ENERGETIC AND EXERGETIC ASSESSMENT OF WASTE HEAT RECOVERY SYSTEMS IN THE GLASS INDUSTRY

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08.10.2013

ASME ORC 2013
2nd International Seminar on ORC Power Systems
October 7th & 8th, 2013   De Doelen, Rotterdam, The Netherlands

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Waste Heat Recovery in Glass Industry

- High Energy Consumption; 300 Tbtu/year
- 70 % of the consumed energy is devoted to glass melting
- Glass melting is energy intensive requiring temperatures at about 1200-1500°C
- Exhaust gases around 500°C (typical for "old" glassworks)

Case study Yioula Glassworks S.A. – Attiki,Greece

480 °C

1200 °C
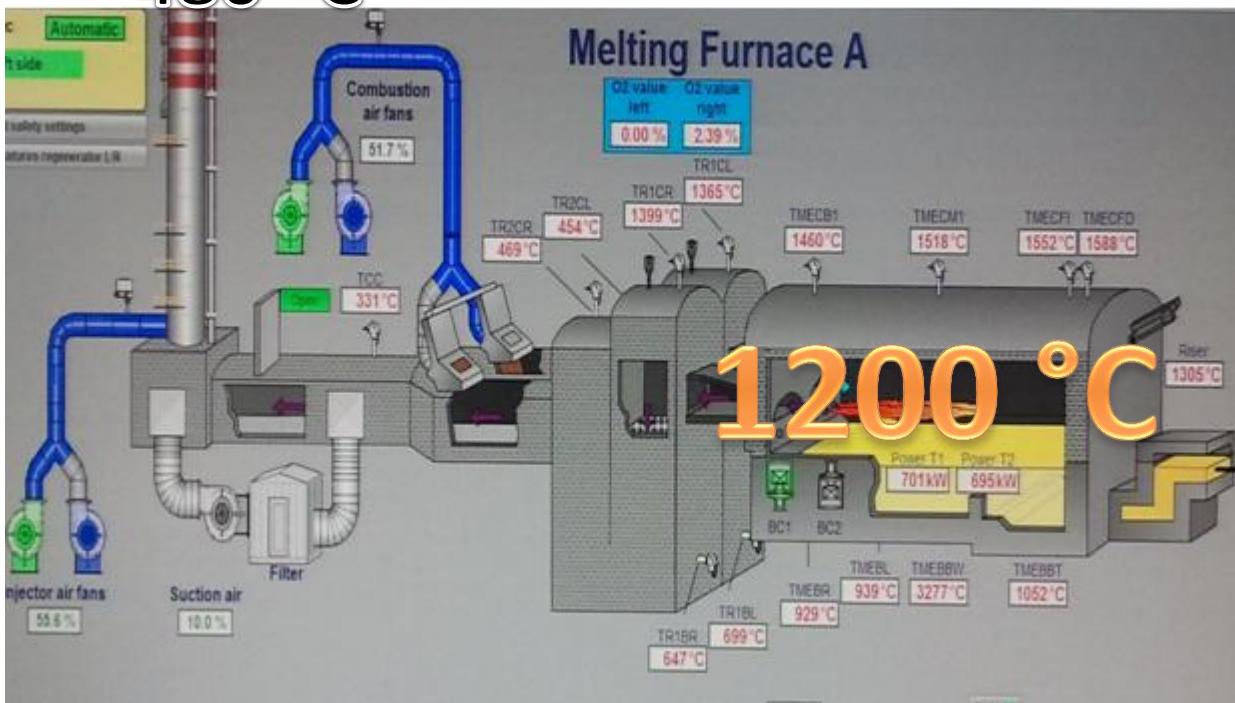
The case of Yioula Glassworks S.A.
4184 kJ/ kg$_{glass}$
furnace thermal needs 16 MW
Fuel consumption 1560 Nm³/h
Air-fuel ratio   λ=1,1
Tgas_out =450-500°C
Regenerative furnace

Waste heat in flue gases **4,0 MW$_{th}$**

The Rankine Cycle

- The exhaust gases leave the system at 180°C – industrial constraints   **2,7 MWth**

- Only dry fluids examined (no superheating)

$$\eta_{HT} = \frac{Q_{in}}{Q_{in,max}} \qquad \eta_{th} = \frac{P_{el}}{Q_{in}} \qquad \eta_{sys} = \eta_{HT} \cdot \eta_{th}$$

VS.
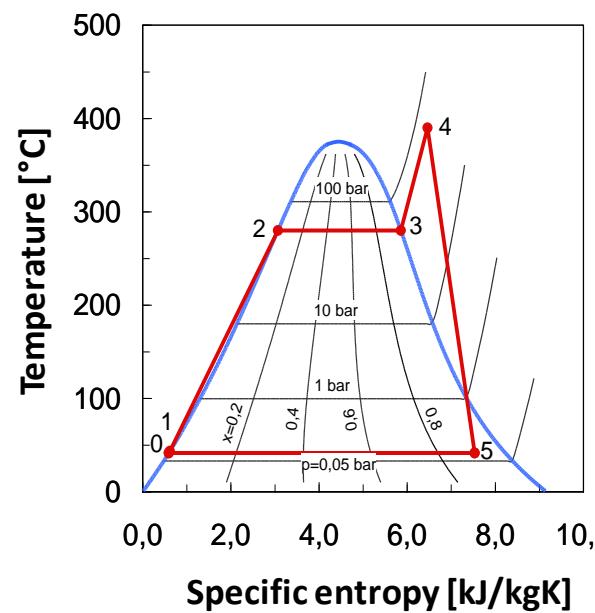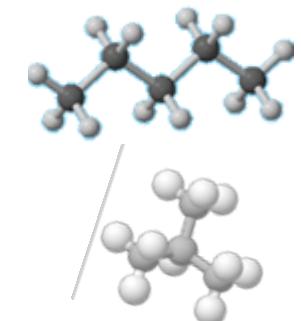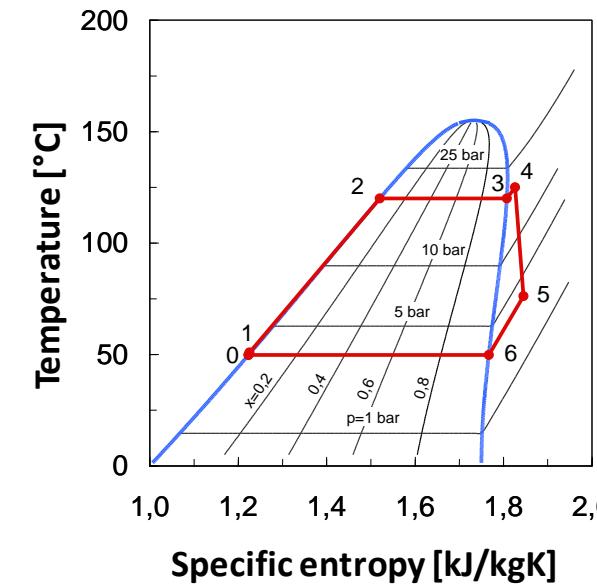
water

organic fluids

Water- Steam Rankine Cycle

480°C

exhaust gas

T-S chart
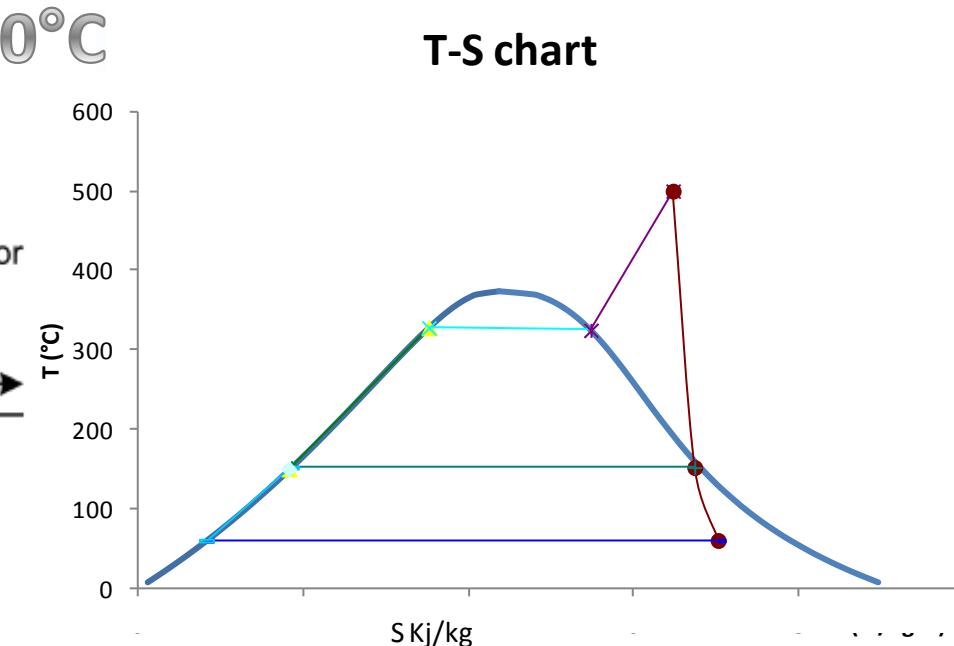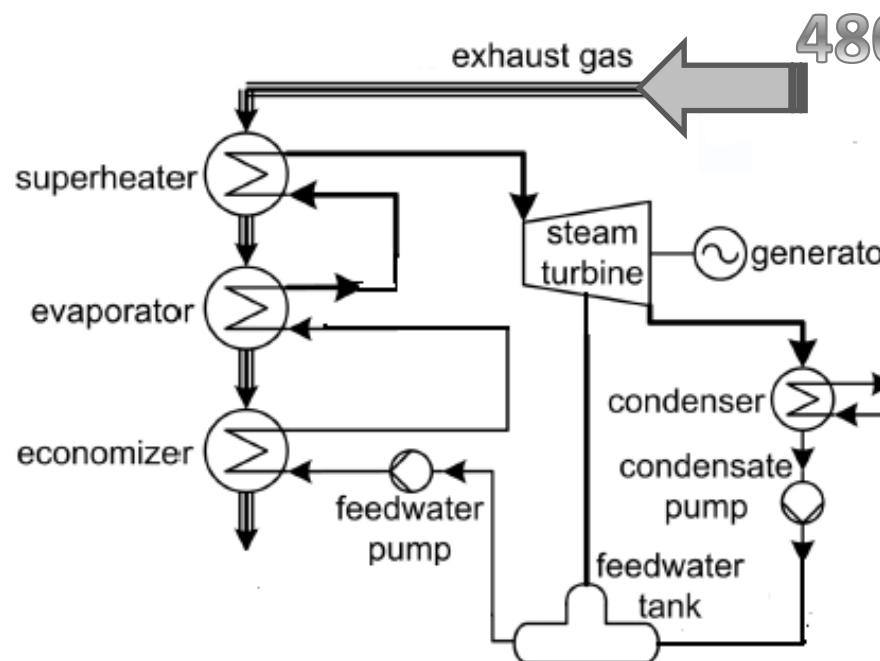
Assumptions	
Water condensation temperature/ pressure	60° C/ 0,198bar
Gases' temperature at the inlet / exit of the WHR system	483 /180° C
Maximum superheating temperature	460 ° C
Isentropic efficiency Turbine Pump	 80% 70%
Electric efficiency/ mechanical efficiency	98% / 99%

Water Steam Rankine Cycle-Thermodynamic optimization

Parameters	value
High pressure	26,5bar
Superheating temperature	460 °C
P_{el}	701,8 kW
η_{th}	26,05%
η_{HT}	66,16%
η_{sys}	17,23%
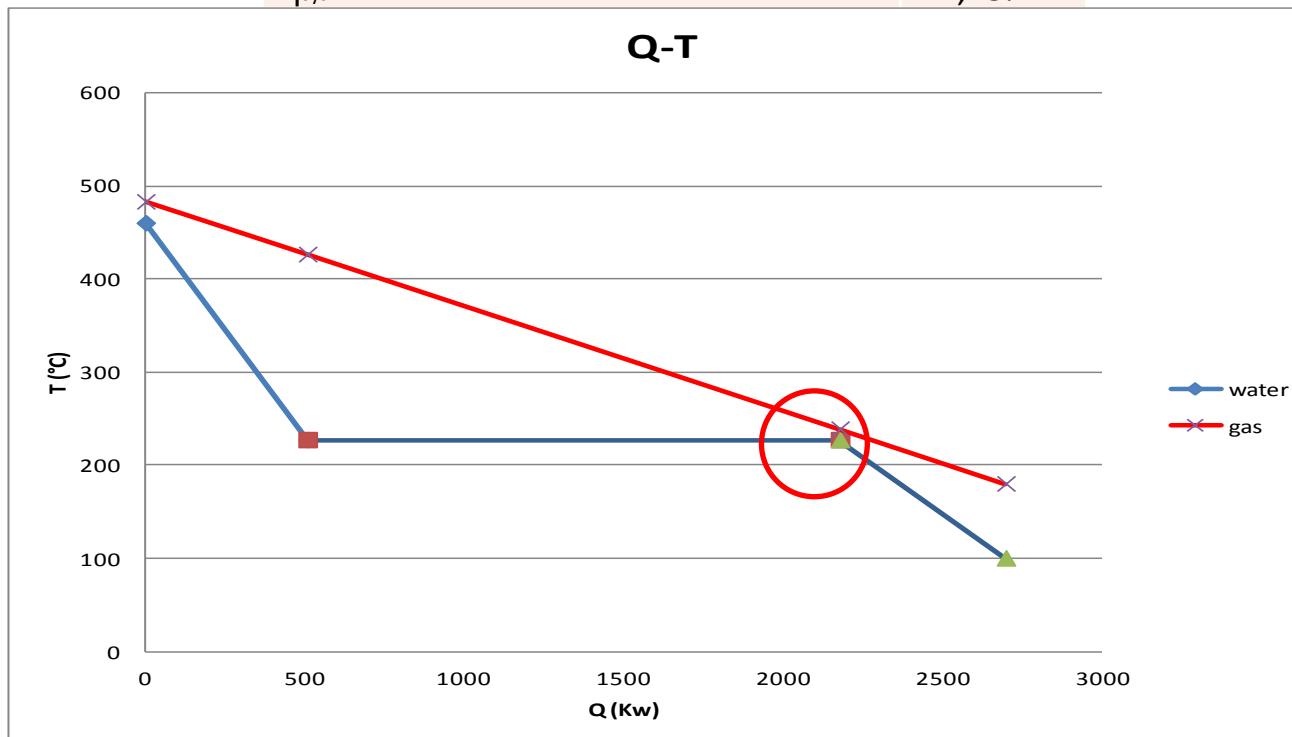
The Organic Rankine Cycle

Organic fluid	Condensation temperature $T_{cond}(°C)$	Condensation pressure p_{low} (bar)
MM	60	0,2598
MDM	66,6	0,05
D4	87,1	0,05
D5	143,2	0,05
toluene	60	0,1843
pentane	60	2,136

Subcritical Saturated Cycle
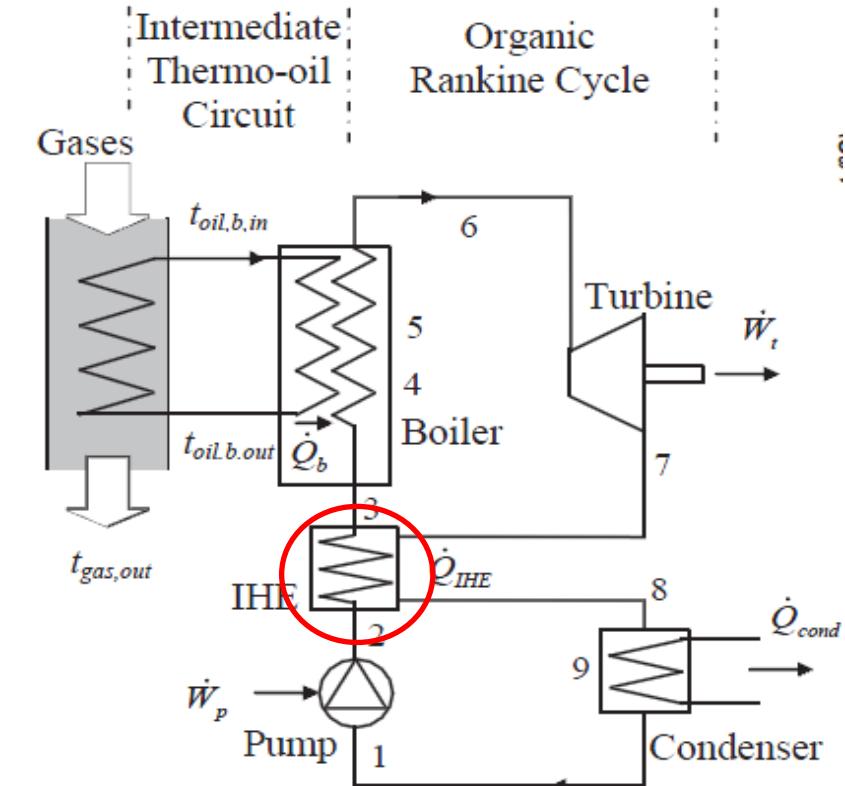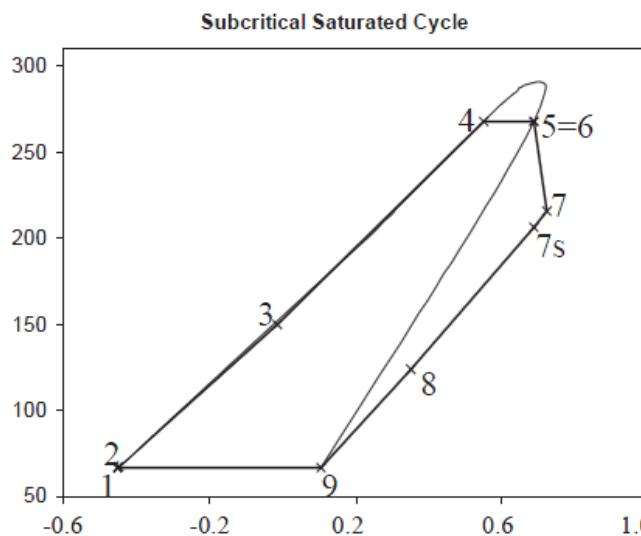
| Organic fluid	CAS-NU	p_{crit} (bar)	T_{boil} (°C)	T_{crit} (°C)
MM	107-51-7	19,51	100,52	245,6
MDM	107-46-0	14,15	152,53	290,94
D4	556-67-2	13,32	175	313,35
D5	541-02-6	11,6	210,95	346
Toluene	108-88-3	41,06	110,6	318,64
Pentane	109-66-0	33,6	36	196,7

Organic Rankine Cycle

• Non Regenerative ORC- Turbine inlet saturated steam

Organic fluid	T_{cond}(°C)	Condensation pressure p_{low} (bar)
MM	60	0,0266
MDM	66,6	0,05
D4	87,1	0,05
D5	143,2	0,05
toluene	60	0,184
pentane	60	0,213

assumptions	
Exiting gas temperature	180° C
Maximum temperature of diathermal oil	380° C
Isentropic efficiency Turbine Pump	 85% 70%
Electrical efficiency/ Mechanical Efficiency	98% / 99%

Non Regenerative ORC – Thermodynamic Optimization
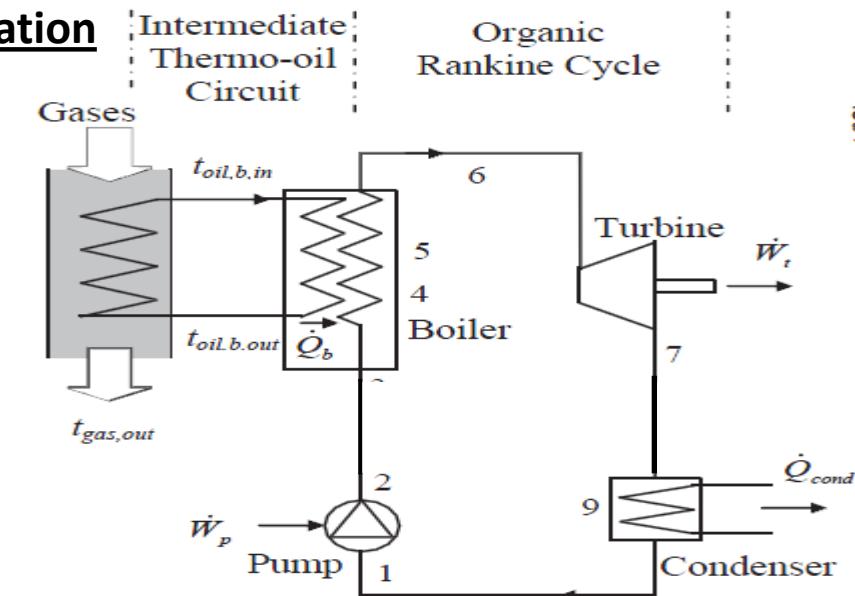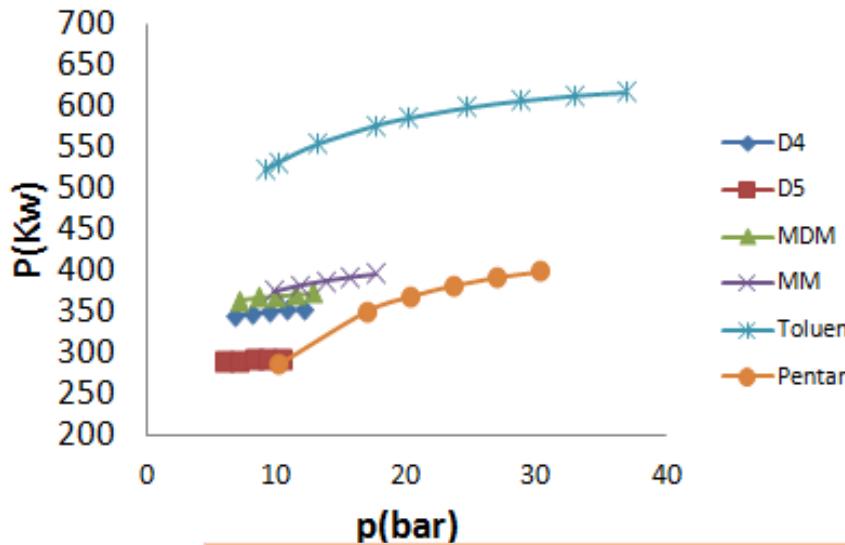
	P_{evap} (bar)	T_{evap} (°C)	η_{HT}	η_{th}	η_{sys}	P_{el} (kW)
MM	17,56	239	65,64%	14,7%	❄%	415,0
MDM	12,74	264,056	65,84%	13,79%	9,08%	383,9
D4	11,988	306	65,85%	13,09%	8,62%	363,9
D5	10,44	339,1	65,61%	10,82%	7,1%	302,1
toluene	36,9	309,68	68,93%	22,92%	15,8%	642,2
pentane	30,24	189,2	63,15%	14,19%	9,34%	436,3

Regenerative ORC – Thermodynamic Optimization
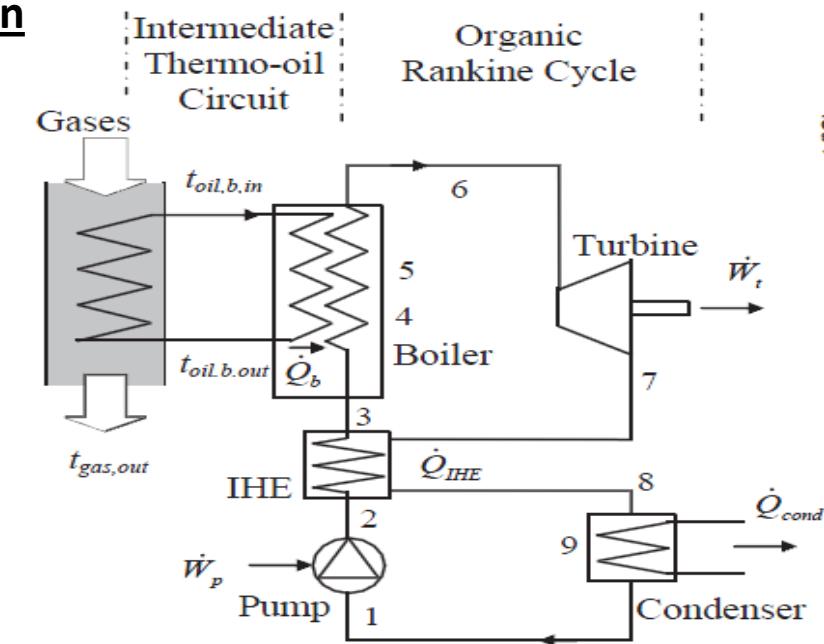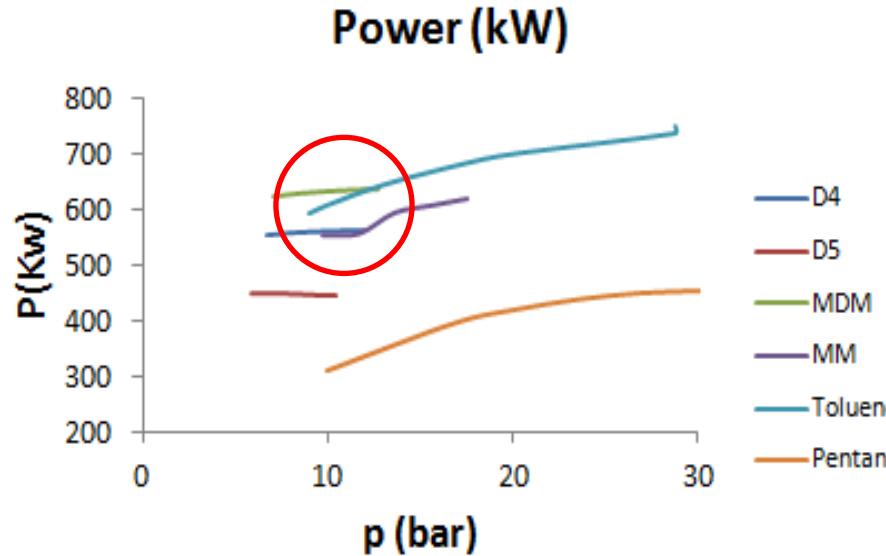
|	Pevap (bar)	Tevap	ηHT%	ηth%	ηsyst %	Pel (kW)
MM	17,56	239	68,84	21,79	15	645,1
MDM	12,74	264,06	59,59	26,11	15,56	657,7
D4	11,1	306	54,3	25,3	13,74	581,2
D5	10,44	339,1	44,75	24,33	10,89	461,2
toluene	36,9	309,68	65,81	27,67	18,21	772,2
pentane	30,24	189,2	75,34	14,65	11,09	497,0

20%

How the regenerator affects the system's efficiency ?

$\eta_{syspentane}$ 9,3% ⟹ **11%**

η_{sysMDM} 9% ⟹ **15,56%**

Non Regenerative ORC

0,9% self consumption

100%

Flue gases heat input

22,3% **Power** Output

0,92% other **losses**

75,28% **condenser**

Increased Power output
Decreased condensation requirements

Regenerative ORC

1,1% self consumption

100%

Flue gases heat input

27,75% **Power** Output

1,1% other **losses**

70,05% **condenser**
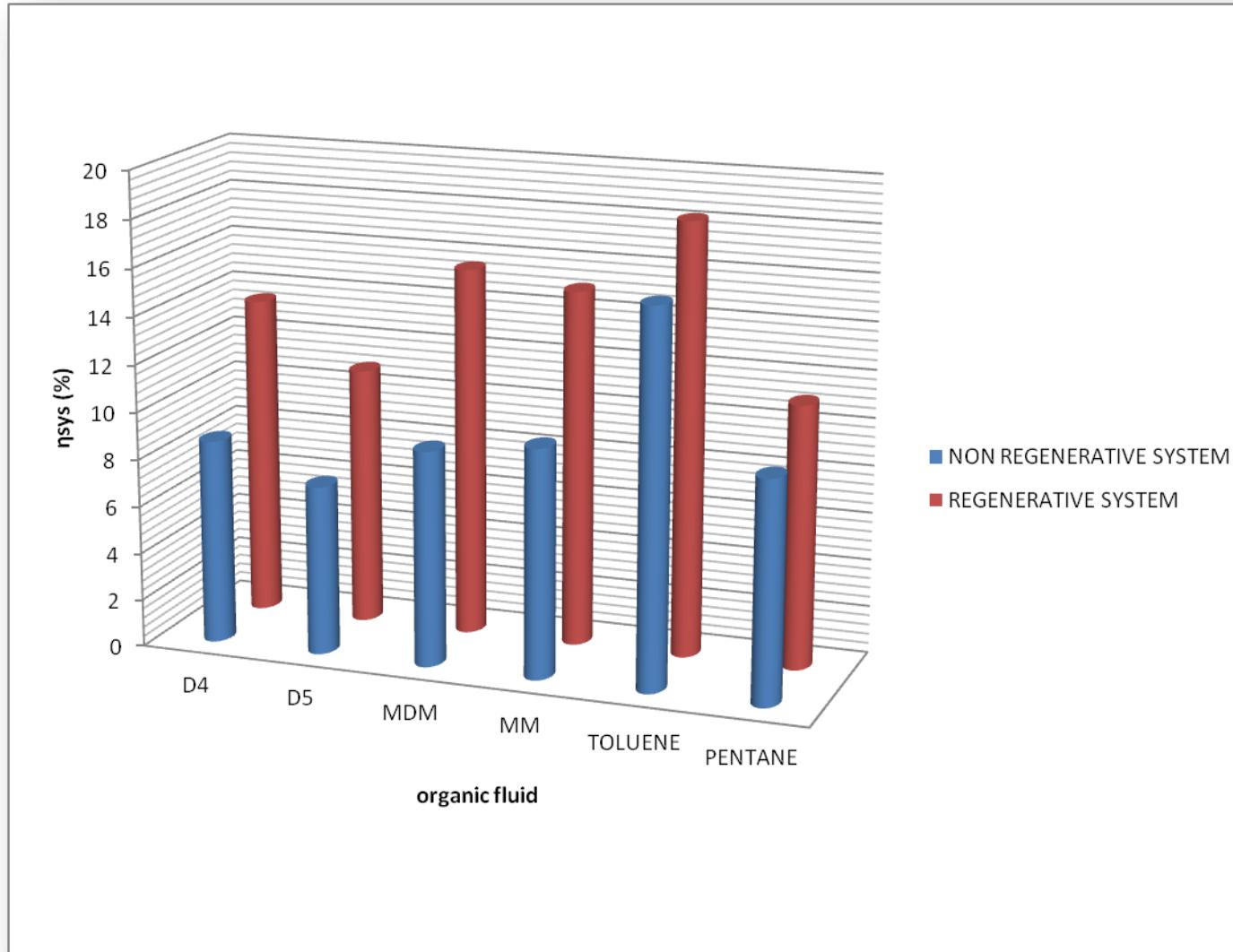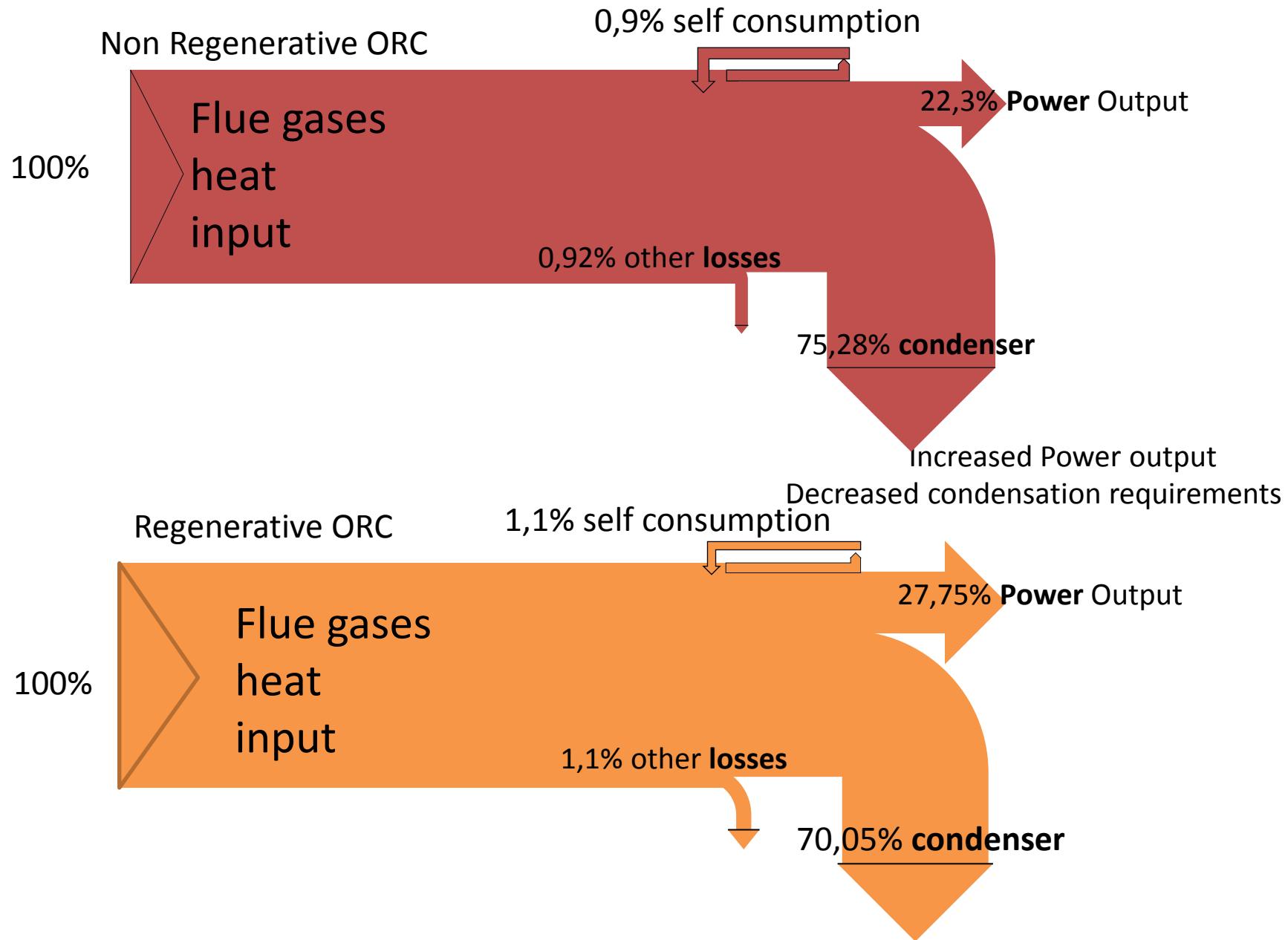
The regenerator decreases the exergy destruction in this case
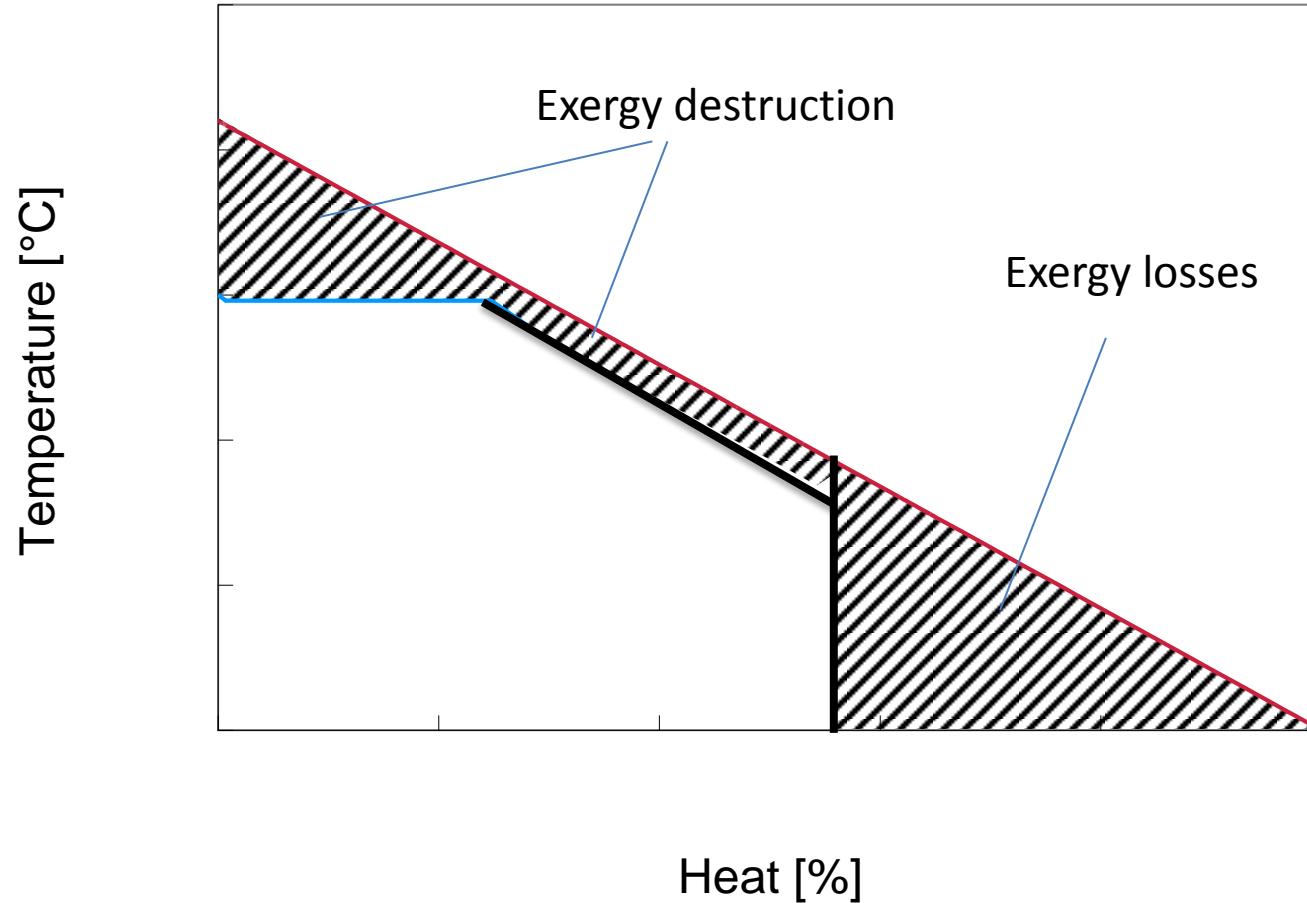
EXERGETIC COMPARISON   -   IRREVERSIBILITIES

component	Water steam I (kW)	N/R ORC I (kW)	R –ORC I (kW)
Gas_oil hex	-	117,23	117,23
economizer	31,44	123,17	21
Evaporator	157,29	99,30	94,62
Superheater	64,1	-	-
Regenerator	-	-	23,96
Feeding pump	0,86	6,88	8,33
Pump2	0,02	-	-
Turbine	121,8	96,65	117,02
Condenser	219,16	274,26	202,75
Generator losses	22,54	6,56	7,94
Exergy exiting exhaust gases			
Generator	733,91	617,87	748,14
EXERGETIC EFFICIENCY	**29,58%**	**24,8%**	**30,15%**

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➢Thermodynamic optimization of waste heat recovery system

   ✓*Energetic comparison*

   ✓*Exergetic comparison*

➢ **Economic evaluation**

➢Conclusions

LOAN 50% OF INVESTMENT COSTS

Payback Period Water steam
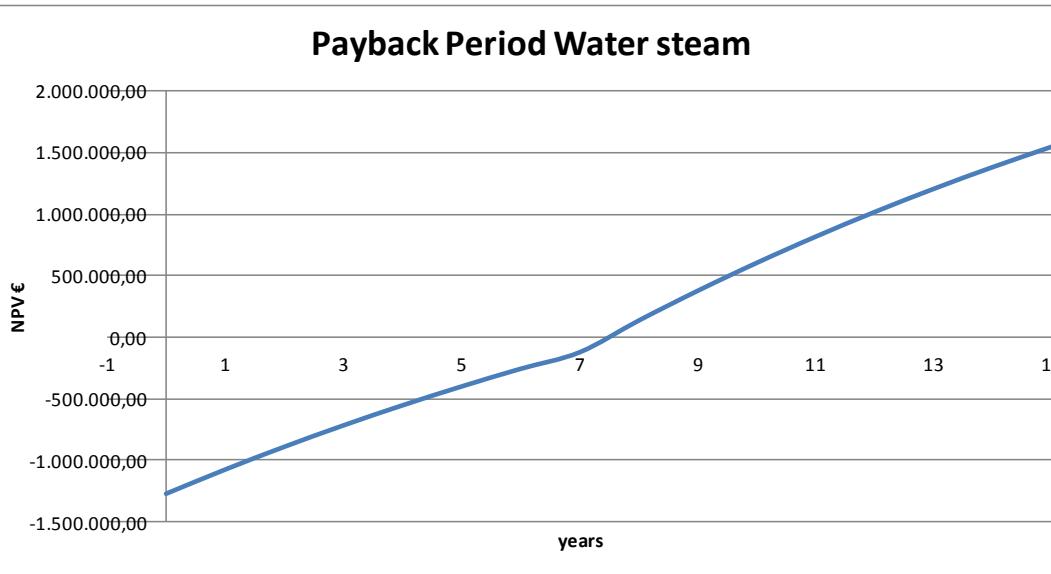
WATER STEAM RANKINE CYCLE

Payback period 7,5 years

IRR: 21%

SEPC Toluene Regenerative
0,053€/kWh

ORC

Payback Period 4 years

IRR 33%

Payback Period ORC
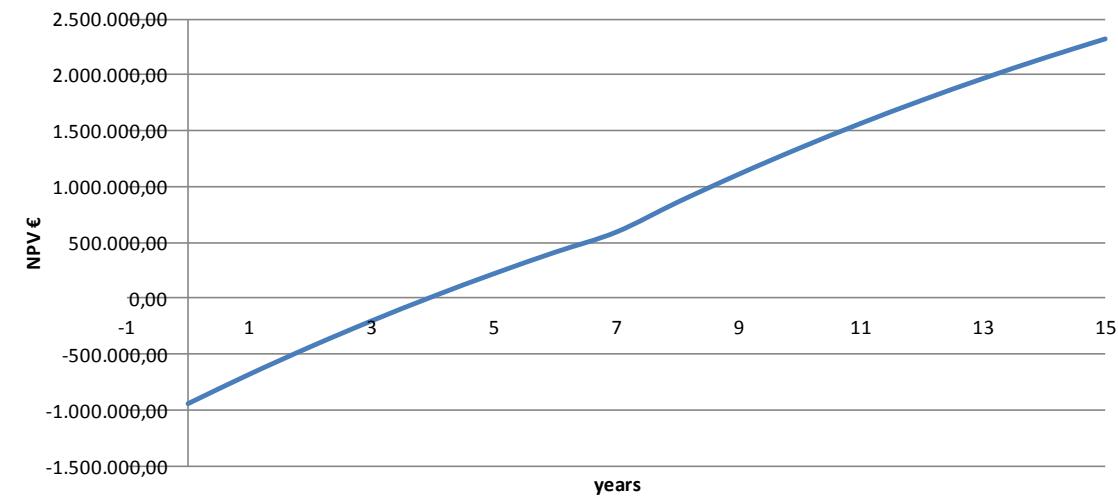
How the spot market price affects the feasibility of the investment?
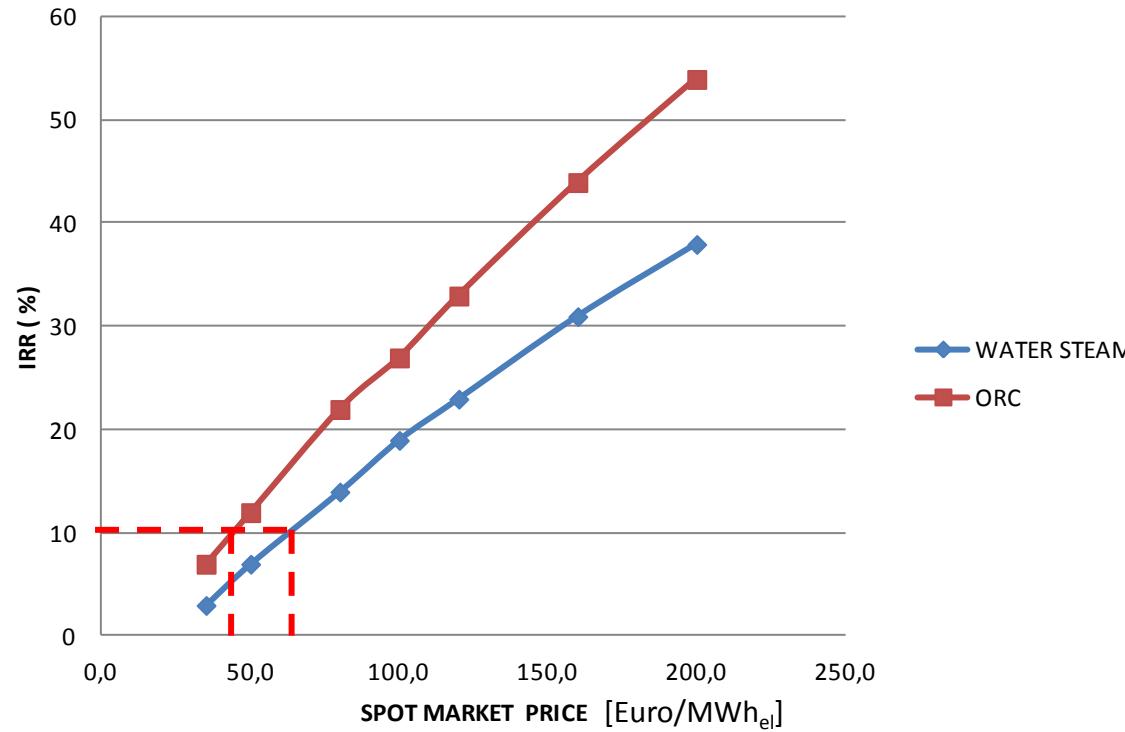
The ORC Regenerated with toluene as working fluid can be feasible even at lower spot market prices

CONCLUSIONS

Given heat source temperature level ≈500°C:

• If the condenser is air cooled, ORC systems recover energy more efficiently than water steam systems

• The use of a regenerator increases the efficiency and the profitability of the project.

• Toluene and MDM are very competent in the field of waste heat recovery.

Thank you for your attention !

At your disposal for further analysis!