NOWASTE: WASTE HEAT RE-USE FOR GREENER TRUCKS

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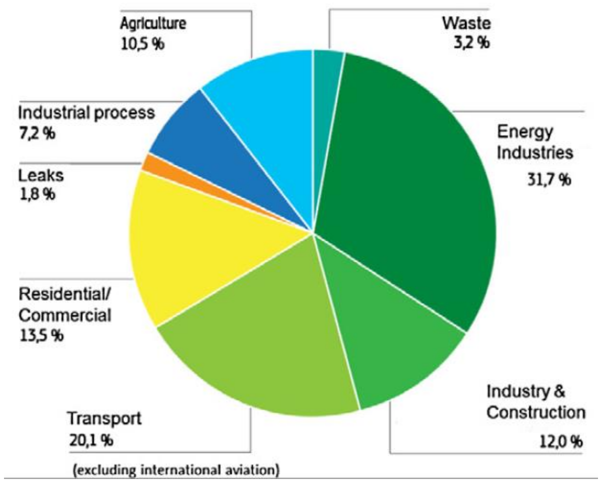
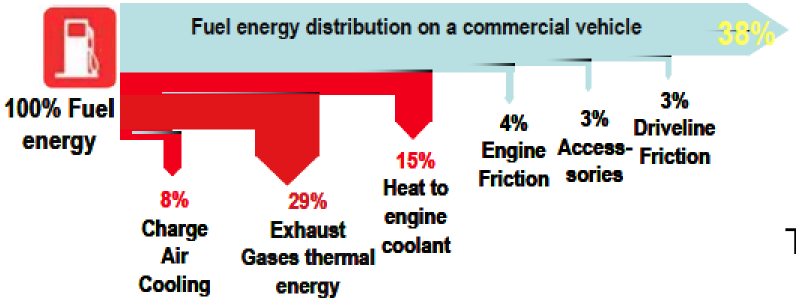
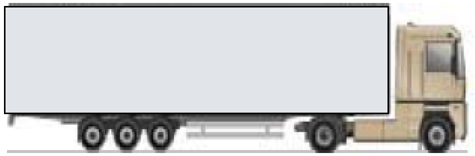
Introduction

Context

- ✧ Reduce fuel consumption is necessary
  - ➢ to reduce GHG emissions (HD represents ¼ of EU road transport emissions)
  - ➢ to increase competitiveness of transportation by trucks (fuel=28% of the total operating cost of the truck)
- ✧ How could we reduce fuel consumption?
  - ➢ Waste heat valorization is a promising solution
  - ➢ Even with a large engine efficiency, 50-60% of fuel energy is lost in waste heat





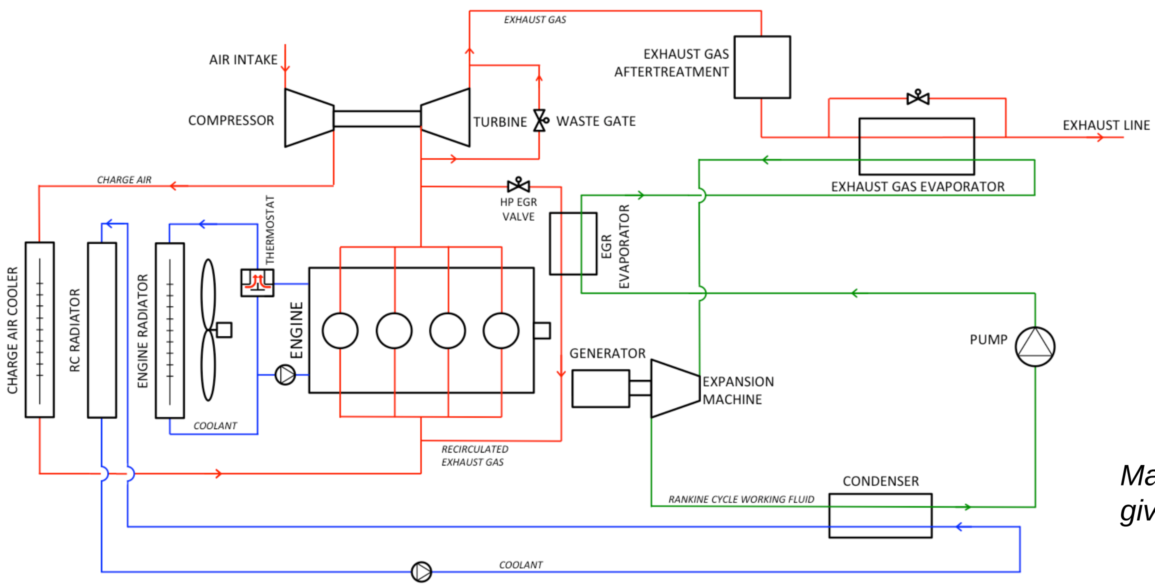


Typical energy distribution on a euro 5 engine

Introduction

Rankine cycle systems

- Among the WHR techniques, the Rankine cycle is one of the most promising ones.



Many possible architectures for given boundary conditions

- However, R&D activities are still necessary to find the most appropriate architecture (working fluid, heat source/sink, expansion machine, etc.) in order to reach an acceptable economical profitability and to increase reliability

NoWaste project

Consortium

- FP7 project
- Duration: 42 months / Start: October 2011
- Coordinator: CRF
- Main partners:

NoWaste project

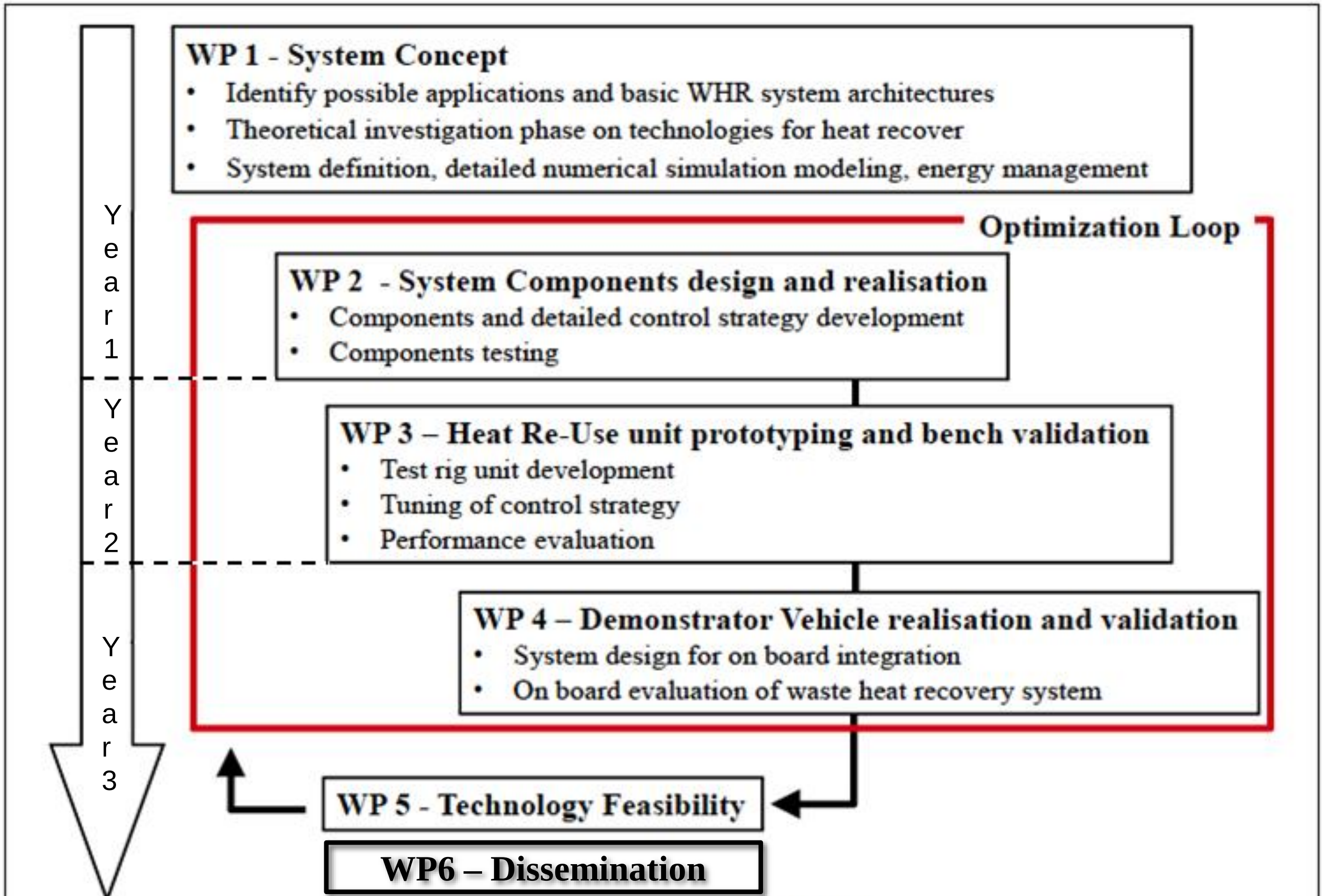
Objectives and challenges

- ✧ Develop and validate 2 ORC-based waste heat recovery systems for HD trucks.

- ✧ Challenges of the NoWaste project:
  - ➢ New components should be compliant with automotive constraints (weight, cost)
  - ➢ System should be compliant with incoming regulations about GHG emissions (e.g. F-gas regulation)
  - ➢ Impact on vehicle architecture and performance should be limited (for instance cooling drag, back pressure, etc.)
  - ➢ Optimize the energy management system (production/storage/use of energy)

NoWaste project

Project organization



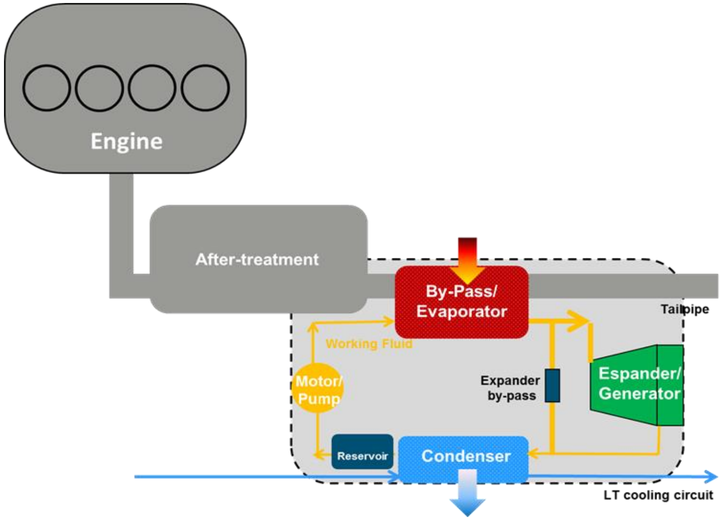
NoWaste Project WorkFlow

Content of the presentation

1. Introduction
2. NoWaste project
3. **Architectures of ORC systems**
4. Experimental characterization of prototypes
5. Economical analysis
6. Conclusions

Architectures of ORC systems

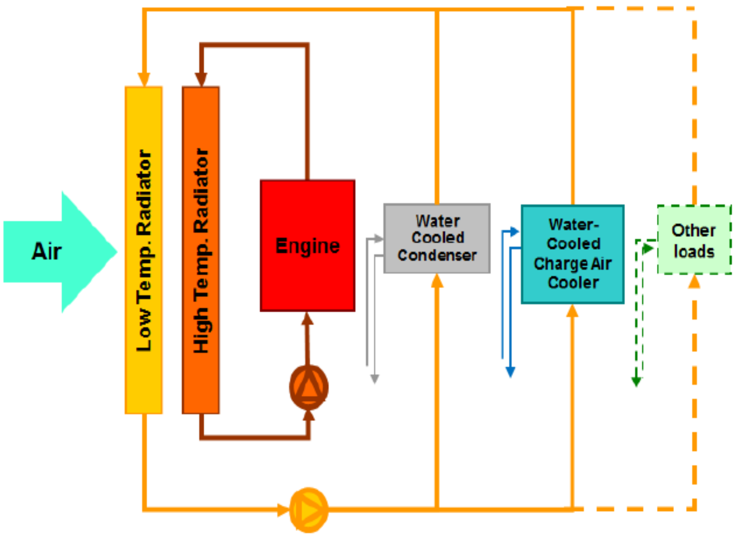
CRF application



- Trade off between impact on overall vehicle efficiency and simplicity/cost/volume/weight
- *Heat source*: Exhaust gas only (no EGR): lower temperature heat source
- *Heat sink*: low temperature cooling circuit (capacity limited to 35 kW)
- Electrical output power
- No flammable fluid (security):
    - R245fa
    - R1233zd: GWP<5 and potentially better performance

Architectures of ORC systems

CRF application



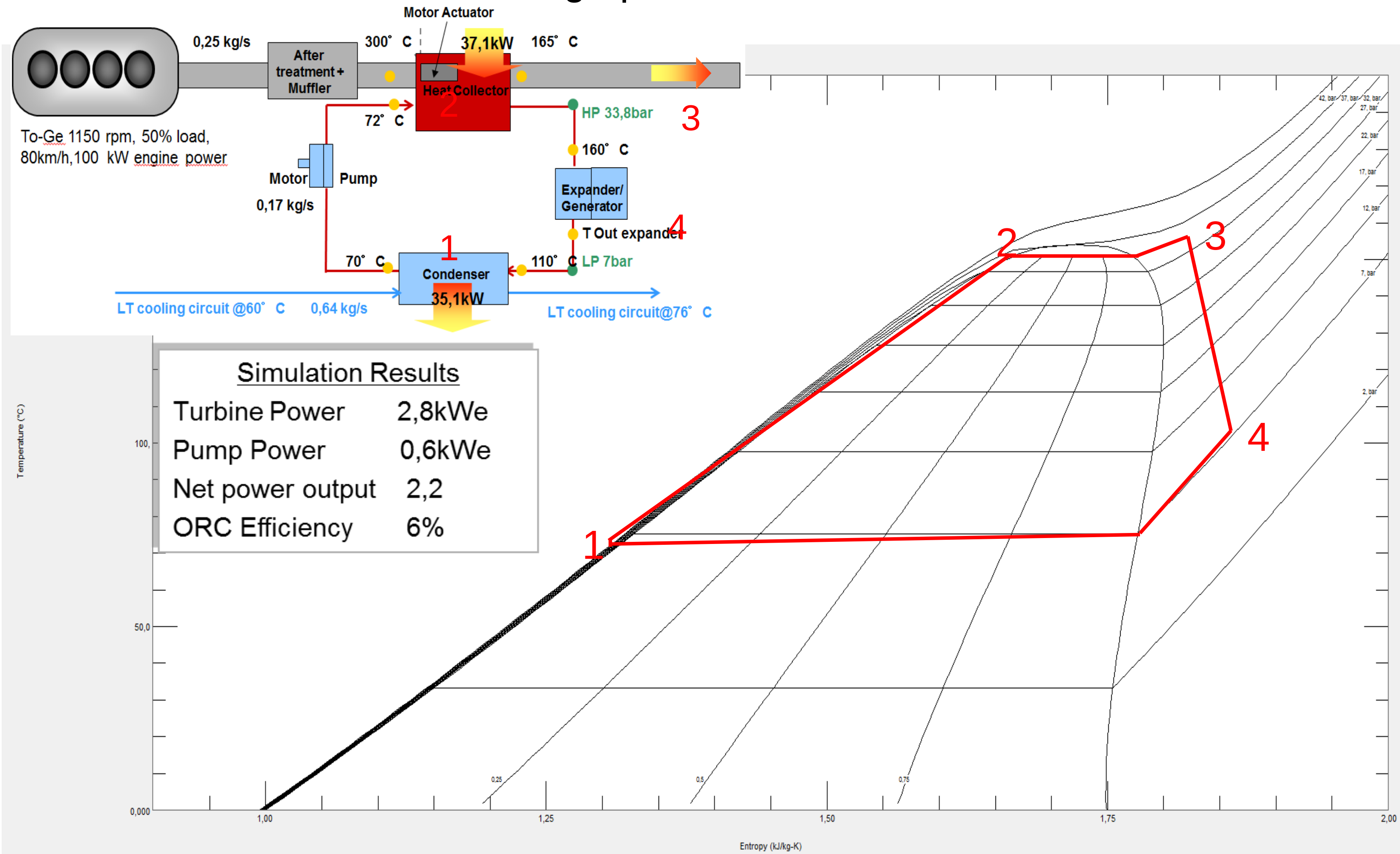
Components:

- *Expander*: Axial impulse turbine + reducer + generator: electrical output power
- *Boiler*: stainless steel plate-fin heat exchanger
- *Condenser*: aluminum plate heat exchanger
- Internal gear *pump*

Architectures of ORC systems

CRF application

Performance estimation @ design point

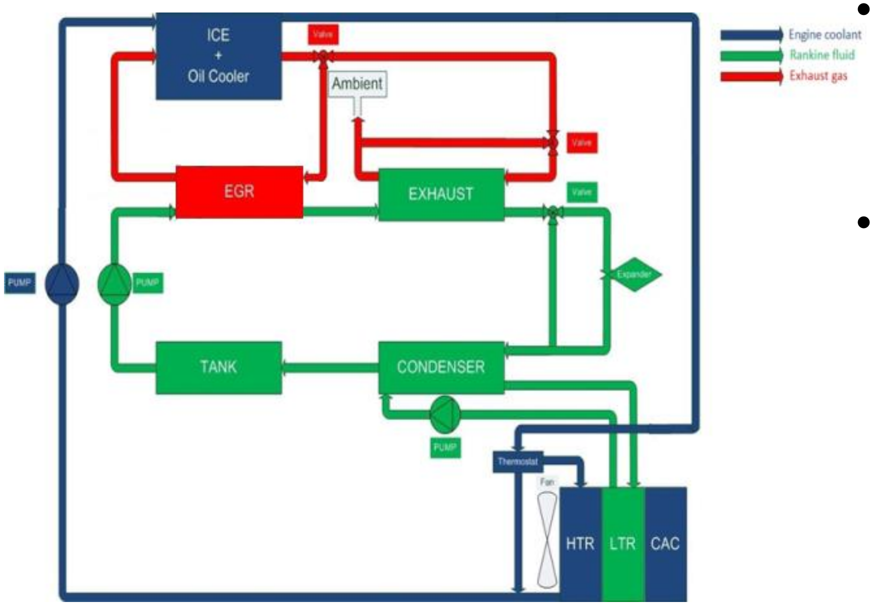


Simulation Results

Turbine Power	2,8kWe
Pump Power	0,6kWe
Net power output	2,2
ORC Efficiency	6%

Architectures of ORC systems

Volvo application

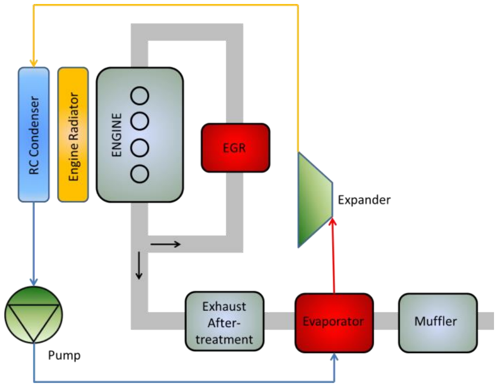


- Trade off between impact on overall vehicle efficiency and simplicity/cost/volume/weight
- *Heat source*:
  - Exhaust gas + EGR cooler (higher temperature heat source)
  - Series or parallel configuration
  - Recirculated gas temperature low enough
- *Heat sink*: low temperature coolant circuit (60-70°C)
- Mechanical output power

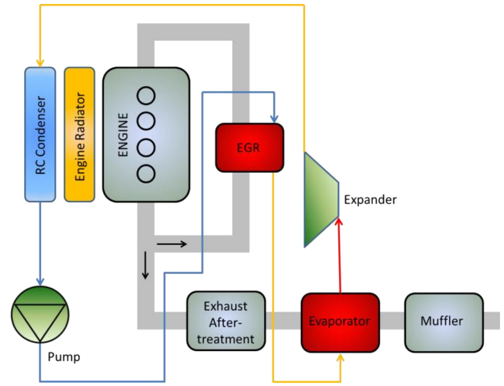
- Working fluid: ethanol
  - Better performance
  - Water-ethanol mixture (reduced flammability and corrosivity)

Architectures of ORC systems

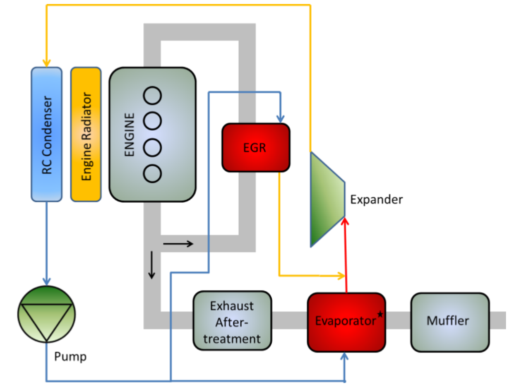
Volvo application



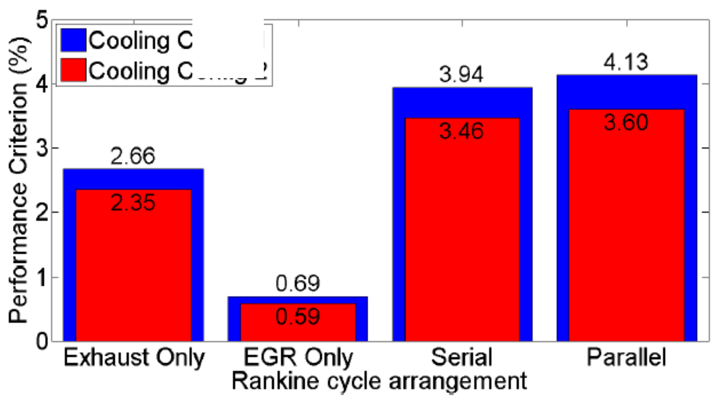
WHR on exhaust gases only



WHR on exhaust gases and EGR gases in serial



WHR on exhaust gases and EGR gases in parallel



Dedicated low temp. radiator

Engine coolant circuit

Source: V. Grelet, T. Reiche, V. Lemort, M. Nadri, P. Dufour, Transient performance evaluation of waste heat recovery Rankine cycle based system for heavy duty trucks. Applied Energy, *In press*

- EGR cooler as preheater (serial configuration of the heat sources)
  - Lower net power production than serial configuration
  - But lower complexity and cost (less valves) and better cooling down of EGR gases

Architectures of ORC systems

Volvo application

Components:

- *Expander*: turbine + reducer + engine mechanical coupling
- *EGR Boiler*: brazed stainless steel heat exchanger with a concept similar as the EGR cooler
- Tailpipe boiler: brazed stainless steel (counter flow) plate heat exchanger
- *Condenser*: brazed stainless steel (plate/plate counter flow) heat exchanger
- External gear *pump*

Architectures of ORC systems

Components specifications

Component	Technical boundary conditions	VOLVO	CRF
EGR boiler	Heat flow range (kW)	15-45	-
	EGR inlet temperature (°C)	400-500	-
	Working fluid pressure (bar)	25 - 40	-
	Working fluid inlet temperature (°C)	65	-
Exhaust boiler	Heat flow range (kW)	25-60	30-50
	Exhaust inlet temperature (°C)	320-350	200-300
	Exhaust mass flow (kg/s)	0.18-0.25	0.2-0.3
	Working fluid inlet temperature (°C)	65-215	63-73
Condenser	Heat flow range (kW)	50-85	25-45
	Working fluid pressure (bar)	1	5-7
	Working fluid inlet temperature (°C)	85-180	100-110
	Coolant inlet temperature (°C)	50-70	50-70
	Coolant mass flow (kg/s)	1-5	0.6-1
Expander	Inlet pressure (bar)	25-40	25-35
	Inlet temperature (°C)	200-280	140-160
Feed pump	Inlet pressure (bar)	1	5-7
	Inlet temperature (°C)	70-80	60-70
	Working fluid inlet mass flow (kg/s)	0.04-0.08	0.1 -0.2

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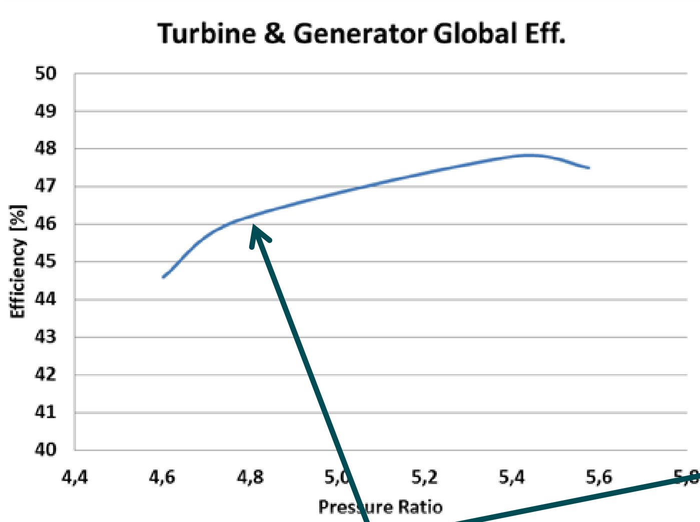
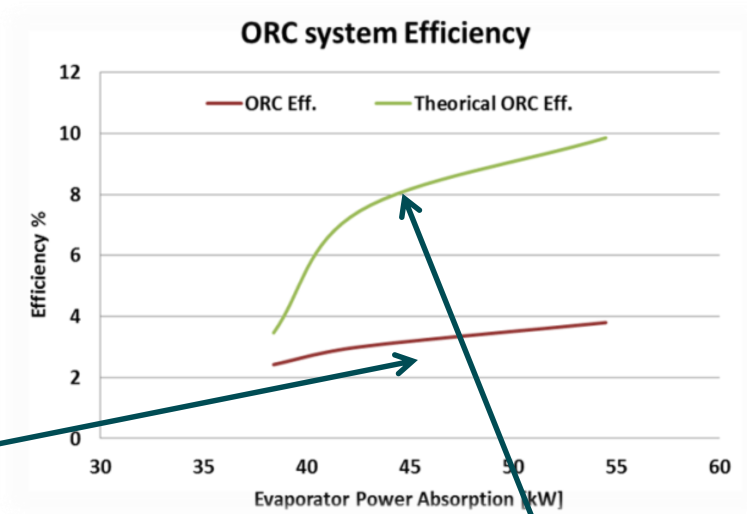
Experimental characterization of prototypes

CRF application

- Tests in steady-state engine regime
- Purpose: Check suppliers' specifications and collect data for simulation models improvement
- All components operated as envisioned, except the turbine whose efficiency is lower than expected.





Includes isentropic, mechanical and electrical efficiencies

Includes isentropic efficiency only

Experimental characterization of prototypes

CRF application

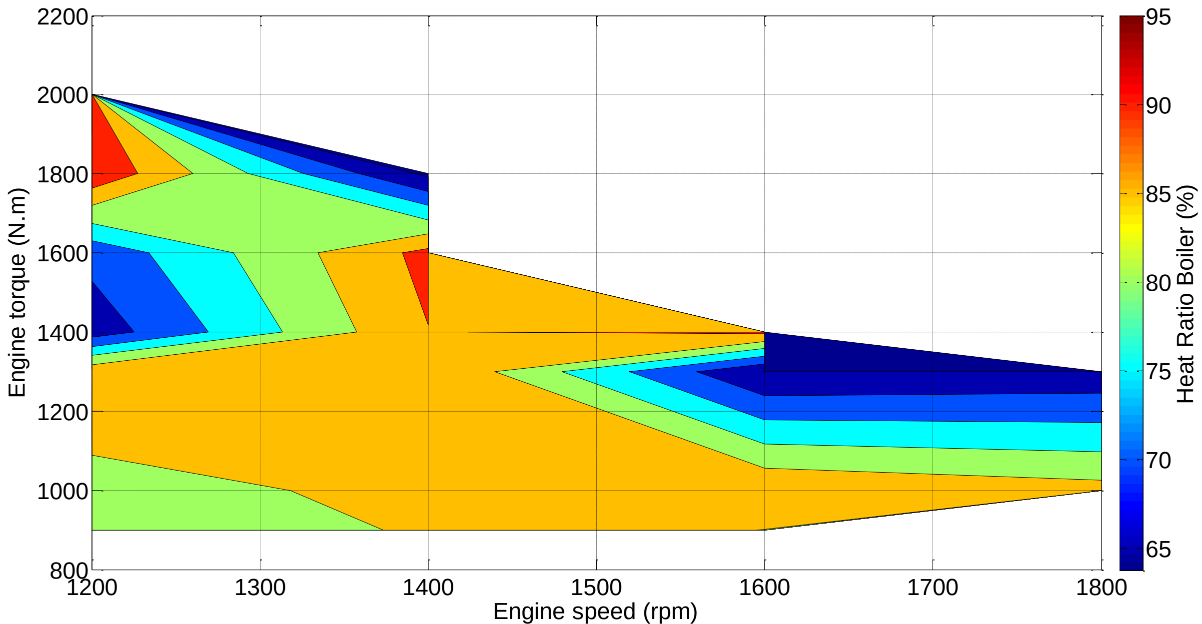
Measured performance at different engine load levels:

Parameter	Engine load 70%	Engine load 80%	Engine load 90%	Engine load 100%
Evaporator heat recovery [kW]	38.4	42.6	48	54.5
Condenser heat rejection [kW]	36.2	40.8	46	51.8
Pump power absorption [kW]	0.27	0.32	0.38	0.43
Electricity generation [kW]	1.2	1.6	2	2.5
Mass flow rate [kg/s]	0.15	0.16	0.18	0.19
ORC global efficiency	2.4	3	3.3	3.8

Experimental characterization of prototypes

Volvo application

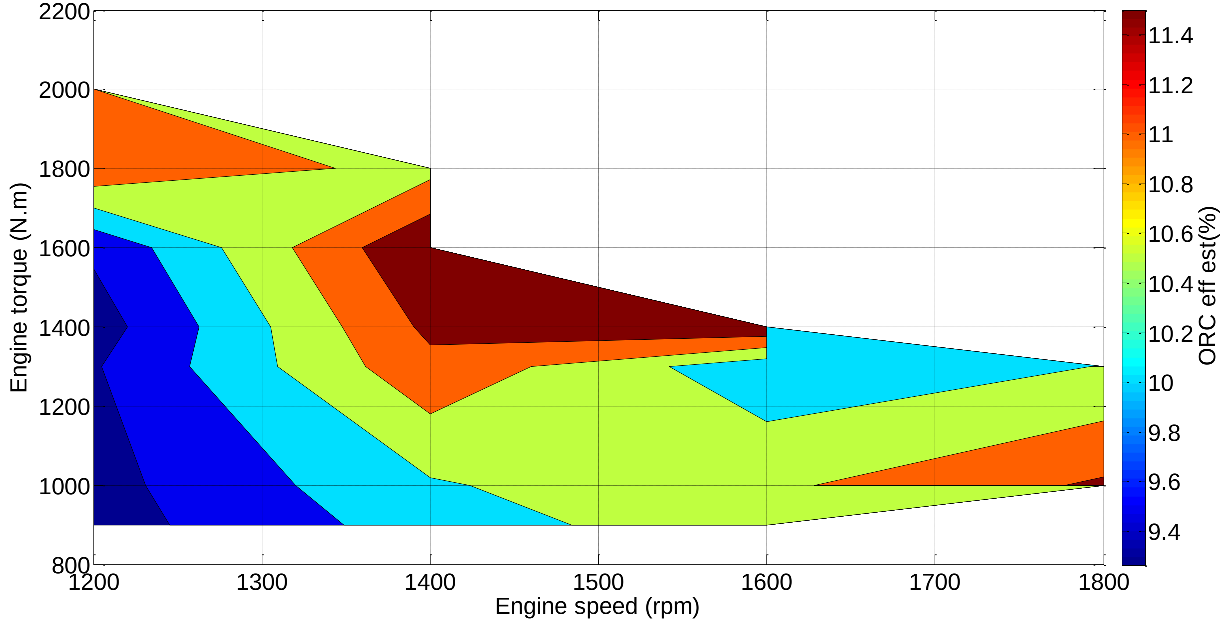
- Tests in steady-state engine regime
- Turbine replaced by a representative orifice.
- Heat ratio = fraction of heat recovered by the working fluid compared to the total heat loss of EGR and exhaust gases
  - => indication of ambient losses (15-25% in steady-state)
  - Insulation would have a non negligible impact on weight and cost



Experimental characterization of prototypes

Volvo application

- Extrapolation of performance with a turbine total efficiency of 65%



  - => average efficiency estimation of 10% over a relatively wide range of engine working points
  - Performance can be increased by improving components' efficiencies and decreasing condensing pressure

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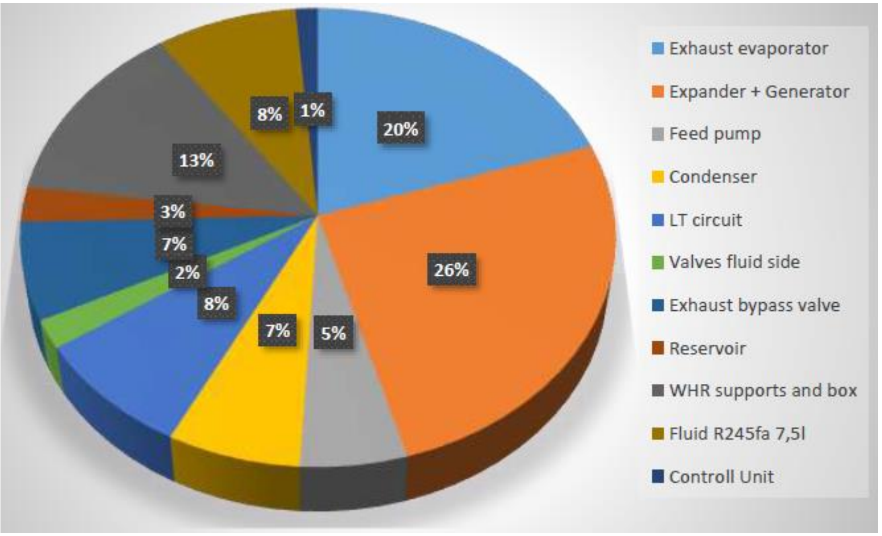
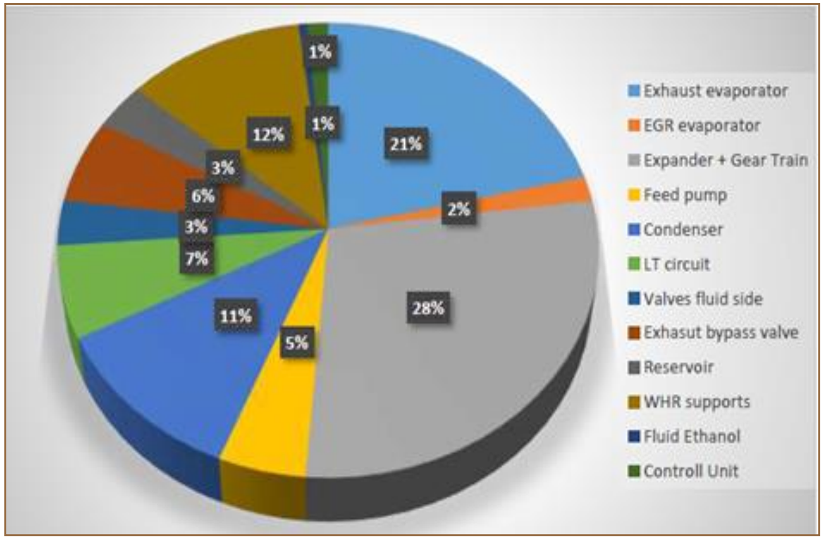
Economical analysis

Production cost breakdown





- CRF system
  - Smaller, more reliable, less efficient
  - 2300 - 3000 EUR

- Volvo system
  - More complex, more efficient
  - 2300 - 3000 EUR

Expander and evaporator are the main drivers of the total cost.

Economical analysis

Return on investment time

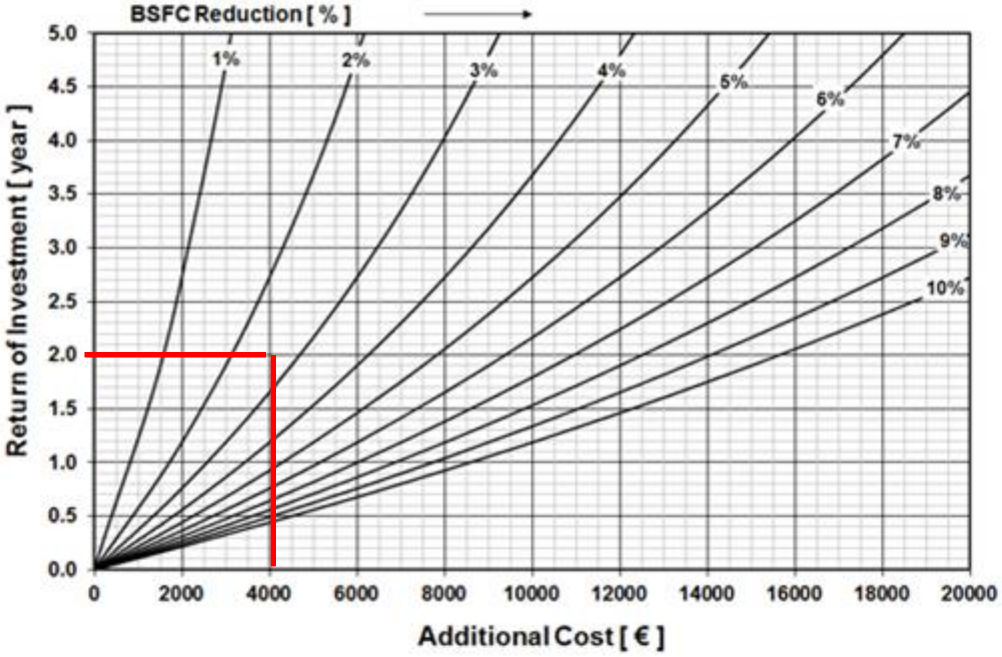
PROPOSED BOUNDARIES

Vehicle price:	95.000 Euro
Mileage :	150.000 km/year
Avg. FC:	35 l/km
Avg. EU fuel price:	1.7 Euro/l
Prod. volume:	< 20.000 units/year

Other costs, like service, repair, tyres, oil, taxes…. are considered

ROI target: max. 1.5 - 2 years

RETURN OF INVEST (ROI) VIEW



Conclusions

Project main achievements

- Relevant improvement in respect of the understanding of the system design and its integration on a heavy duty vehicle application;
- Increased motivation of the Industrial OEM involved and of the components' suppliers in the investment on specific components development;
- Demonstrated energy savings realized on the considered engine applications through a waste heat recovery system based on the ORC technology;
- CRF idea of cheap and "plug and play" system has a low impact on the vehicle's architecture because of its low global size and weight, and no impact on the powertrain's design, can achieve interesting results in terms of electricity power output (~2 kW).
- VOLVO's WHR system showed that efficient EGR cooling and heat recovery can be combined for a long haul heavy duty application showing realistic cycle efficiencies around 10% on all measured engine working points.

Thank you for your attention!

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