2nd International Sustainable Sea Transport in the Pacific Talanoa

Making shipping greener: Organic Rankine Cycle modelling in challenging environments

Santiago Suarez de la Fuente, Alistair R. Greig
University College London

Suva, Fiji Islands

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- Objectives
- Waste Heat Recovery System
- Method
- Results
- Conclusions

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Objectives

- Benefits and requirements of a marine Waste Heat Recovery System (**WHRS**) applied to a passenger Ferry
- Which is the best?

Organic Rankine Cycles' VS Rankine Cycle

(6)

Compare:

- **Power Output**
  - Fuel Consumption
  - CO_2 Emission reduction
- **Equipment size** → Heat exchangers and mass flow rates

Propulsive Energy Map

(5)

50% of the combustion energy is lost in the engine (2)

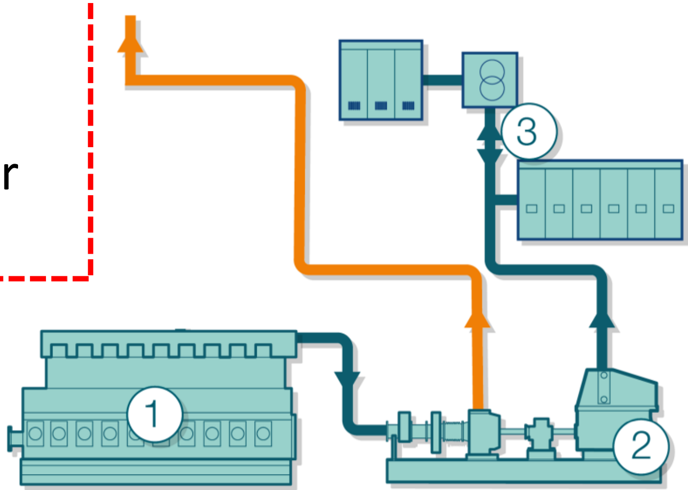
Only a maximum of 35% of the combustion energy ends as propulsion power (2)

Low/Medium waste heat

(Between 30 – 650 C)

- Exhaust gas
- Scavenge air
- Cooling Water
- Other

- Power Increase
- Fuel Consumption reduction:
    - CO_2
    - EEDI
    - $$$$$



(4) Waste Heat Recovery System

Method

Methodology

A. Multi-objective optimization using the genetic algorithm
   1. Electrical Power Output
   2. Working fluid mass flow rate
   3. Heat Exchangers area
B. Weight factors
   1. Electrical Power density
   2. Thermal efficiency
   3. Irreversibilities

Assumptions

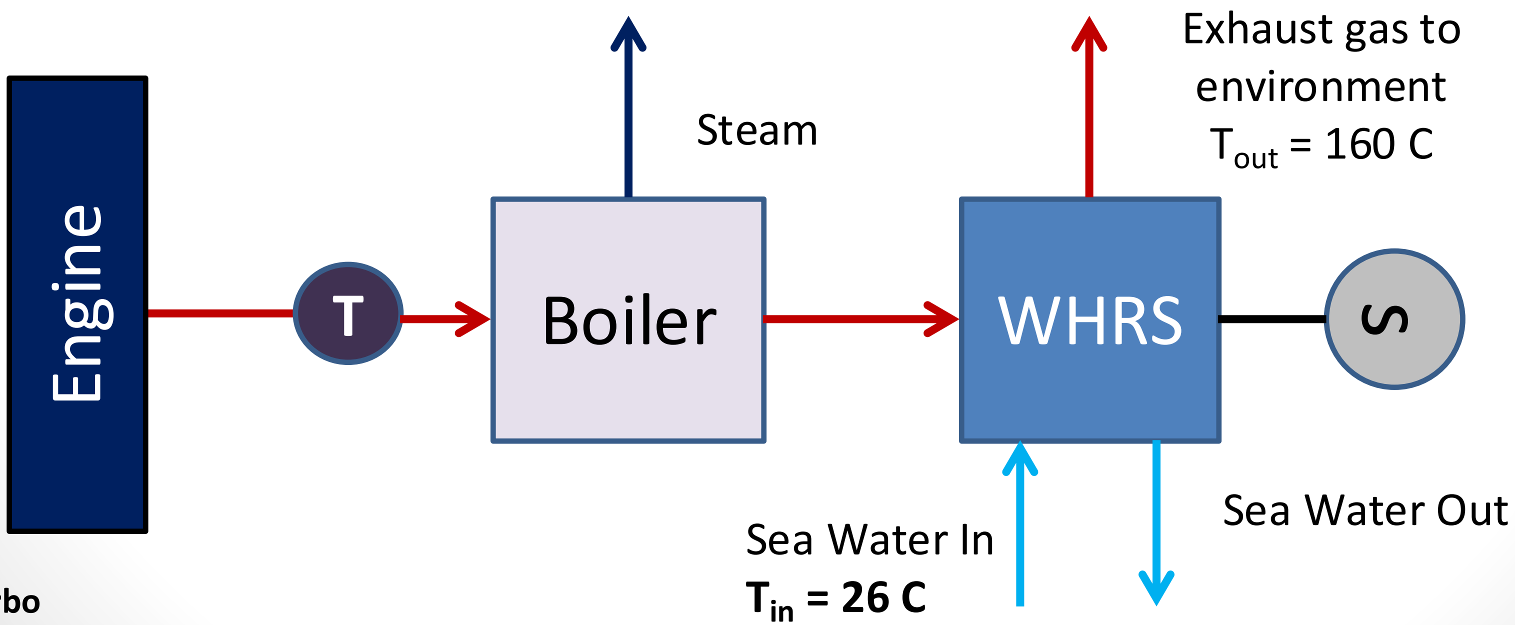
- No pressure changes except for the expander and pump.
- No heat losses in the working fluid circuit except the ones set for the heat exchangers.
- No leakages.
- Steady-state operation.

Ferry

Deadweight (t)	Length (m)	Beam (m)	Draught (m)	Design Speed (kt)
1,300	117	13	4.5	18.6

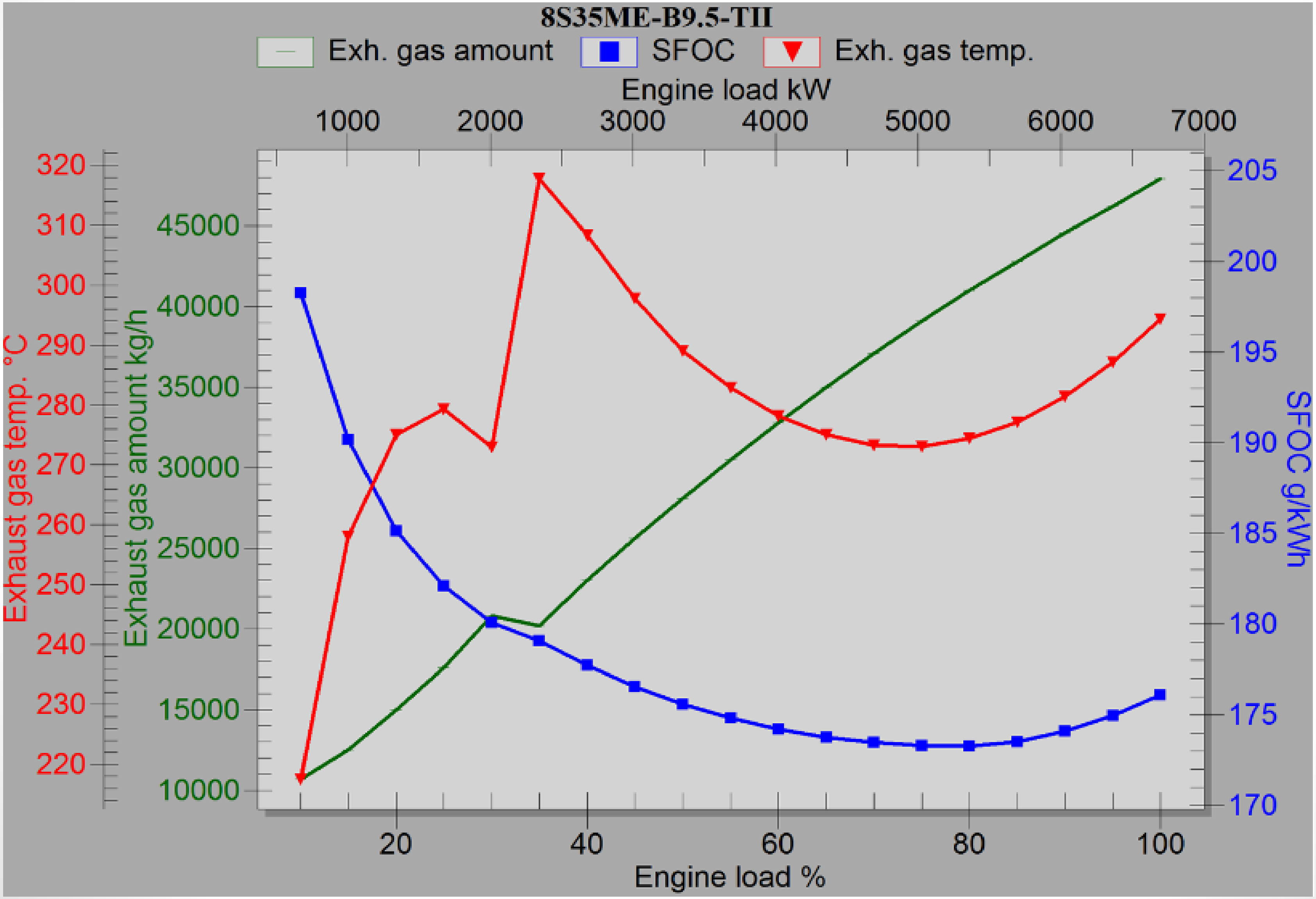
MAN slow speed Diesel Model 8S35ME-B9.5-TII with one turbo (7)

- **Power required @18.6 kt:** 5,025 kW → 75% MCR



T - Turbo

Engine Operational Characteristics



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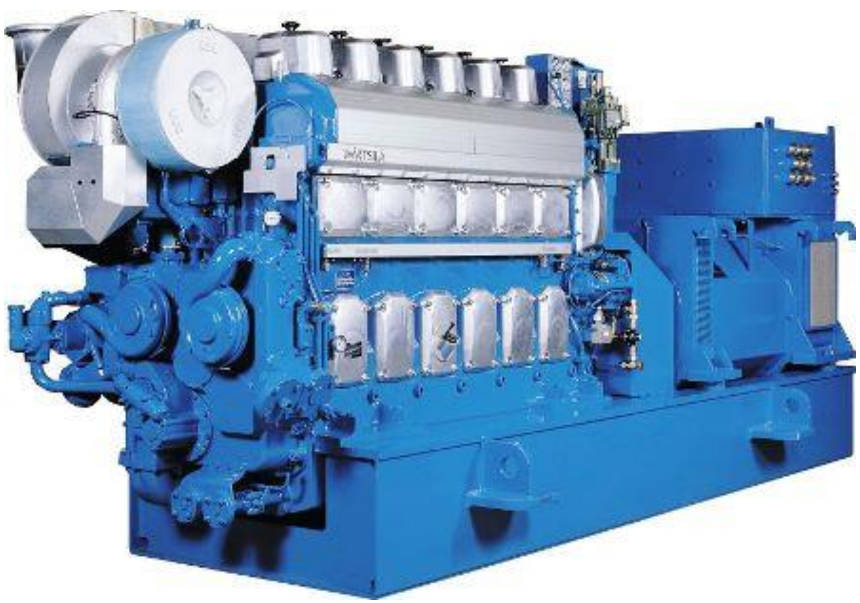
Generator

- In order to understand the magnitude of the fuel savings it was used for this comparison a Wärtsilä 4L20 genset with the following characteristics:
  - Electrical Power: 700 kW_e (with an efficiency of around 96%)
  - Fuel consumption: 187 g/kWh.
  - Fuel used: Marine Diesel Oil.
    - Cost per metric ton: 940 USD (05/2014) (9)



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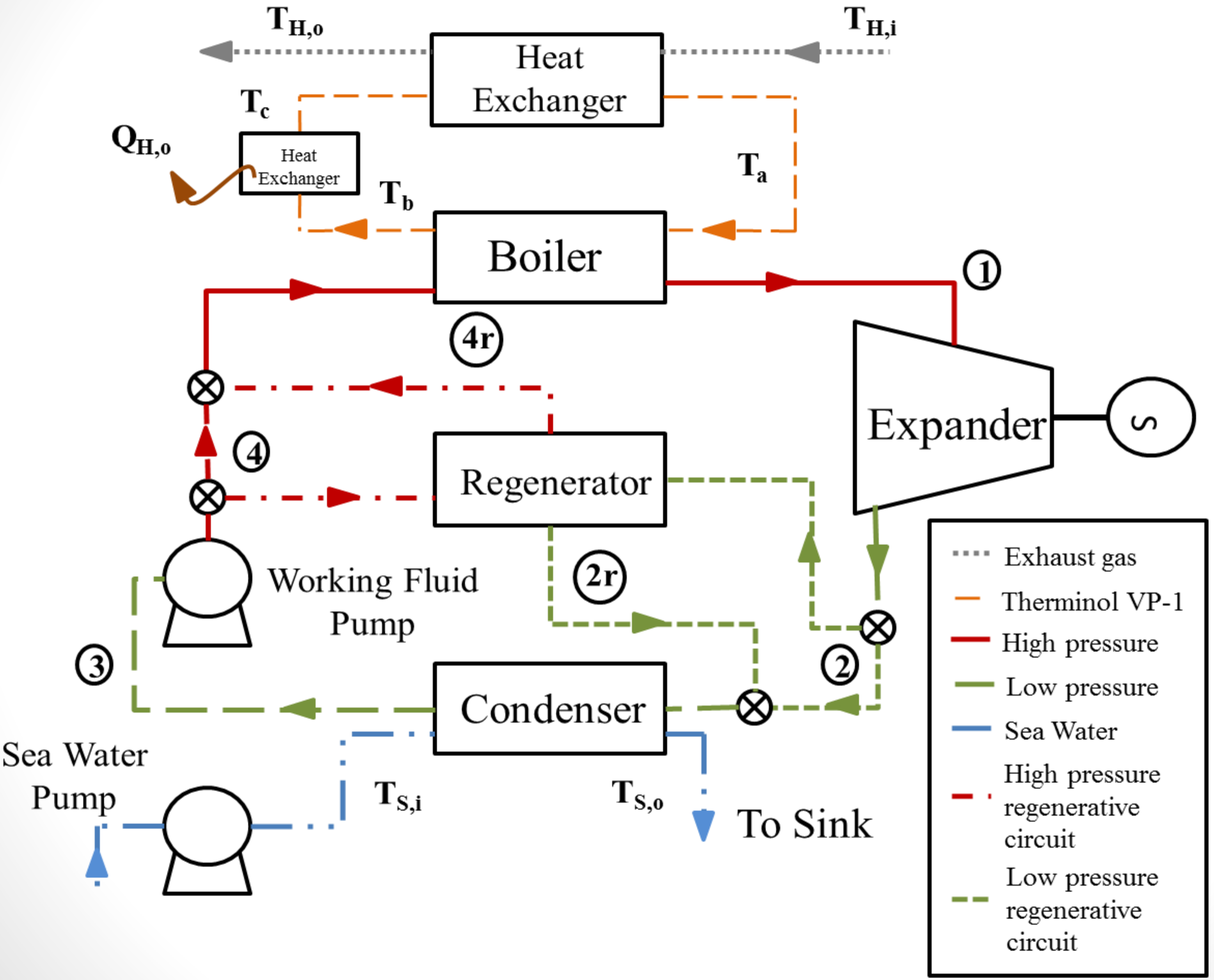
WHRS Layout



$T_{H,o}$
$T_{H,i}$
Heat Exchanger
T_c
$Q_{H,o}$
Heat Exchanger
T_b
T_a
Boiler
1
4r
Expander
4
Regenerator
Working Fluid Pump
2r
3
2
Condenser
Sea Water Pump
$T_{S,i}$
$T_{S,o}$
To Sink
Exhaust gas
Therminol VP-1
High pressure
Low pressure
Sea Water
High pressure regenerative circuit
Low pressure regenerative circuit

Working Fluids - Properties

Working Fluids	Auto-ignition Temperature (K) ‡‡	Decomposition Temperature (K) *	Flash Point (K)‡‡	GWP_{100}
Water	-	2273	-	N/A
Benzene	835	1033	262	N/A
Toluene	809	672	277	2.7
Heptane	496	823	269	3.0
Hexamethyldisiloxane (MM)	614	573	271	<10
R245FA	685 **	523 **	-	950 **

LNG flash point = 85 K

* Water: (10), Benzene: (15), Toluene: (16), Heptane: (17), MM: (18) ** (12)
‡‡ (11)

Operational Profile

Segment	Speed (kt)	Power (kW)	Time (h)
Port A	2.8	20	0.50
At Design Speed	18.6	5,025	1.45
Port B	2.8	20	0.50
Total			2.45

DISTANCE

50 km

OPERATIONAL TIME

The ferry will work around 6,480 hours per year →2,640 trips per year.

(14)

Results

Results: Optimal Design

Electrical Power Output

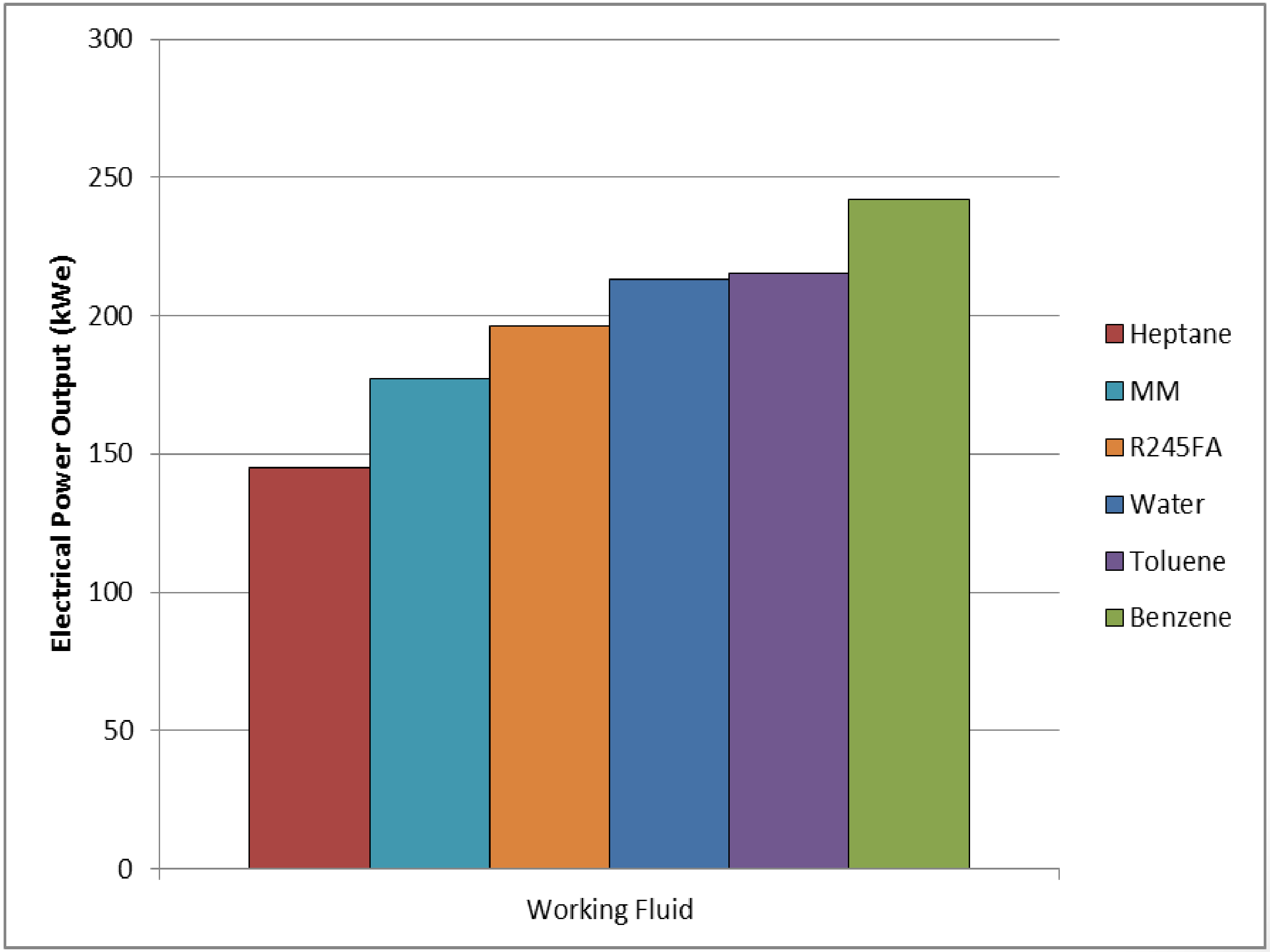
Higher

Benzene
242 kWe

13.7% higher than RC

Lower

Heptane
145 kWe



Results: Optimal Design

Heat Exchanger Area

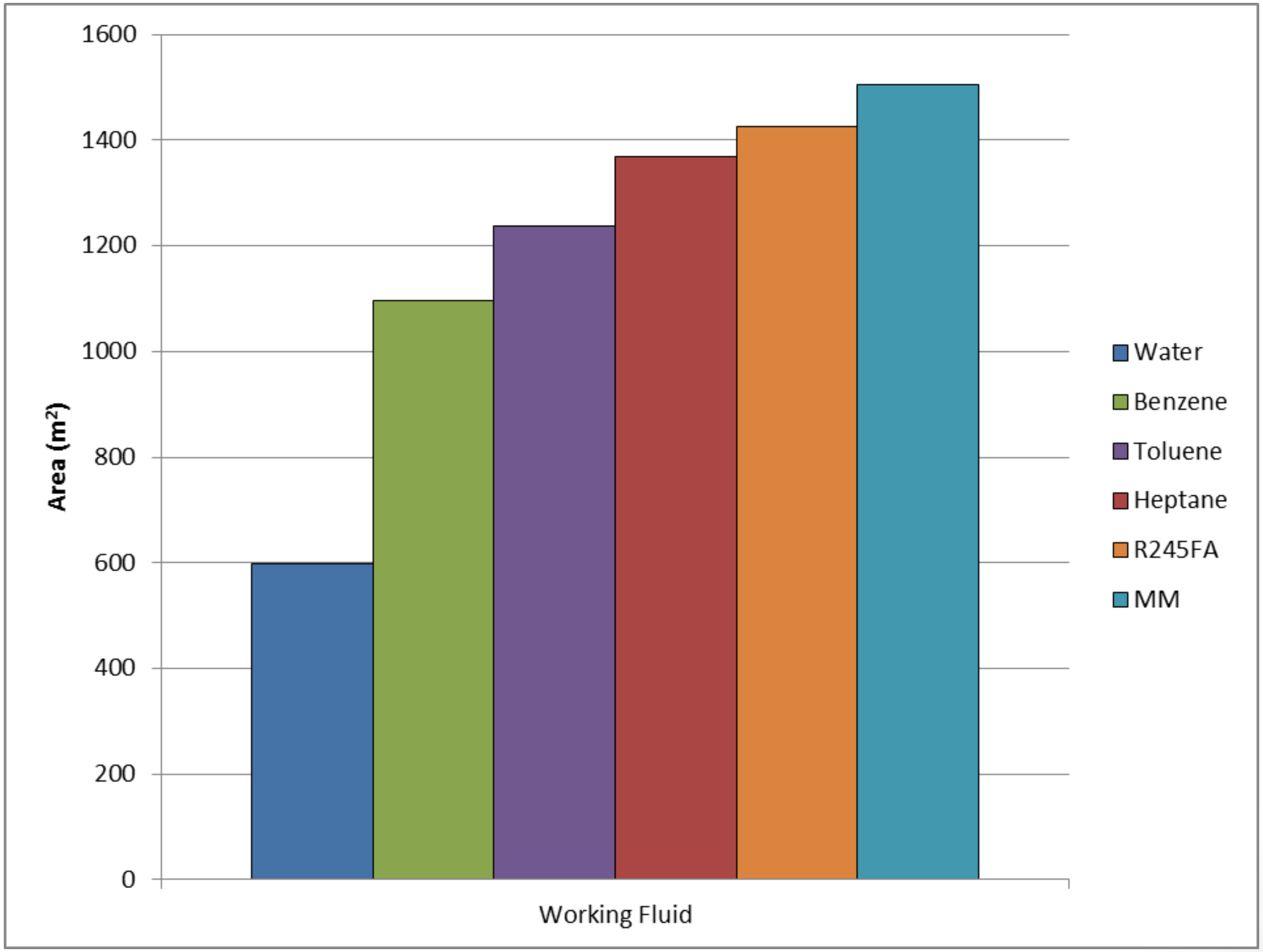
Lower

Water
600 m^2

250% larger

Higher

MM
1,500 m^2



Results: Optimal Design

Mass flow rate

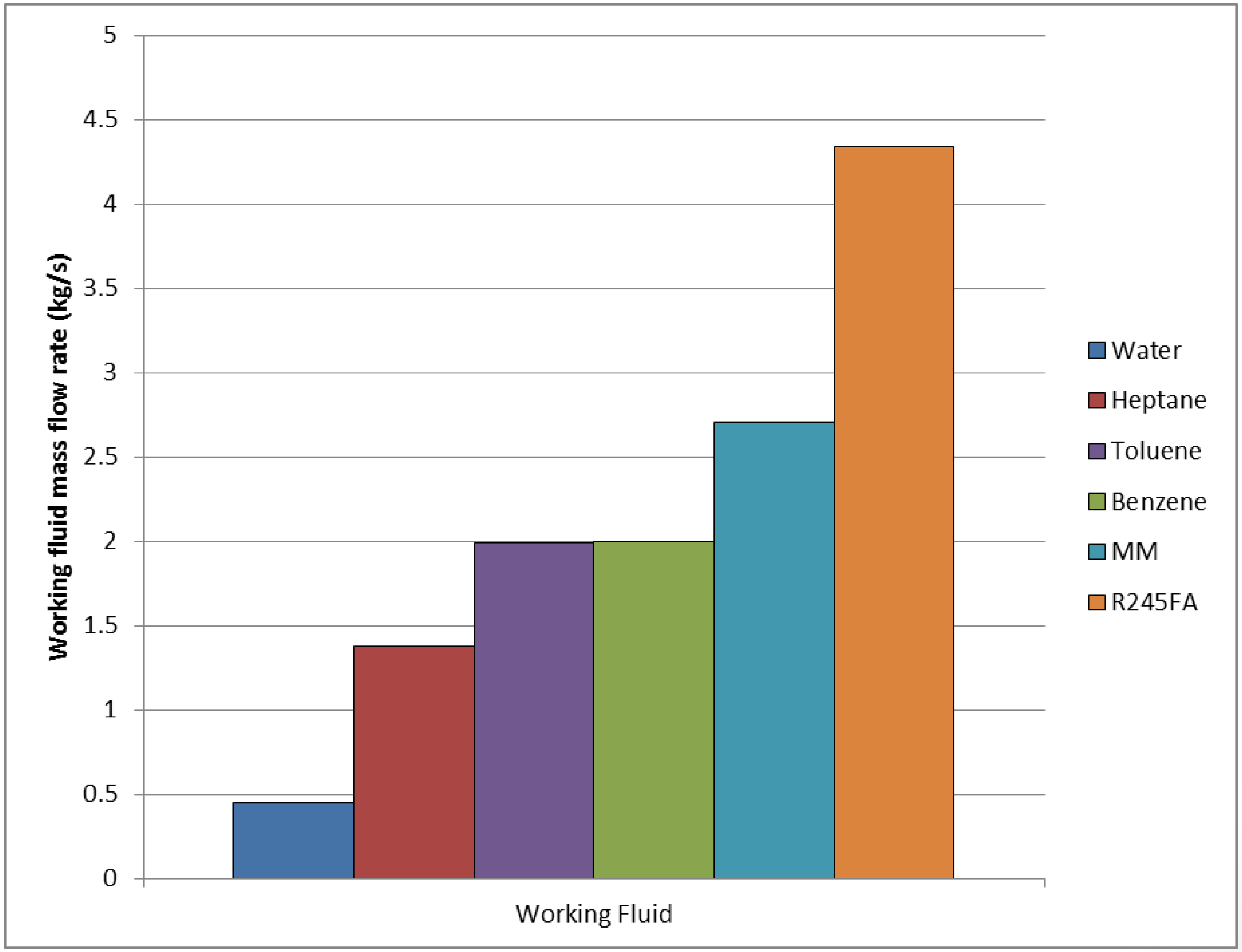
Higher

R245FA
4.3 kg/s

Around 1000% larger

Lower

Water
0.45 kg/s



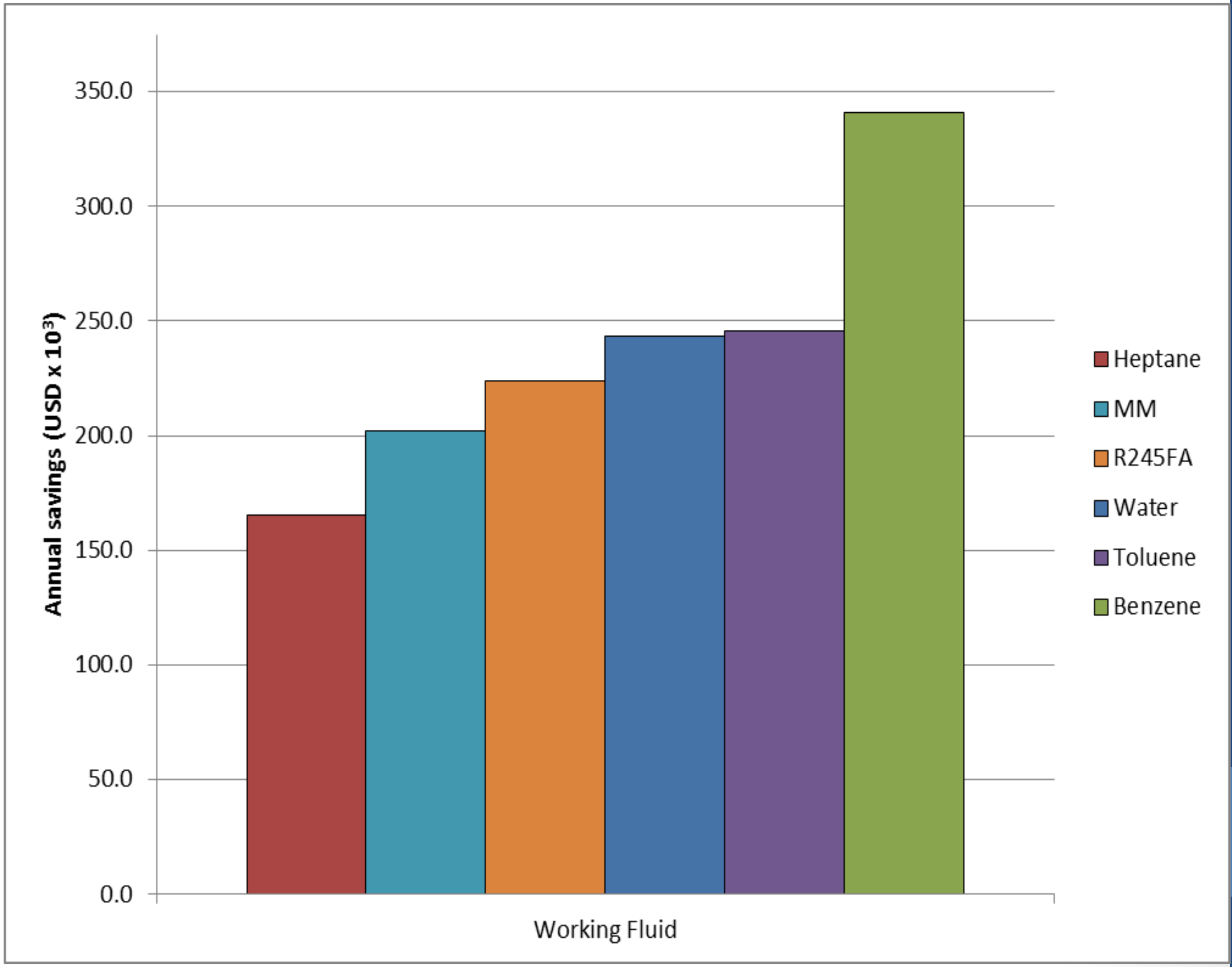
Results: Operating Profile

Fuel savings in a year (2640 trips)

<u>Higher</u>
Benzene
340k USD
per year

In 5 year of operations the benzene ORC will save around **490k USD more** than the RC

<u>Lower</u>
Heptane
165k USD
per year



Results: Operating Profile

CO_2 reductions in a year (2640 trips)

Higher

Benzene

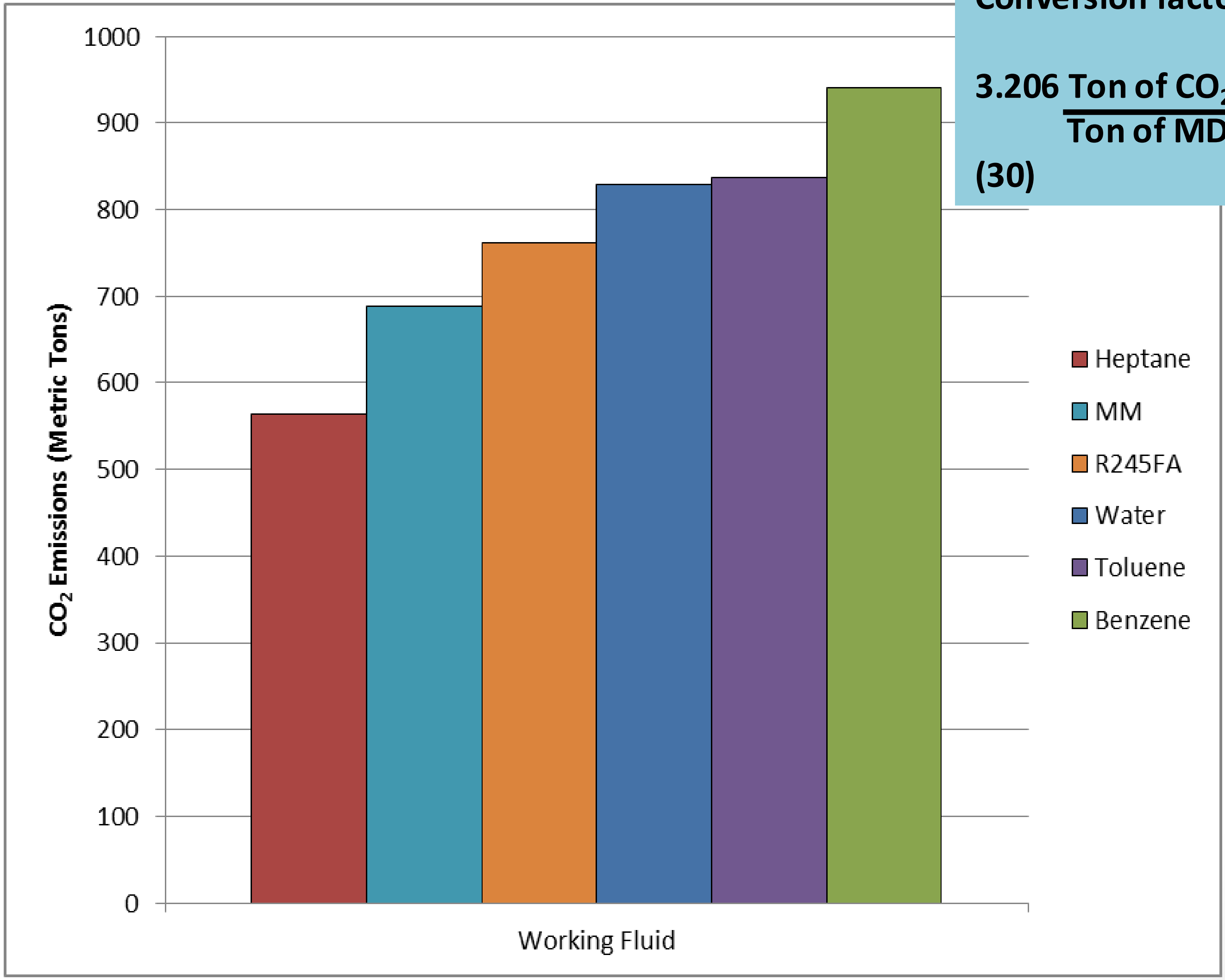
940 CO_2 Tons

In 5 year of operations the benzene ORC will save around **560 CO_2 tons** more than RC

Lower

Heptane

564 CO_2 Tons



Conversion factor:

$\frac{3.206 \text{ Ton of } CO_2}{\text{Ton of MDO}}$

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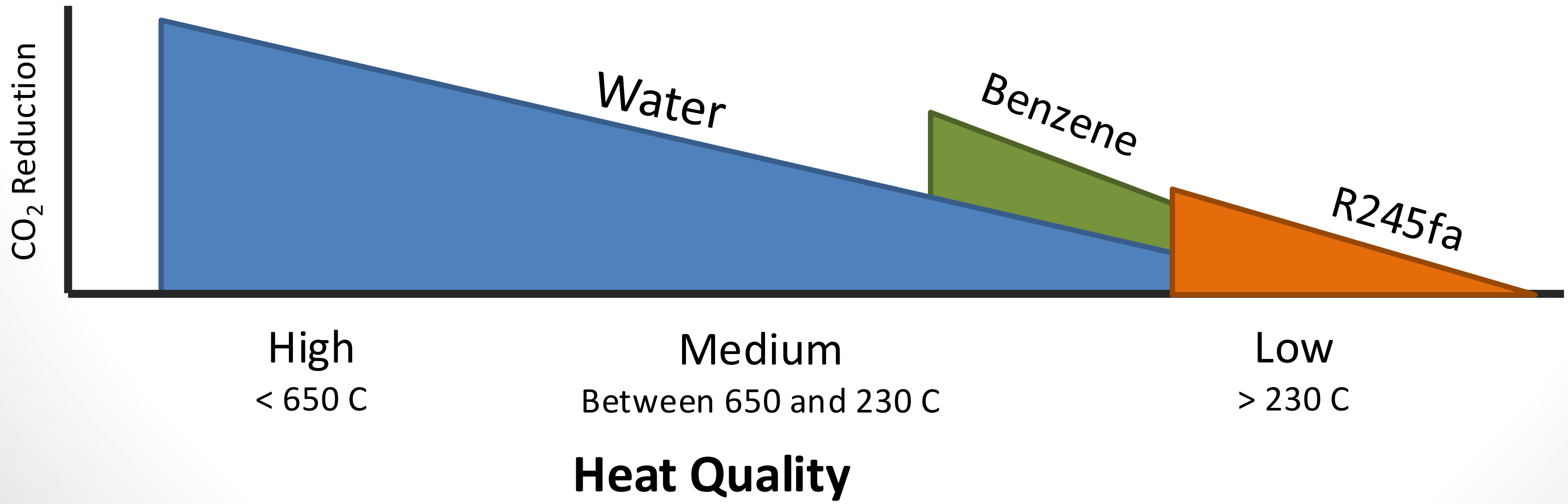
Discussion

- Benzene, toluene and water WHRS benefit of the medium quality heat of the engine ≈ 275 C.
- While MM, R245fa and Heptane could perform better in lower quality sources below 250 C:
  - Removes the thermal oil circuit,
  - Performance, design simplicity and size is affected drastically.



Conclusions

Conclusions

Working Fluid	Area (m^2)	1 Year		5 Years	
		CO_2 (Tons)	Savings (USD $x10^3$)	CO_2 (Tons)	Savings (USD $x10^6$)
Water	600	828	243	4,140	1.22
R245fa	1,425	762	223	3,810	1.12
Benzene	1,095	940	341	4,700	1.71

- WHRS can:
  - ✓ Improve the ferry CO_2 emissions reductions.
  - ✓ Increase the vessel efficiency (fuel and energy savings).
  - ✓ Reduce operational costs.
- ORC WHRS can outperform the water based RC when there is no need of a thermal oil circuit → Benzene and Toluene.
- Water WHRS is the most compact system tested.

Thank you

Questions ?

Contact Details

Email: santiago.fuente.11@ucl.ac.uk

Linkedin: Uk.linkedin.com/in/santiagosuarezdlf

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