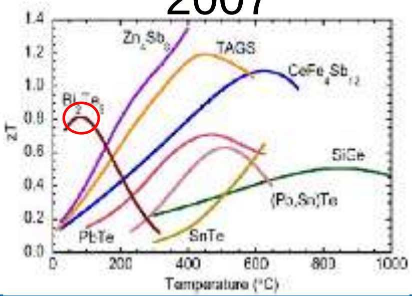
Evolution of Seebeck system efficiency for different dT(hot-cold) versus Merit Coefficient



Industry 2007 | Labo 2008 | Labo 2010 | Long-term…

Evolution of dT = temperature difference between hot side and cold side of ThermoElectric material

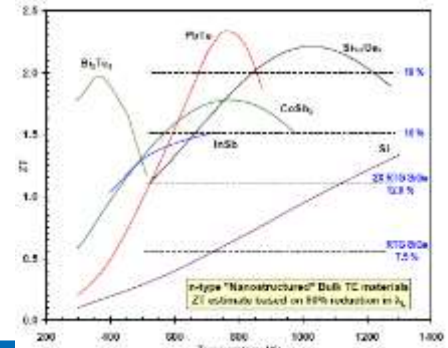
2007



Evolution: ZT doping

Nanostructure ThermoElectric Material

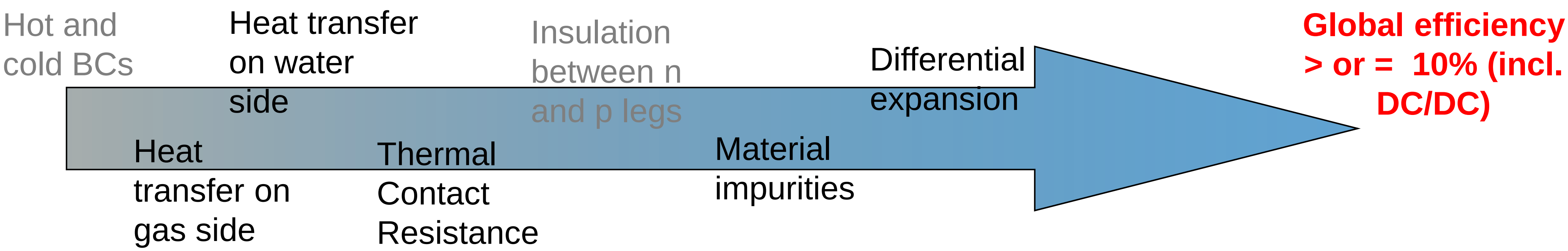
Research laboratories: 2009



Thermogenerator development – challenges for production

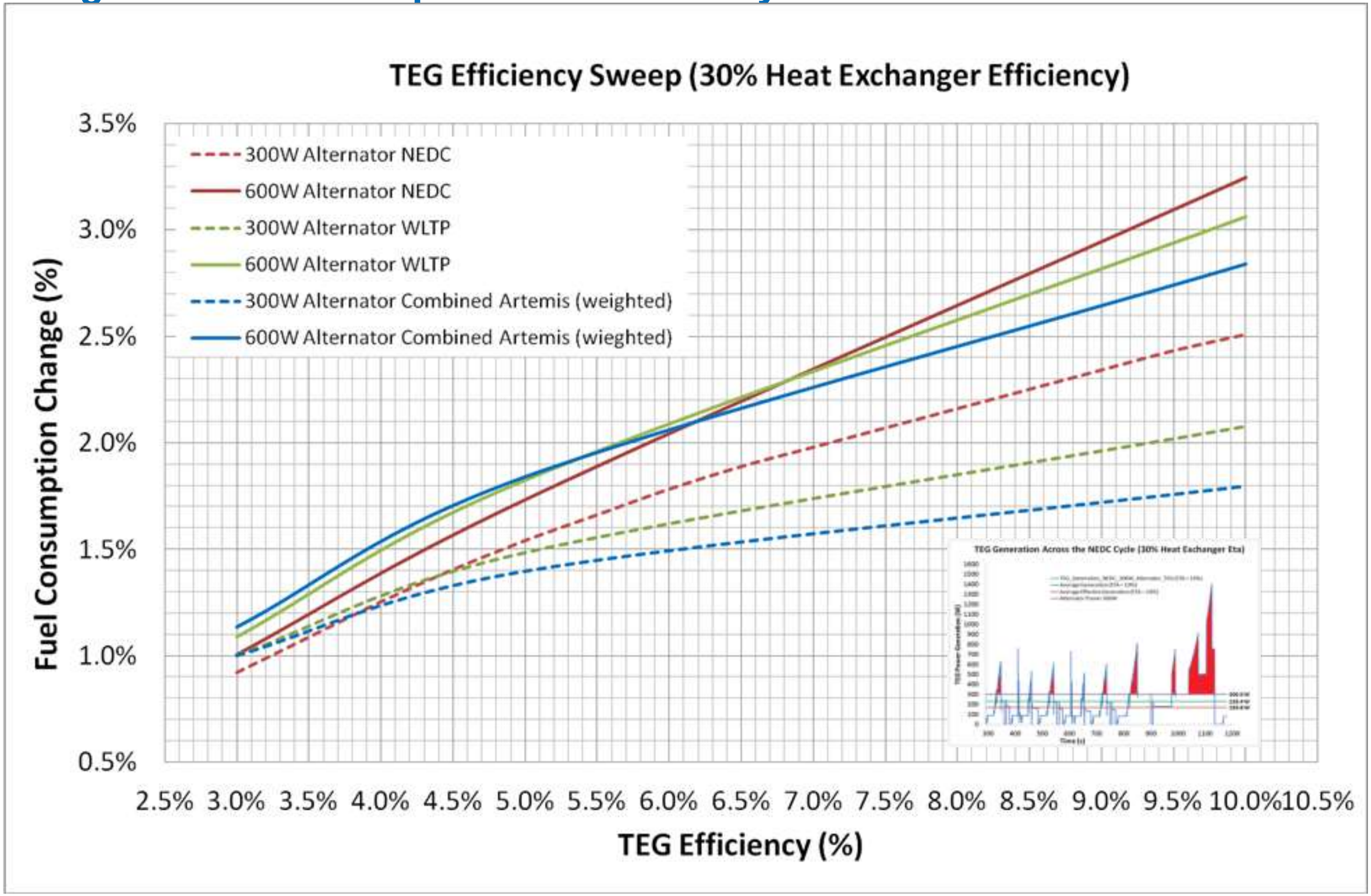
- Challenges in simulations, specifications, tests, FMEA, risk & hazard analysis with the aim of developing a 10% efficiency thermoelectric generator
- **Thermoelectric components :**
  - Assembly process / High T° brazing and differential expansion
  - Insulation for reducing thermal losses between p and n joints (aerogel) => no issue/risk with Silicides
  - Improvement merit coefficient ZT (now 0.8 – objective 1.5-2) : segmentation for materials for optimising ZT / T°
- Efficient heat transfer on exhaust line without increasing the pressure drop (usually: + 100 mbar on exhaust line => - 1 kW on the engine's shaft)
- Electric production strategies (HW / SW) : electric auxiliaries / strategy / DC/DC – MPP Tracker
- **Develop supply chain with Tier1/2 suppliers – see H2020 funded projects**

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



BC: Boundary Condition

Fuel consumption benefit over NEDC/WLTP/Artemis with Thermogenerator – sweep of TEG efficiency

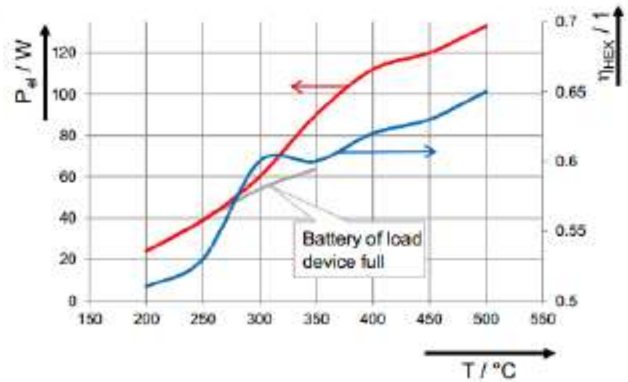


Case study – Powerdriver (European funded project)

- Thermoelectric prototype for 2l GTDI D-segment (prototype built by ETL and Ricardo)

- Test results: > 130W at 500ºC gas

- Testing conditions
  Torque applied to the clamping bolts: increased to 25Nm (from 13Nm in Test 8)
  - Hot Gas: m=150kg/h, Variation of T = 200°C, 250°C, 300°C, 350°C, 400°C, 450°C
  - Coolant: T = 50°C, v = 30ℓ/min
- Results
  - Electricity:
    - at 200°C P = 23.4W
    - at 250°C P = 38.6W
    - at 300°C P = 61,4W
    - at 350°C P = 90.3W
    - At 400°C P = 111.9W
    - At 450°C P =119.6W
    - At 500°C P =133.0W



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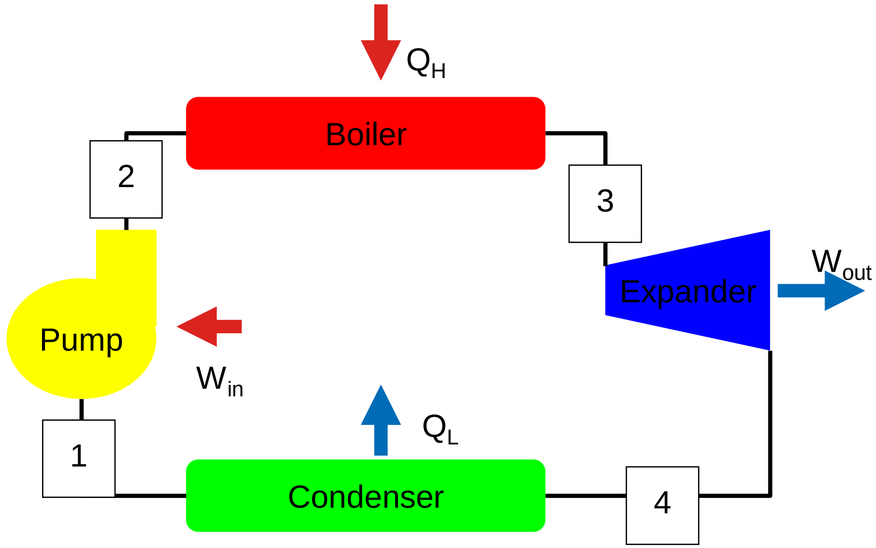
Rankine cycle & Organic Rankine cycle use the traditional 'steam engine' configuration to turn an expander using exhaust and/or coolant heat as input

- The main components of the ORC are shown:
  - Pump
    - Controls fluid mass flow and system pressure
  - Heat exchange:
    - Transfers waste heat from engine to working fluid
  - Expander:
    - Extracts energy from the working fluid
  - Generator:
    - Converts expander rotational power to electricity
  - Condenser
    - Returns the working fluid to a liquid

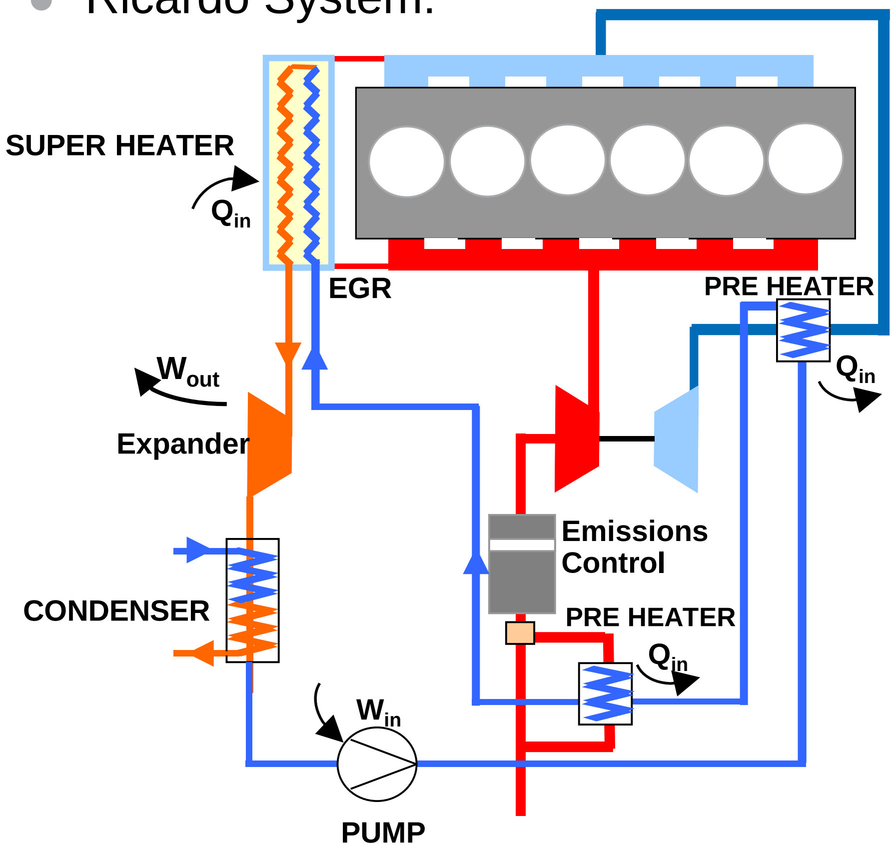


- Organic Rankine Cycle: use organic material as working fluid (ex: R245fa)
  - High molecular mass
  - Low working temperature

Ricardo has made significant investments in developing waste heat recovery technologies & has defined a practical system

- Ricardo experience:
  - Exhaust heat recovery Rankine cycle analysis and heat exchanger specification
    - Rankine cycle analysis and specification experience
    - Components sourced from available hardware
  - Organic Rankine cycle simulation, design, definition, procurement
    - Design of test cell installation of WHR system applied to engine
    - Simulation and specification of components
    - Source and procurement of components
    - Definition of control system
    - Test plan and instrumentation definition

- Ricardo System:



- Drive Cycle (HDD):

	ORC 5% efficiency	ORC 10% efficiency
Approximate average power recovered (kW)	4.2	8.5
Approximate energy recovered (MJ)	15.2	30.4
Total brake energy produced by engine (MJ)	484.7	
% energy recovered compared to brake energy output	3%	6%

Case Study: HDD (US DOE Supertruck project)
Fuel Economy Improvement using ORC from Exhaust and EGR

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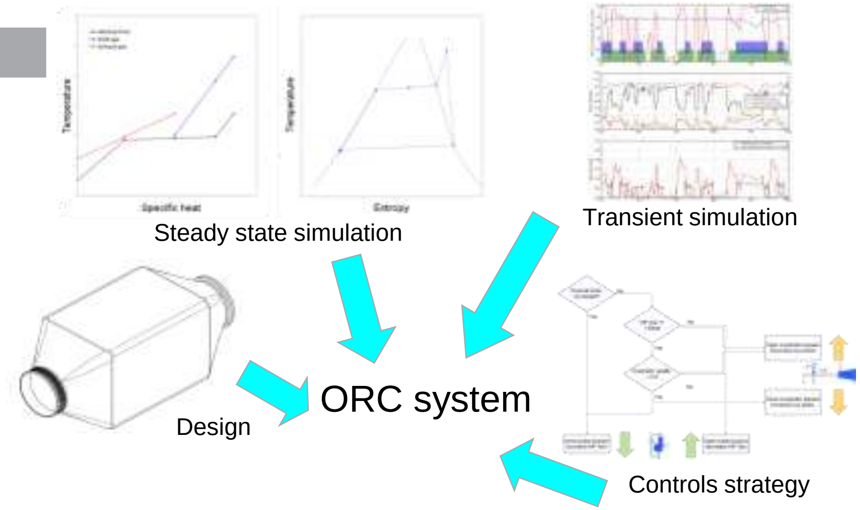
Waste Heat Recovery	ORC system simulation, design and test

Situation and Objective

- Design, build and test a mechanically direct coupled ORC system using EGR and exhaust
- Steady state simulation completed to establish system layout, working fluid, component sizes
- Transient simulation completed to design control strategy to achieve EGR temp, limits and power
- System procured and installed on engine
- Testing, development and ORC strategy calibration under way



Ricardo Responsibilities

- Working fluid, component selection and design
- FMEA and risk assessment
- Component procurement and build
- Steady state and transient simulation
- Controls strategy and controller
- Test ORC system installed onto engine

Results and Benefits

- >6% fuel economy improvement possible, drive cycle dependent
- System designed to minimize additional heat from cooling pack
- EGR temperature maintained during transient events

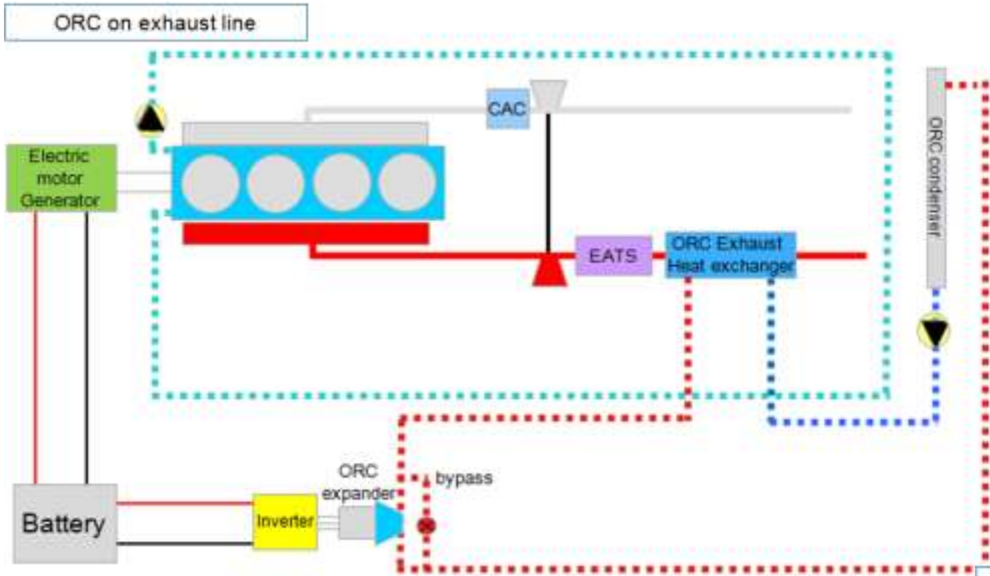
UK funded project: Thermal Energy Recovery System (TERS) - Series HEV bus with dual ORC loop

- 3 year project: Thermal Energy Recovery System
  - 2011-2014
- Collaboration between four partners
  - Queen's University Belfast
  - Wrightbus
  - Ricardo
  - Revolve
- Project funded by :
  - Invest Northern Ireland
  - UK Technology strategy Board

Wrightbus Gemini II as shown at the CENEX 2013 event
With two ORC systems

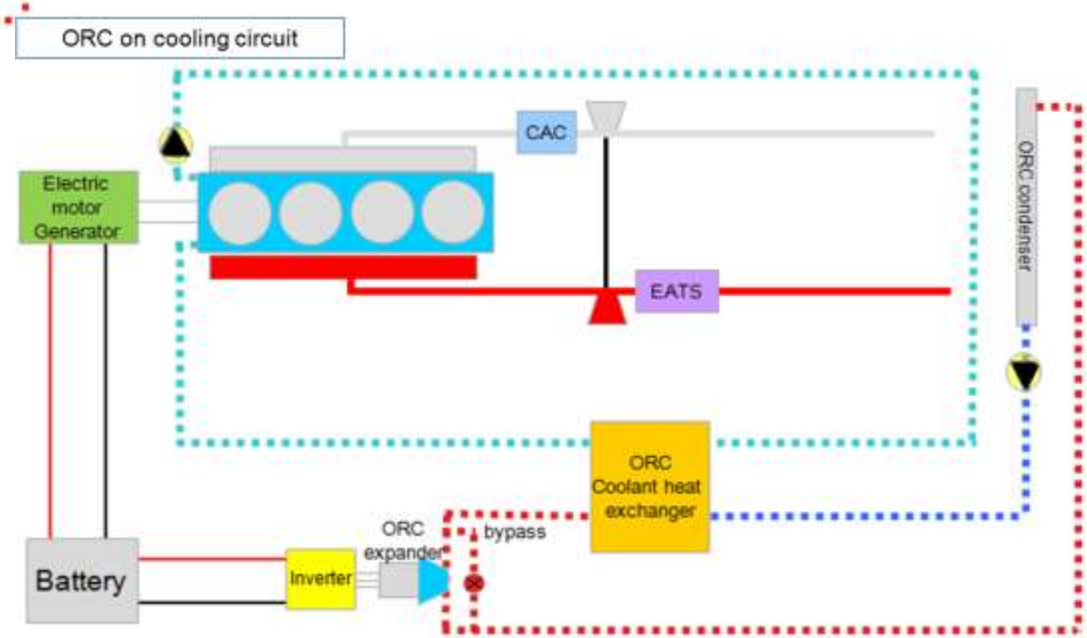
- Objective
  - To improve the double deck bus fuel economy by 10%
- The objective to be met through the thermal management of the bus
  - Research focussing on Waste Heat Recovery
- Develop a prototype system capable of demonstrating the potential
- Demonstration on Series HEV bus using an ORC on exhaust line and an ORC on engine cooling circuit

Hybrid Double Deck Bus: Vehicle Prototype with Two ORC Systems



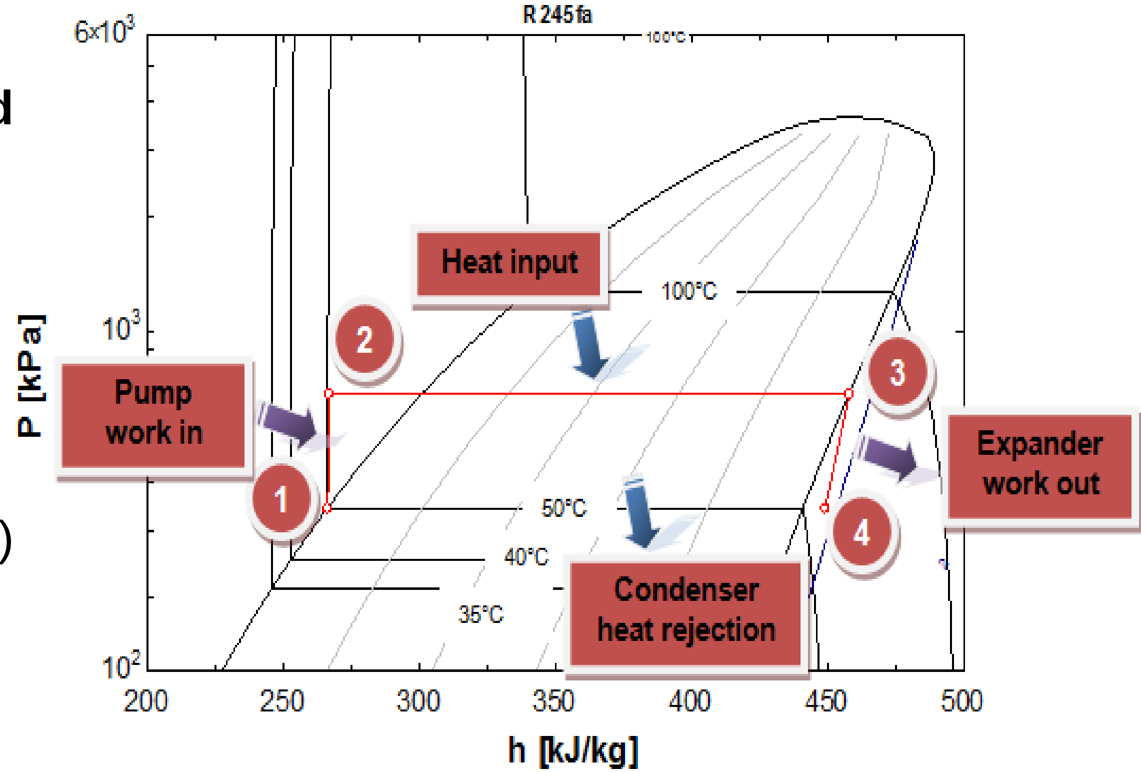
ORC on exhaust line requires additional cooling system

ORC on engine coolant does NOT require additional cooling system as it is replacing engine radiator by ORC condenser (only additional cooling required for reaching cold refrigerant temperature



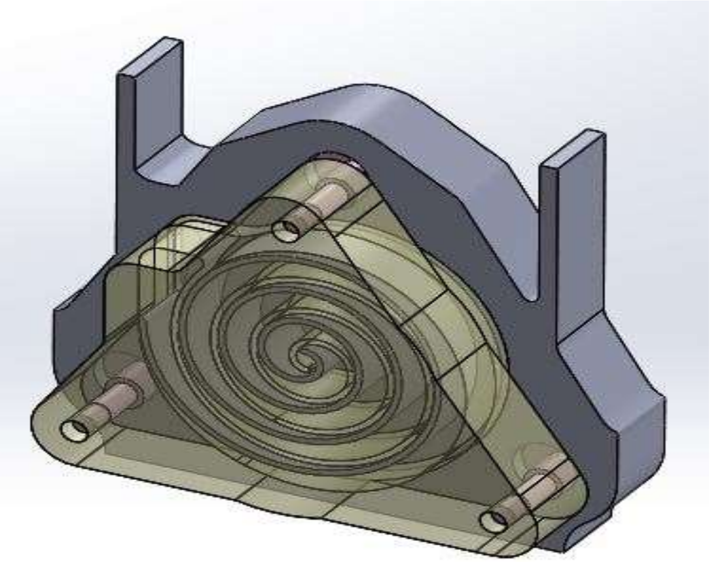
ORC Components – Fluid selection

- Refrigerant
  - **R245fa used in TERS => replaced by 1233zd**
  - **Ethanol used mainly (HDD)**
  - Other fluids:
    - R134a, R1234yf, R245ca, R236fa, butane and carbon dioxide, toluene, CO_2 (supercritical, future applications)
  - Considerations:
    - Public safety
    - Toxicity
    - Flammability
    - Environmental impact
    - Fluid compatibility with system/seals
    - Working pressure
    - Temperature degradation



ORC Components - Expander

- Expander choice
  - **Scroll used in TERS project**
    - Rotational speed
    - Not sensitive to droplet formation
    - Compatible pressure ratio
    - Relatively low cost
    - Reliable as a compressor in refrigeration industry
    - Low part count & no valves
    - Self starting

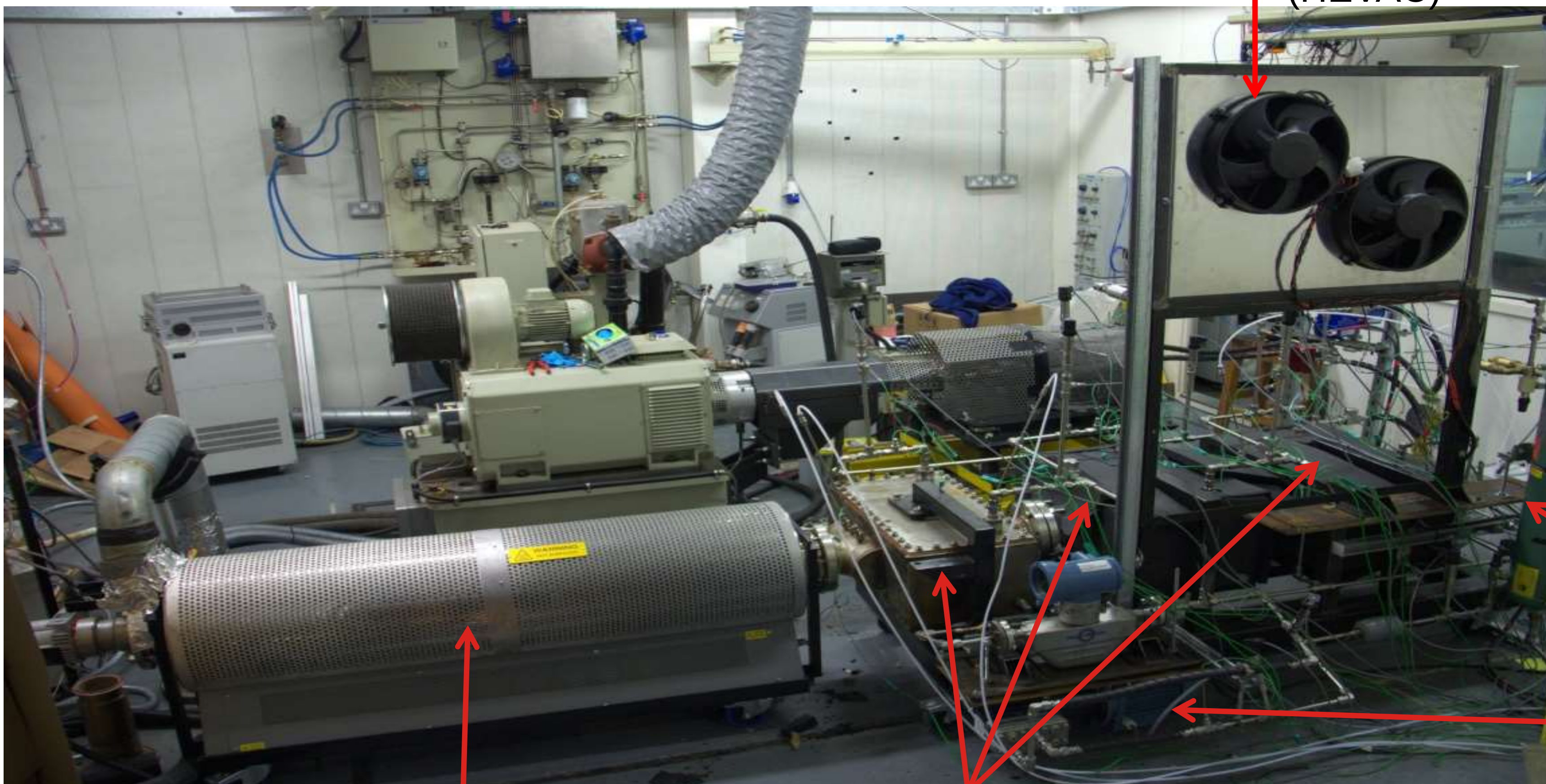


Internal model of a scroll expander

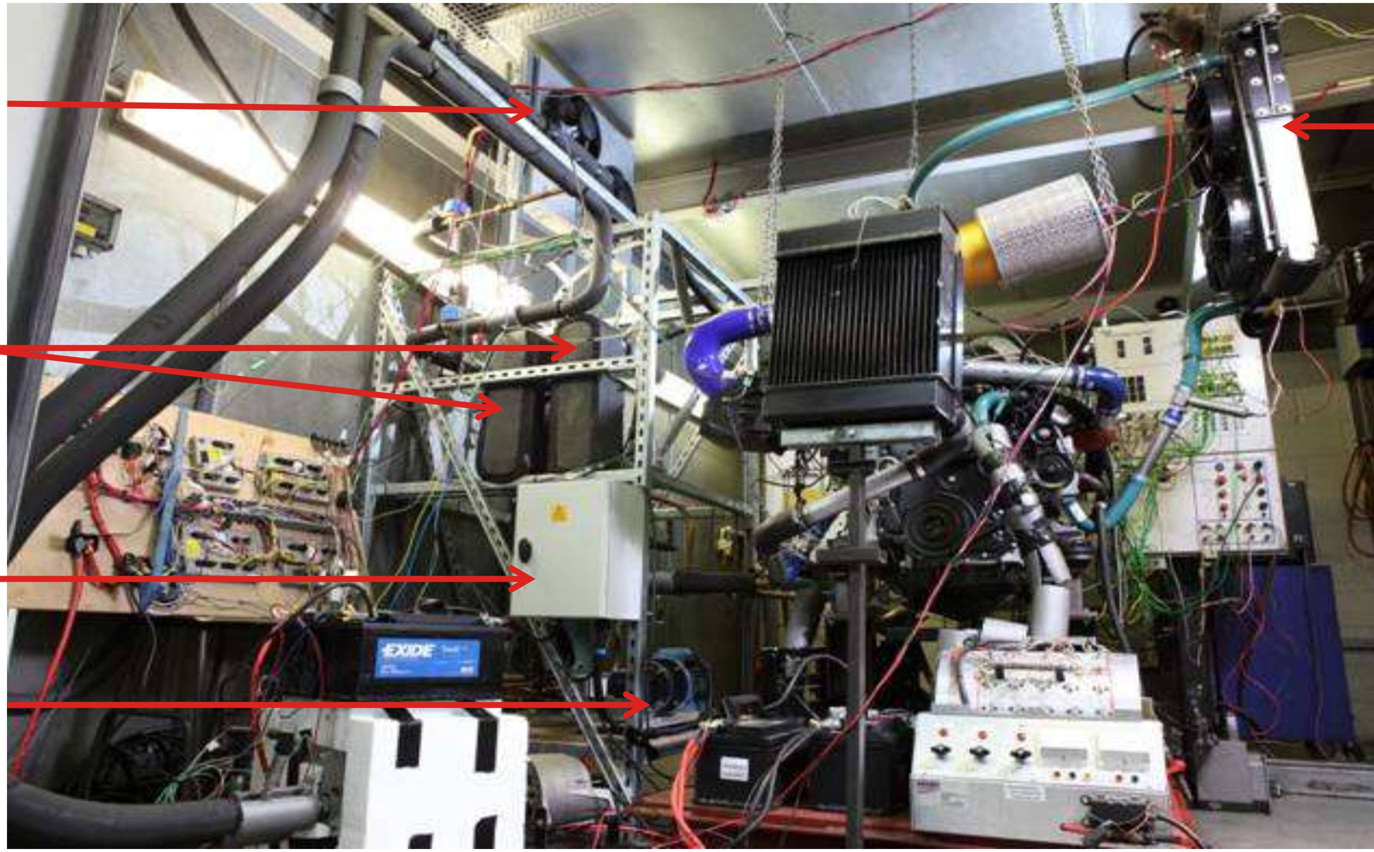
- Other options explored
  - Reciprocating piston
  - Sliding vane
  - Swash-plate
  - Turbine
  - Gerotor

Exhaust ORC testrig

- ORC exhaust testrig using hot air furnace used to commission the ORC system



Coolant ORC

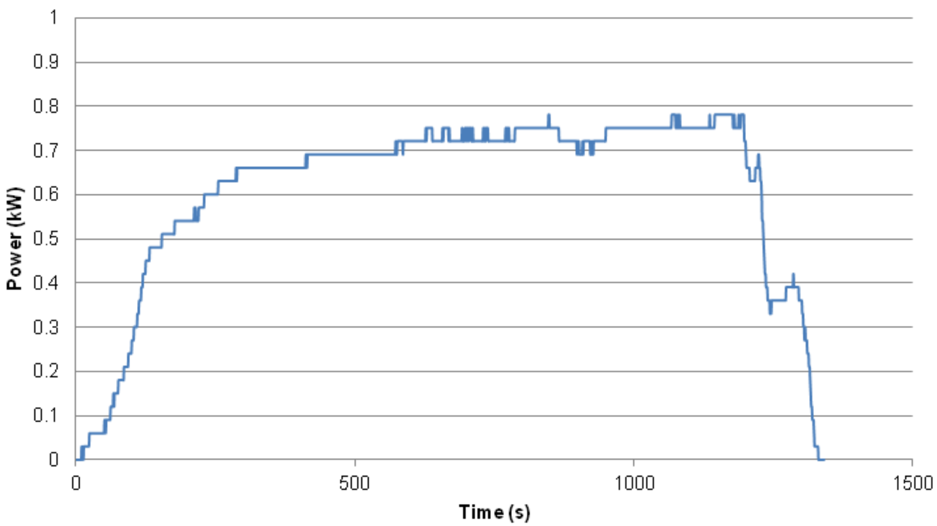


Engine test Cell Setup

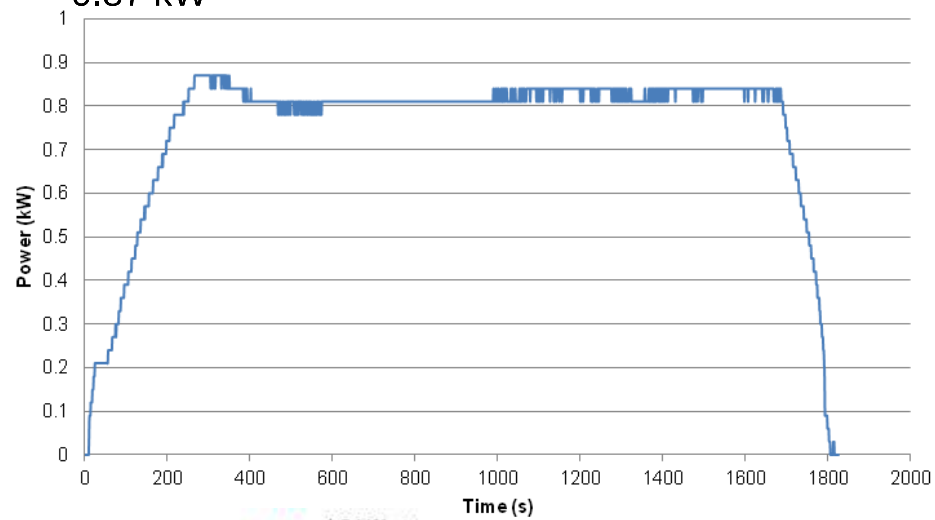
Diesel engine with R245fa heat exchangers, control board, expander unit, variable load bank, mass air flow meter, temperature and pressure instrumentation, smoke and emissions equipment installed

Vehicle Testing: Coolant and Exhaust ORC Power Delivery

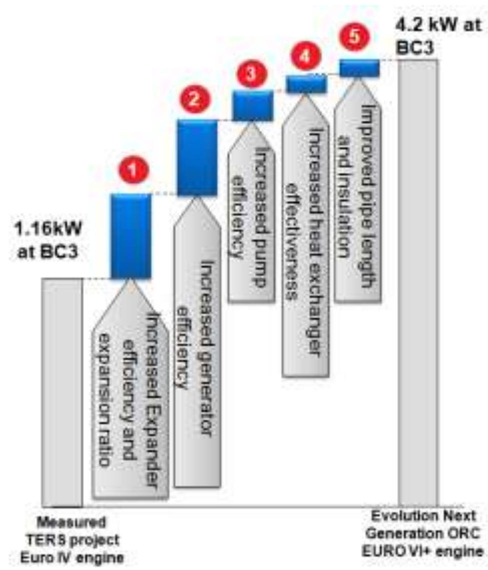
- Coolant system performance
  - At BC 3, coolant expander generated: 0.75 kW



- Exhaust system performance
  - At BC 3, exhaust expander generated: 0.87 kW



- Improvements to the next generation of ORC for hybrid bus should include the following technical solution:
  - Actual components were not at higher efficiencies due to the use of “off-the-shelf” components



ORC testbed in Brighton University, UK

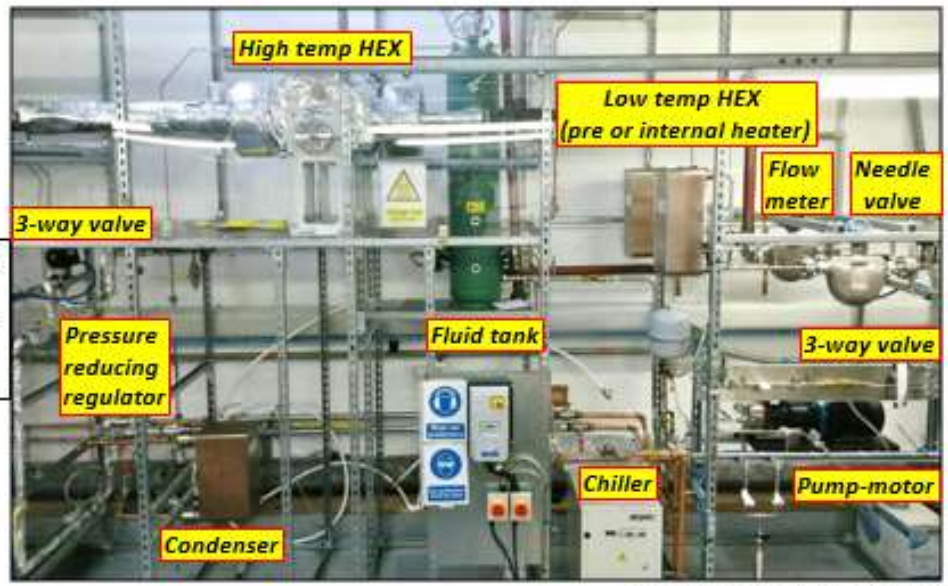
Contact: Dr. Rob Morgan (R.Morgan2@brighton.ac.uk)

University of Brighton

An in-house flexible organic Rankine cycle test-rig

- Fluids: alcohol, water & alcohol-water blends
- Heat source quality & quantity: 250°C & 25kW to 500°C & 100kW (Note: dependent on heat exchanger back pressure)
- Heat recovery arrangement: Series and parallel heat recovery (Note: option to modify for internal heat recuperation and coolant heat recovery possible)
- Flexibility: Wide range of component testing possible
- Max. fluid pressure: 40bar
- Max. fluid temperature: 275°C
- Min. fluid temperature range: 20-70°C
- Auxiliaries: Additional cooling and lubrication loops for expanders & turbines possible

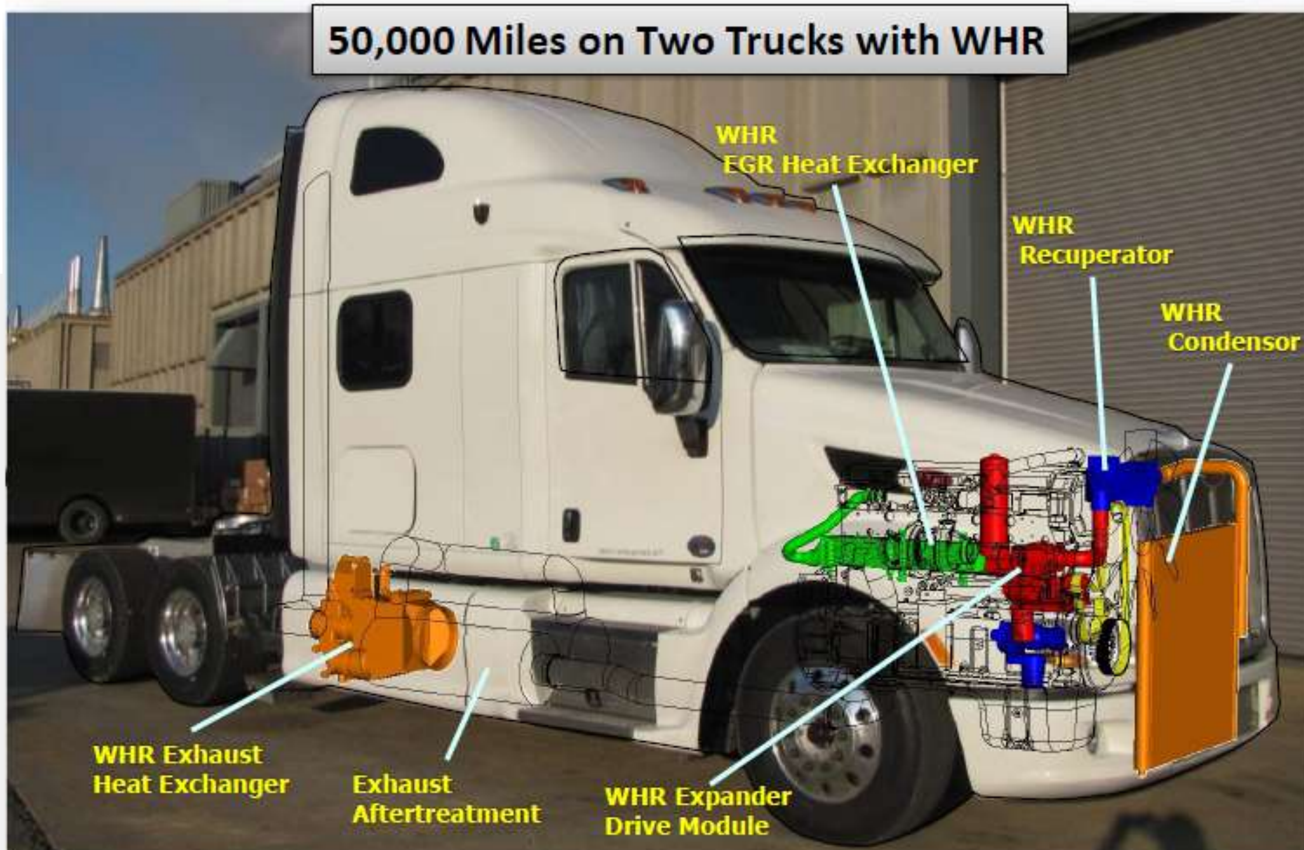
Current work involves integration a free piston expander



Acknowledgement: Innovate U.K

Example of ORC integration: Cummins presentation showed prototype Truck System testing

Waste Heat Recovery Trucks on Road



Significant focus on System Cost

26

Cummins Inc. - 9th Diesel Emissions Conference & AdBlue Forum Europe 2013

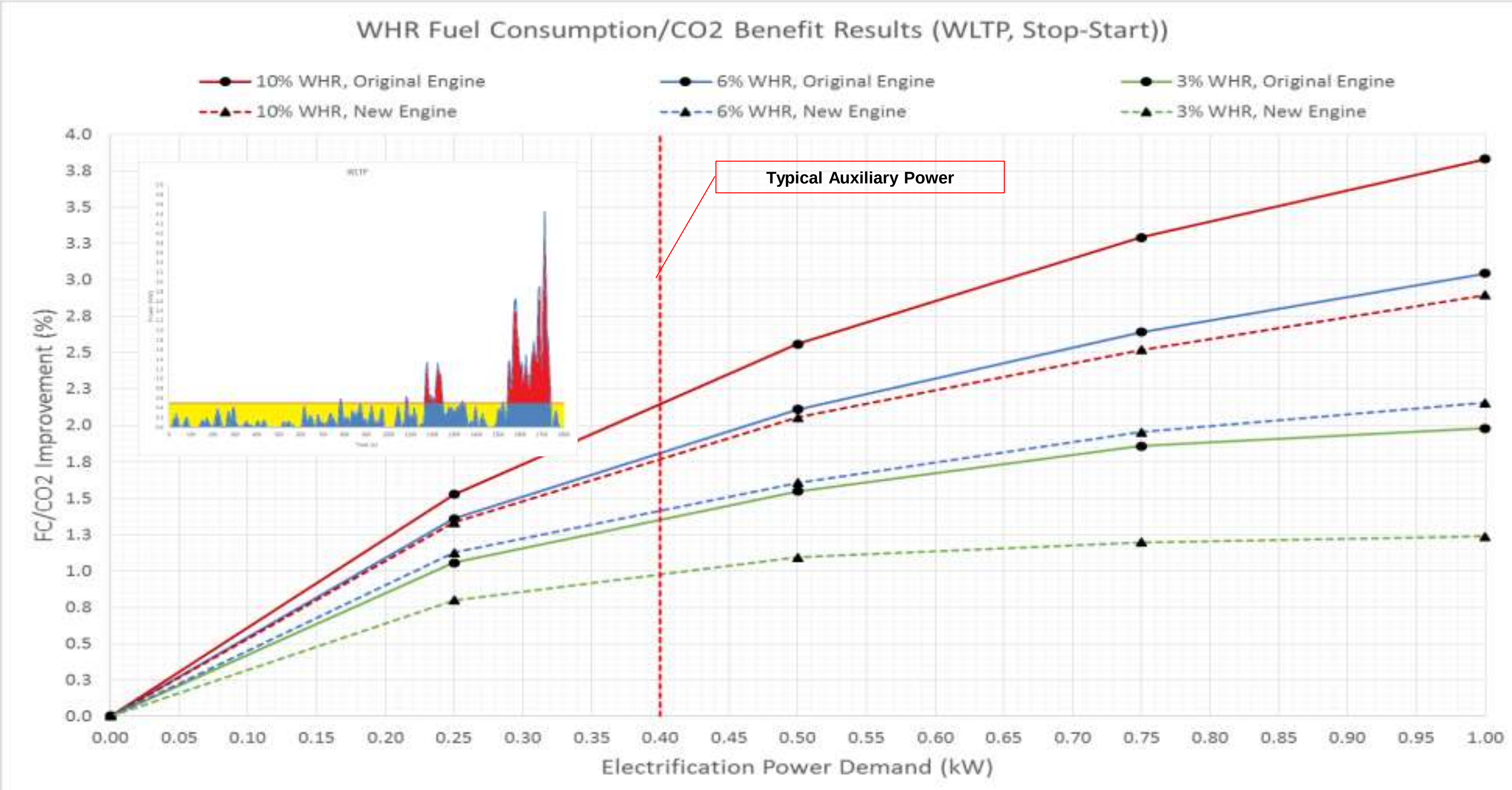
ORC on passcar (2l GTDI) – sensitivity study to ORC efficiency ORC using exhaust gas only here

- **New 2l GTDI engine with latest technologies (lower exhaust gas temperature for close to lambda 1 operation) (called New Engine concept)**

Technology	Effect on BSFC	Effect on Exhaust Gas Temperature
High compression ratio (13:1) with Deep Miller valve timing	High compression ratio results in thermodynamic efficiency improvement	Greater expansion ratio **decreased exhaust gas temperature**
Cooled external EGR	Reduced pumping Decreased combustion chamber heat transfer Combustion dilution leading to reduced temperature, helping achieve lambda 1 at high load	**Reduced exhaust gas temperature** due to dilution with EGR, despite increased heat retention in-cylinder
IEM	Fuel enrichment at high load eliminated through reduced turbine inlet temperature (i.e. lambda = 1 across the whole map)	**Reduced exhaust gas temperature** across the map due to additional cooling Increased exhaust gas temperature at high load due to elimination of fuel enrichment

2l GTDi – WHR FC/CO_2 Improvement Results (WLTP) with different assumptions for WHR efficiency

- Effect of WHR on FC and CO_2 emissions (both for the **Original** (2l GTDI with conventional CR, no EGR, no IEM) and the **New** Engine Concept) over the **WLTC**
  - when the recovered exhaust energy is used to power electrical auxiliary loads.



Organic Rankine Cycle (here: R245fa) Simulation Results Net Power Output

- EES used to perform the simulation
- One design point investigated for each heat of the three engine operating conditions; the results were then used for the sizing study
  - For example, mass flow rates, heat transfer and pinch temperatures were all used

Engine BC's			Exhaust BC's				ORC
Speed	Load	Brake power	Mass flow rate	Temperature Into ORC Boiler (post CAT)	Temperature Out of ORC Boiler	Exhuast Heat Into ORC	Net Power Output
rpm	Nm	kW	kg/s	°C	°C	kW	kW
2000	200	41.9	0.03951	716	134	24.7	3.00
2400	300	75.4	0.087	770	134	59.8	7.30
1600	75	12.6	0.015	483	132	5.518	0.67

Temperatures around ORC Circuit				Pressures			Heat Transfer			
T1: Pump inlet	T2: Pump outlet	T3: Boiler outlet	T4: Expander outlet	Pressure Ratio	P Low	P high	Q Boiler	Q Condenser	Mass Flow of R245fa	Air Flow over Condenser
°C	°C	°C	°C	-	kPa	kPa	kW	kW	kg/s	kg/s
35	38.6	199	135	15	211	3164	24.7	21.7	0.076	0.5
35	38.6	196	132	15	211	3164	59.8	52.5	0.1861	0.5
35	38.6	198.2	134.2	15	211	3164	5.518	4.845	0.01702	0.5

Content

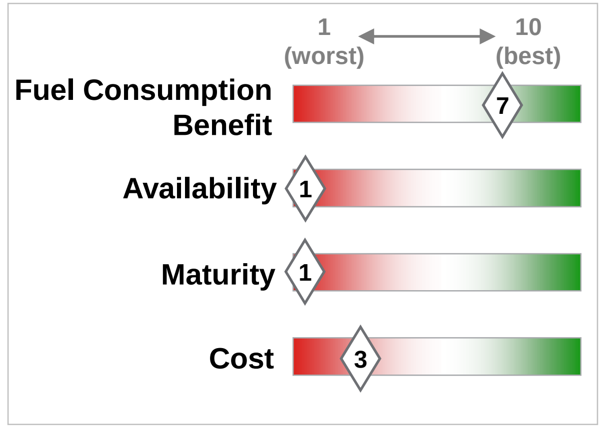
- Waste Heat Recovery Systems
  - Energy Balance
  - WHRS comparison
- Focus on some Waste Heat Recovery Systems
  - Turbocompound
  - Seebeck thermogenerator
  - Organic Rankine Cycle
- **Conclusion**

Next step – Example: Thermoacoustic Generator

Summary

- **Concept:** Turning heat energy in vehicle exhaust into acoustic power by using temperature gradient to create and amplify a soundwave, which in turn can drive a generator to produce electrical power
- **Base Functioning:** Exhaust gas and cooling system are used to heat and cool opposite ends of a 'thermoacoustic engine' (often referred to as a 'stack' or 'regenerator'), consisting of a porous solid body through which a pressurised fluid passes. Acoustic waves travel through resonator tubes (or 'resonant cavity) to a 'thermoacoustic pump', which converts the acoustic power into electrical power through means of a generator, or by creating a temperature gradient
- **CO_2 Benefit:** Claimed fuel economy benefit for HD truck of ~5% by one supplier; some prototype testing indicates between 3-5% for a passenger car gasoline engine
- **Costs:** Claimed system cost of ~$1k for HD truck by one supplier

Ratings of Technology



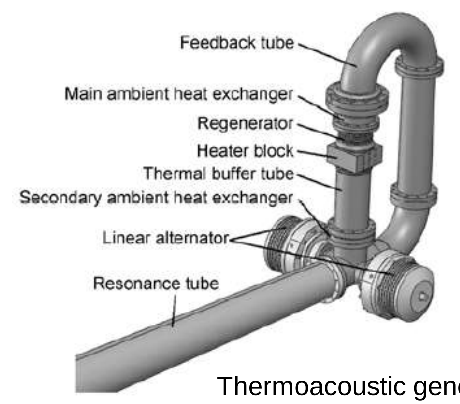
Safety and Limitations

- ✓ Few or no moving parts; resultant low maintenance and long operational life
- ✓ Potentially low-cost system
- ✓ Working fluids are benign and low risk
- ⊖ Some prototype testing has yielded low thermo-electric conversion efficiency

Technology Applicability

- Technology has been tested in several industrial applications
- Use in smaller applications has so far generally been restricted to University/supplier laboratory tests
- One example of automotive scale system demonstrating technology
- A few examples of suppliers currently developing technology for automotive and truck applications – at least one is planning on introducing to market: Etalim

Visualisation



Thermoacoustic generator setup by Wu et al

Source: Ricardo research, Ricardo evaluation,

WHR systems (available and future) - comparison

Type	Fuel Economy Improvement	Cost / benefit	Size	Complexity	TRL Technology Readiness Level
Turbocompounding (electrical)	+	HDD: 4500 euros / 12kW	+	-	9
Thermoelectric device	+	HDD: 1500 euros / 4 kW Pascar: 250 euros / 0.6kW	++	-	7
ORC (mechanical) HD ROI < 2 years	++	HDD: 2500 euros / 15 kW Pascar: 500 euros / 4 kW	- -	-	8
Thermoacoustics	+	N/A too early stage	-	-	3
Stirling engine	++		-	- -	4
Brayton cycle	++		-	- -	3
Supercritical CO_2 cycle	+++		-	- -	3
Kalina cycle	++		-	- -	3
Absorption (Heat to Cool)	+ (cold power)		- -	- -	3
Goswami cycle	++		- - -	- -	3
AMTEC	++		- -	- -	2
Fuel reforming	+		- - -	- -	4
Split cycle engine	+++		New engine	- -	4

On board water recovery for Water Injection in high efficiency gasoline engines (high compression ratio gasoline engine)

- VW example: Exhaust heat exchanger used to condense water vapor in exhaust gas into water liquid to be reinjected into combustion chamber
- Water Injection on market in BMW M4 – using Air Conditioning condensates to top up water tank
  - In future: ? synergy between exhaust gas condensation to generate water on board and Heat to Power (Seebeck, Rankine, …) ?

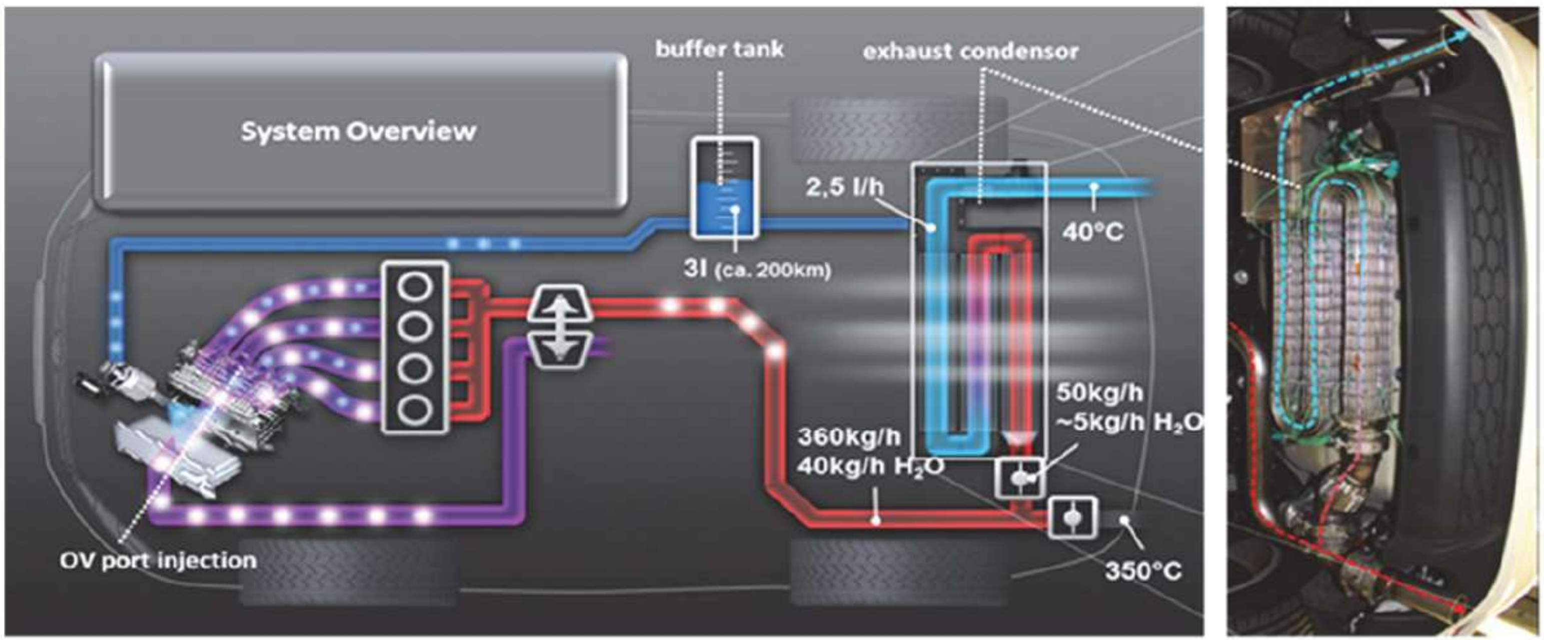


Figure 4: System layout overview (simplified)

Source: VW, Stuttgart Symposium 2017

Conclusion

- Several waste heat recovery solutions exist on exhaust line, cooling circuit in order to reduce CO_2 emissions
- The 1st **solutions** applied on the market are: **Exhaust heat recovery for cabin/engine warm-up** for passenger cars, **mechanical turbocompound for HDD**, **ORC and e-turbine for gensets**
- Solutions such as ORC for HDD and themoelectric generator for HDD and passenger cars are under development in order to start production before 2020.
  - **Supply-chain needs to be developed** in order to get those solutions onto the market
- Those solutions present **cost/benefit ratios < 0.12 - 0.5 € / W**

- **After 2020**, Waste Heat Recovery Systems should be more widespread as the share of hybrid electric powertrains will increase – e.g. leading to a **good synergy with electrified powertrain / electric ancillaries** (EV mode in urban conditions, HEV mode with WHRS from Internal Combustion Engine on motorways/highways)
  - **Possible synergy with water generation on board and exhaust gas cooling below dew point**
- Solutions such as **fuel reforming** using exhaust heat and **heat to cool systems** would appear **after 2025** on HDD and passenger (premium application 1st); **disruptive technologies** such as **AMTEC or ThermoAcoustic, supercritical CO2 Brayton cycle** need **more research activities** before understanding the potential of its application on automotive applications **after 2025**

Thank you for your attention
Any questions?