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ENHANCEMENT OF THE ELECTRICAL EFFICIENCY OF COMMERCIAL FUEL CELL UNITS BY MEANS OF AN ORGANIC RANKINE CYCLE: A CASE STUDY

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ORC 2011, 23 September 2011 – Delft (NL)

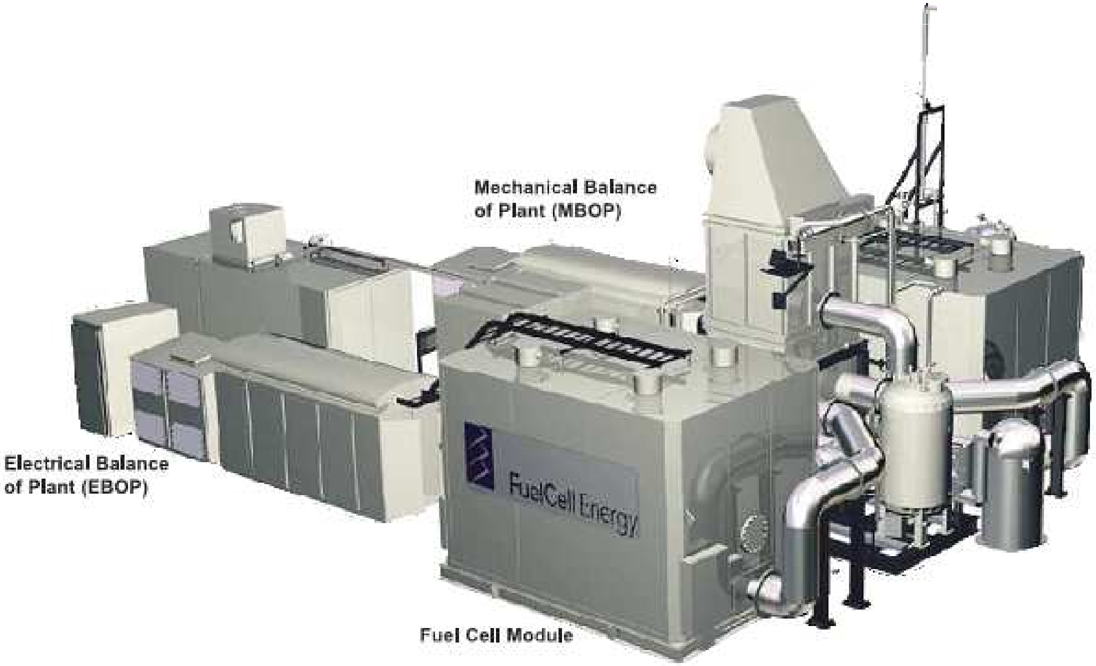
Introduction

Molten carbonate fuel cell (MCFC) are a promising technology for distributed electricity production, especially for power applications in the few hundred kW to 10 MW size range.

MCFC units are commercially available (proposed by Fuel Cell Energy Company), but they have not yet achieved significant penetration into energy market, mainly due to their high specific costs (2500-2800 €/kW_{el}).

DFC 3000

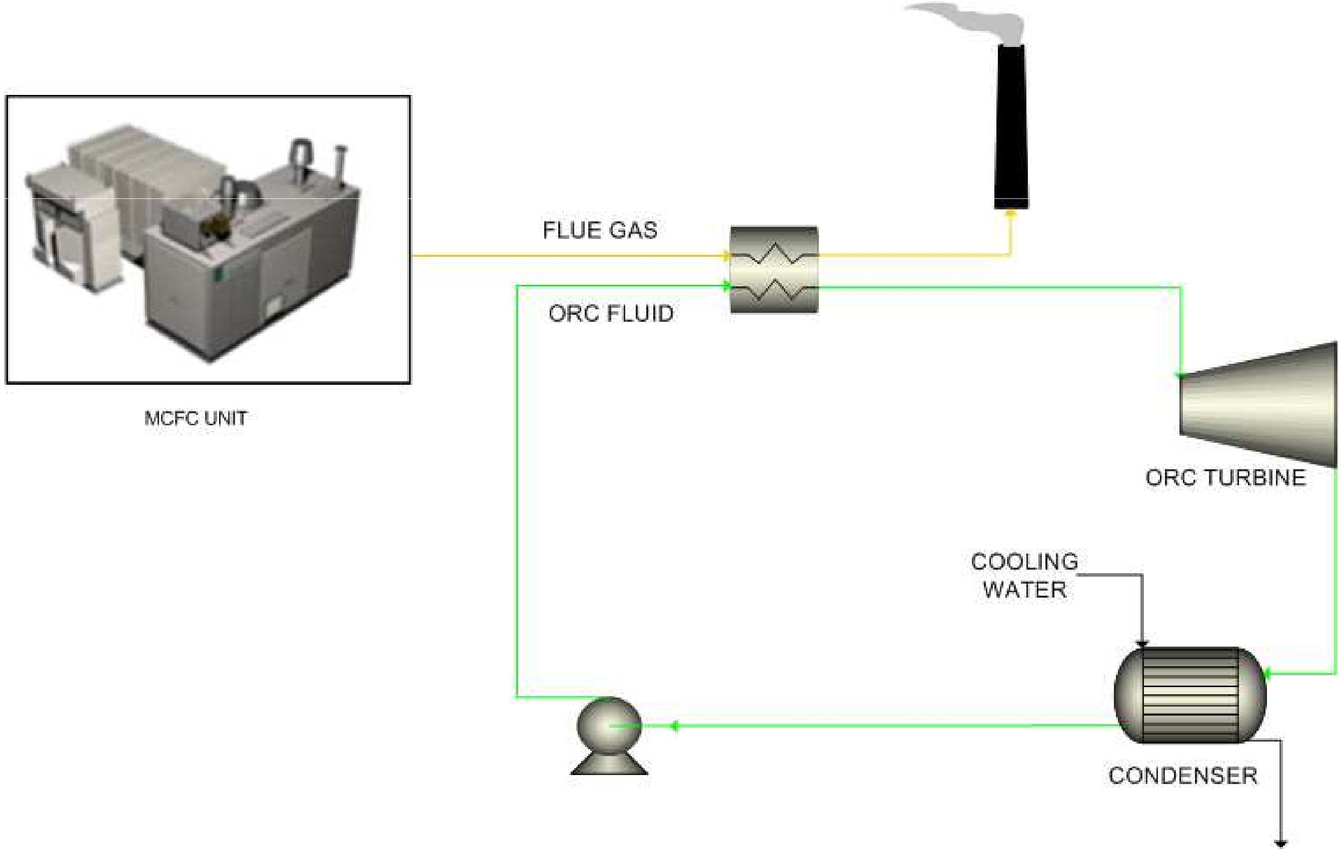
Power Output	
Power @ Plant Rating	2,800 kW
Efficiency	
LHV	47 +/- 2 %
Available Heat	
Exhaust Temperature	379 +/- 10 °C
Exhaust Flow	16,600 kg/h
Pollutant Emissions	
NOx	4.5 g/MWh
SOx	0.045 g/MWh
PM10	0.009 g/MWh
Greenhouse Gas Emissions	
CO_2	445 kg/MWh



Introduction

In order to improve the FC power plant economics, the MCFC unit can be applied to combined heat and power, recovering heat dissipated by stack exhaust gases.

When the power plant cannot be installed in presence of a heat demand, the flue gases waste heat could be exploit by means of an Organic Rankine Cycle (ORC) used as a heat recovery bottoming cycle.

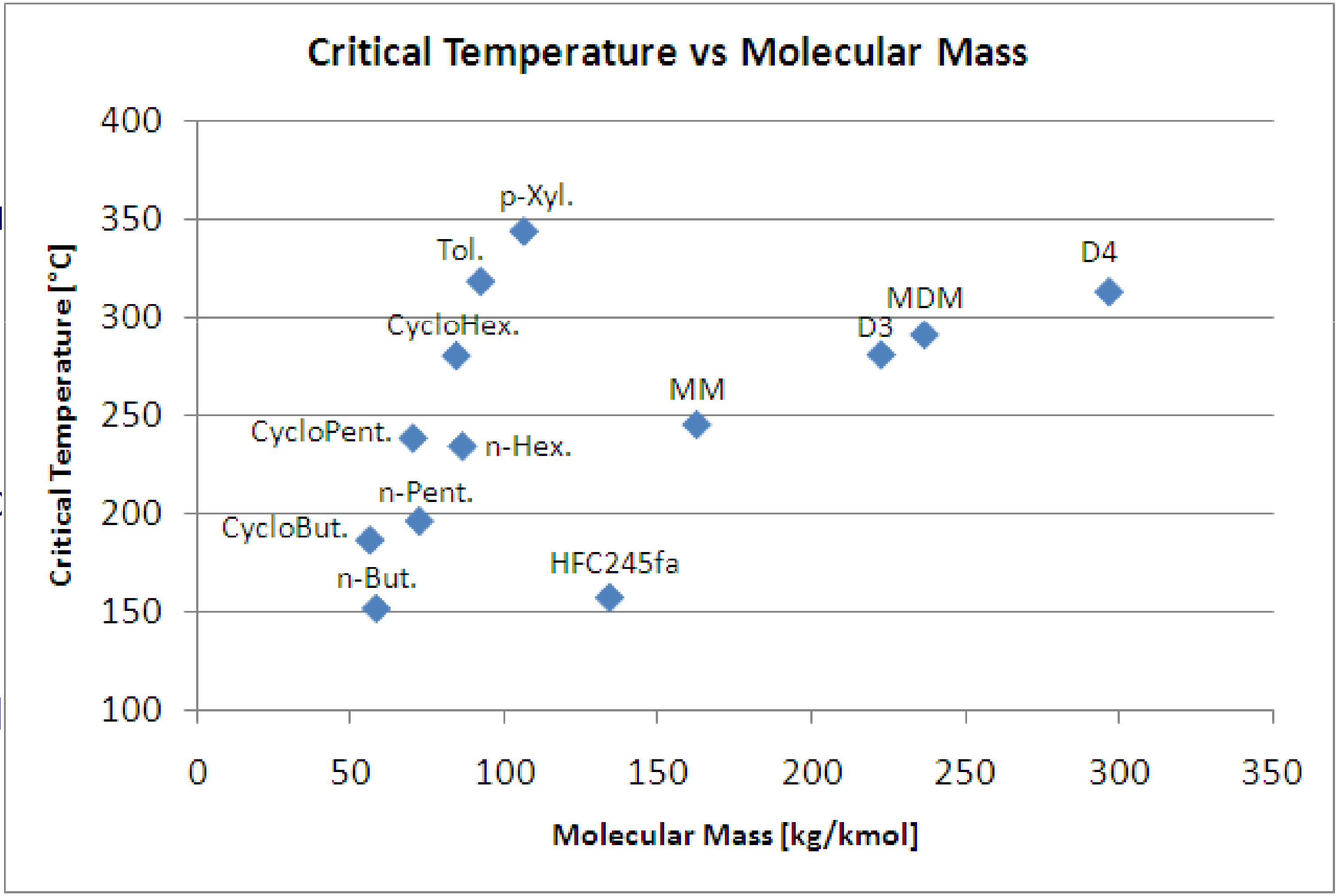


Objective & Methodology

In this study, the potential benefits of the combined plant are assessed by evaluating the effects of the working fluid properties on the ORC optimum operating conditions, performances and costs.

The fol

1. **Aroı**
2. **Alip**
   - ➢
   - ➢
3. **Silo**
   - ➢
   - ➢
4. **Hyd**



Objective & Methodology

Simulations of the bottoming cycle are performed in Aspen Plus® environment, obtaining detailed energy and mass balances.

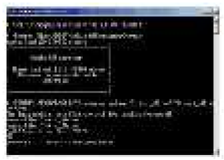
For each working fluid, the net power of the energy recovery cycle is maximized via a Matlab® code, which evaluates the objective function running, at each iteration of the optimization algorithm, the Aspen Plus model.

Modify the parameters of the Aspen Model Input File

Run the Aspen Model by the Aspen Plus simulation engine

Read the Aspen Model report File and update the objective function

aspentech



Optimization Assumptions

Optimization variables

1. P_{ev}: working fluid evaporation pressure
2. $T_{max:}$ Maximum temperature of the cycle

Fixed parameters

1. Components efficiency

   Turbine: η_{is} = 82%; η_{el} = 96%; Pumps[1]: η_{is} = 80%; η_{el} = 94%
2. Heat Exchangers minimum temperature approach

   Primary heat exchanger: ΔT_{pp} = 30°C; Regenerator: ΔT_{pp} = 15°C;

Other assumptions

Working fluid: $T_{cond} \geq 36$°C; $P_{cond} \geq 0.1$ bar

Cooling water: T_{in} = 15°C; ΔT_{max} = 8°C;

[1]Feed pump & cooling water pump

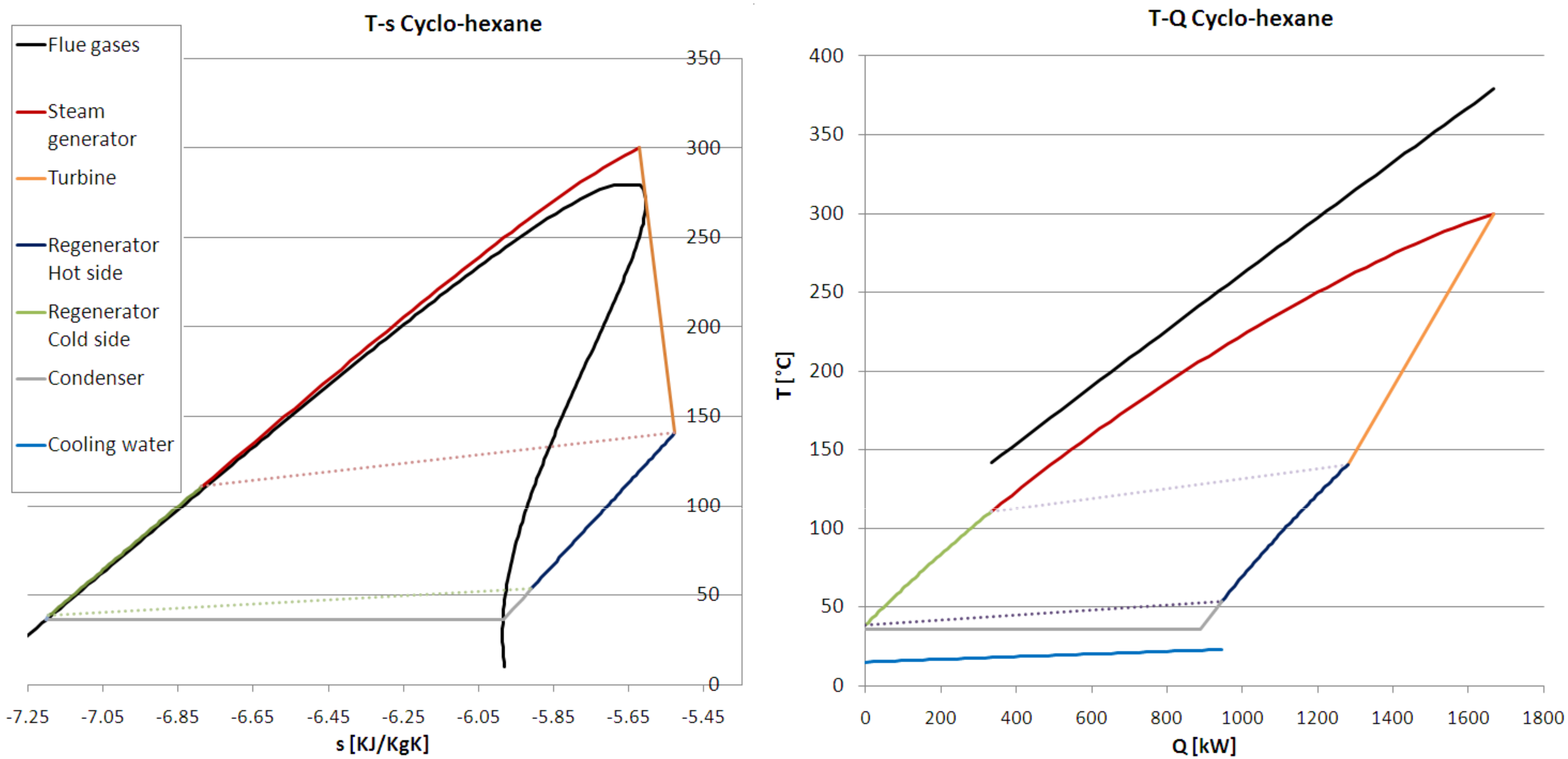
Optimization Results

ORCs performance assuming 1 MW_{th} of recoverable heat in the flue gases (T_{min} at stack =85°C)

	Tc [°C]	Pc [bar]	Recovered Heat [kW]	T flue gases at stack [°C]	Tcond [°C]	Pcond [bar]	Pev [bar]	Tmax [°C]	Gross Power [kW]	Net Power [kW]	η_{tot}	Cycle
Cyclohexane	280.5	40.8	812	142	36	0.2	57.7	300	239.2	218.3	26.9%	SUPER
Cyclopentane	238.6	45.0	877	123	36	0.6	88.9	290	248.9	217.3	24.8%	SUPER
Cyclobutane	186.8	49.9	835	135	36	2.2	151.0	305	253.7	207.1	24.8%	SUPER
Toluene	318.6	41.3	805	144	46	0.1	15.8	245	212.0	202.0	25.1%	SUB
n-Hexane	234.5	30.2	809	143	36	0.3	65.0	275	225.1	198.2	24.5%	SUPER
n-Pentane	196.5	33.7	802	145	36	1.0	93.0	275	227.9	191.2	23.8%	SUPER
HFC245fa	157.6	36.4	778	152	36	2.2	147.0	290	232.4	184.7	23.8%	SUPER
MM	245.5	19.1	747	161	36	0.1	28.7	260	199.0	181.4	24.3%	SUPER
n-Butane	152.0	38.0	764	156	36	3.4	134.9	285	230.1	179.5	23.5%	SUPER

For the other fluids examined (p-Xylene, MDM, D4), ORC performances are much lower, mainly due to the high condensation temperature.

Best Fluids: 1. Cyclohexane



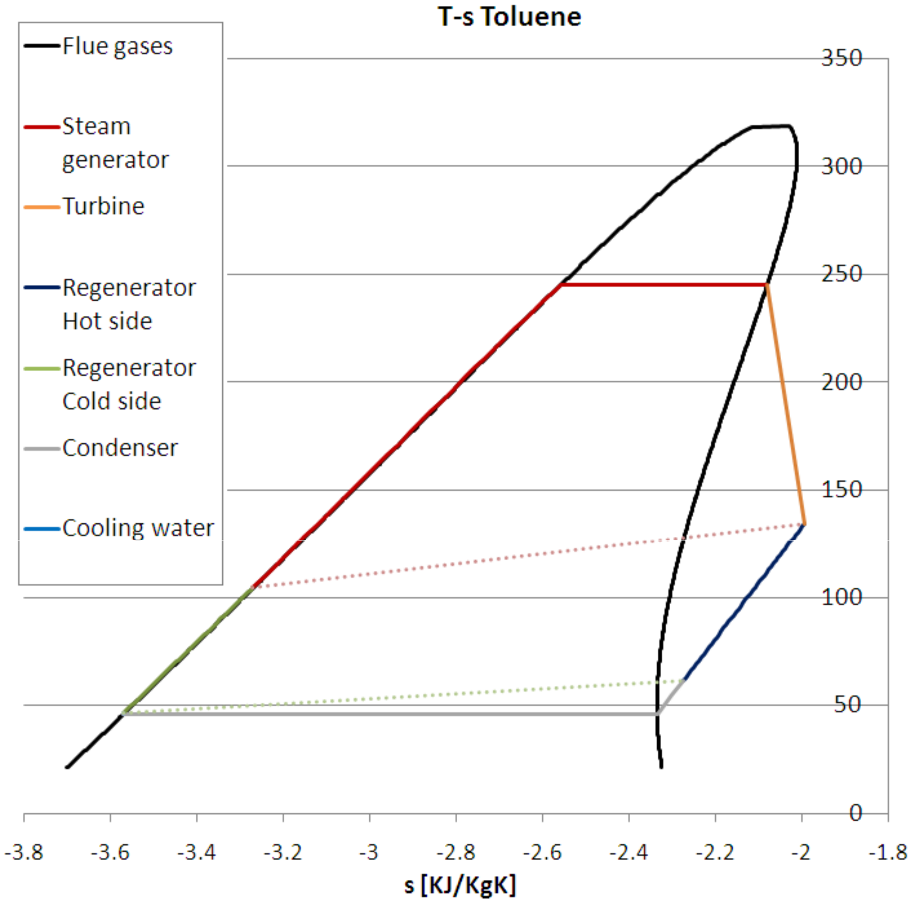
Pros

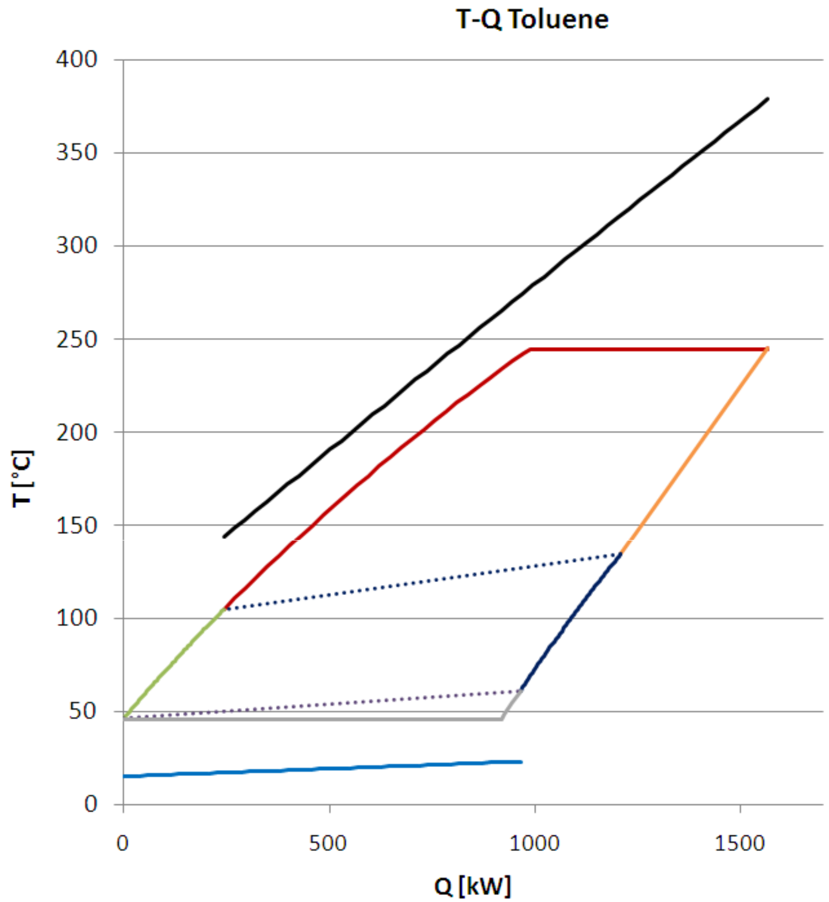
- **Optimal matching between hot & cold streams in steam generator**
- **The regenerator is not needed (w/o cogeneration)**

Cons

- **Toxicity**
- **Flammability**

Best Fluids: 2. Toluene

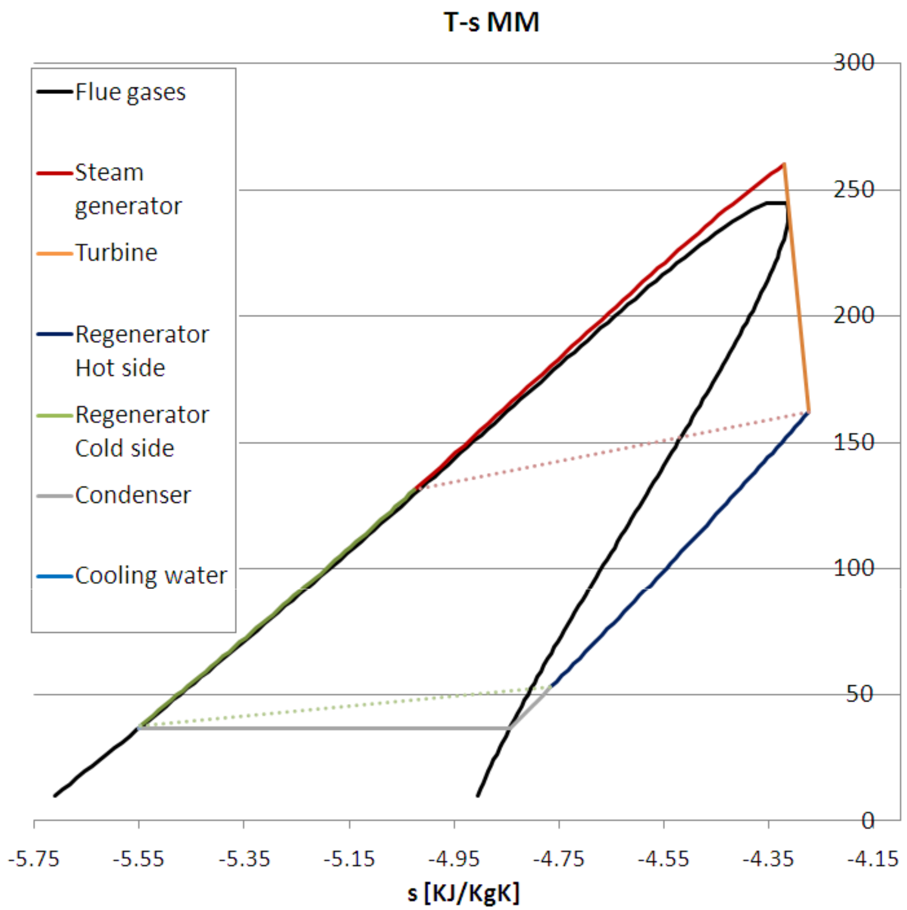


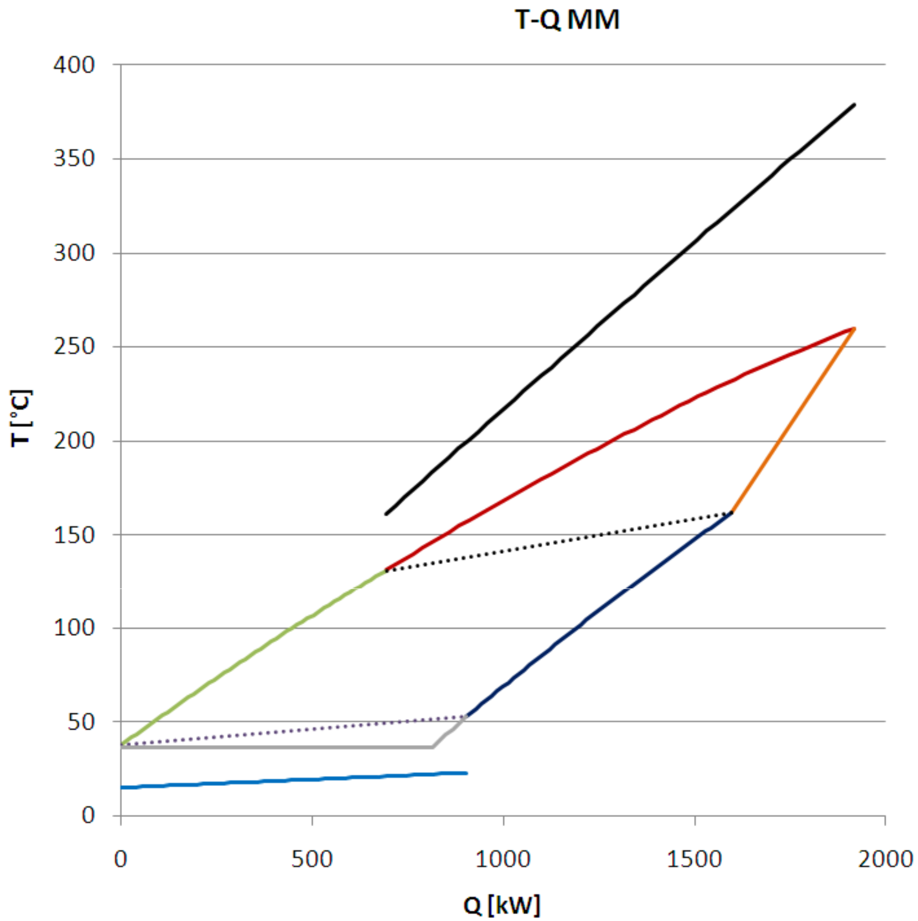


Pros
- **Low cycle pressure**
- **The regenerator is not needed (w/o cogeneration)**

Cons
- **Higher condensing temperature**
- **Toxicity**
- **Flammability**

Best Fluids: 3. MM





Pros

- Low toxicity
- Low cycle pressure

Cons

- The regenerator is required (otherwise -10% in achievable P_{el})
- Lower performance, that could be improved by cogeneration

Economical Analysis

For each one of the selected working fluids, we have examined 4 different configurations, in order to point out scale effects on the integration and the impact of cogeneration on the economy of combined plant.

Case	ORC size	Cogeneration	Regenerator	DFC3000 modules
1	500-700 kW_{el}	-	-	2
2	500-700 kW_{el}	Yes	Yes	2
3	1-1.4 MW_{el}	-	-	4
4	1-1.4 MW_{el}	Yes	Yes	4

The benefits of the integration were assessed evaluating the levelized cost of electricity (LCOE) of the combined plant. With respect to the MCFC plant:

Current DFC 3000 LCOE (no cogeneration): 11.5 €c/kWh, assuming:

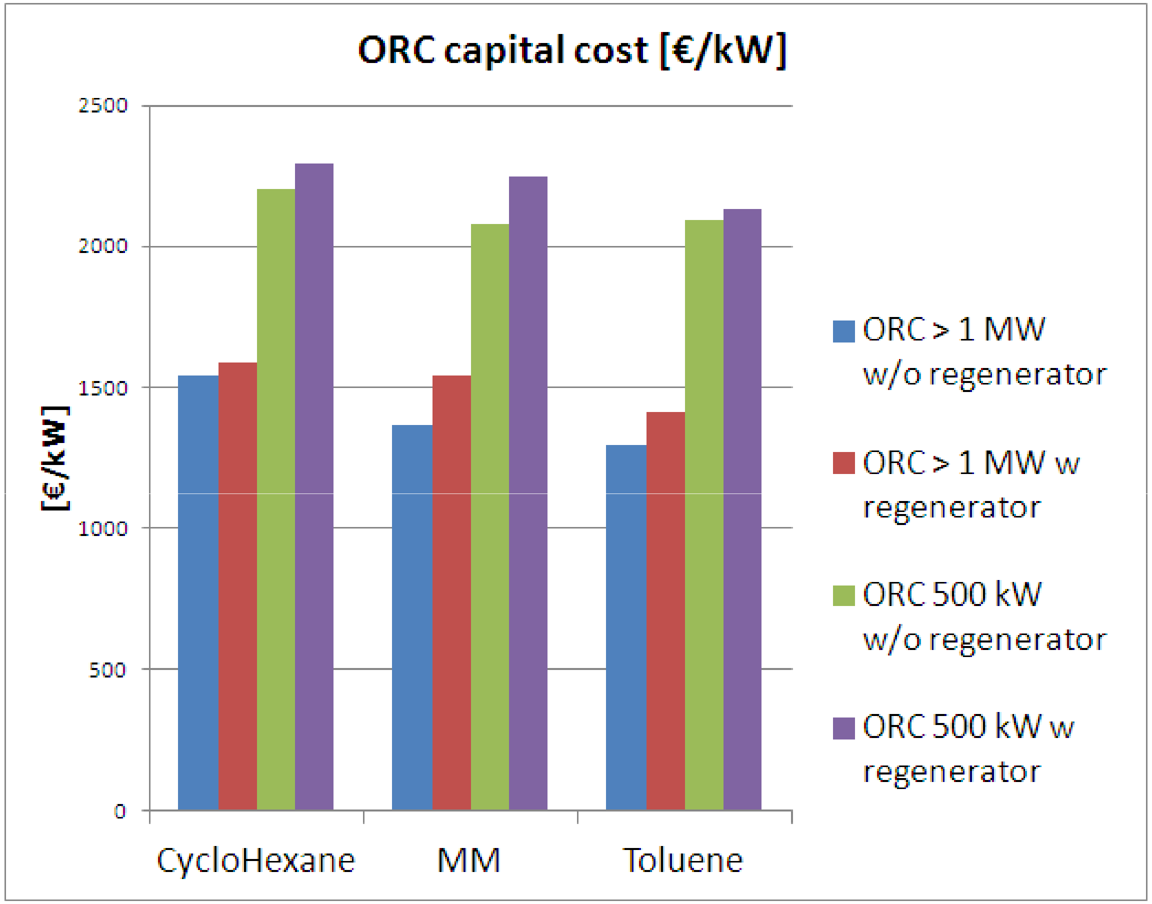
- **Capital costs amortized over 15 years**
- **Fuel cost at € 5.1/GJ**

DFC 3000 LCOE (with cogeneration): 11.25 €c/kWh (-2.3%)

- **Thermal power cogenerated for each module: 1640 kW (2000 h_{eq})**
- **Heat price: 25 €/MWh**

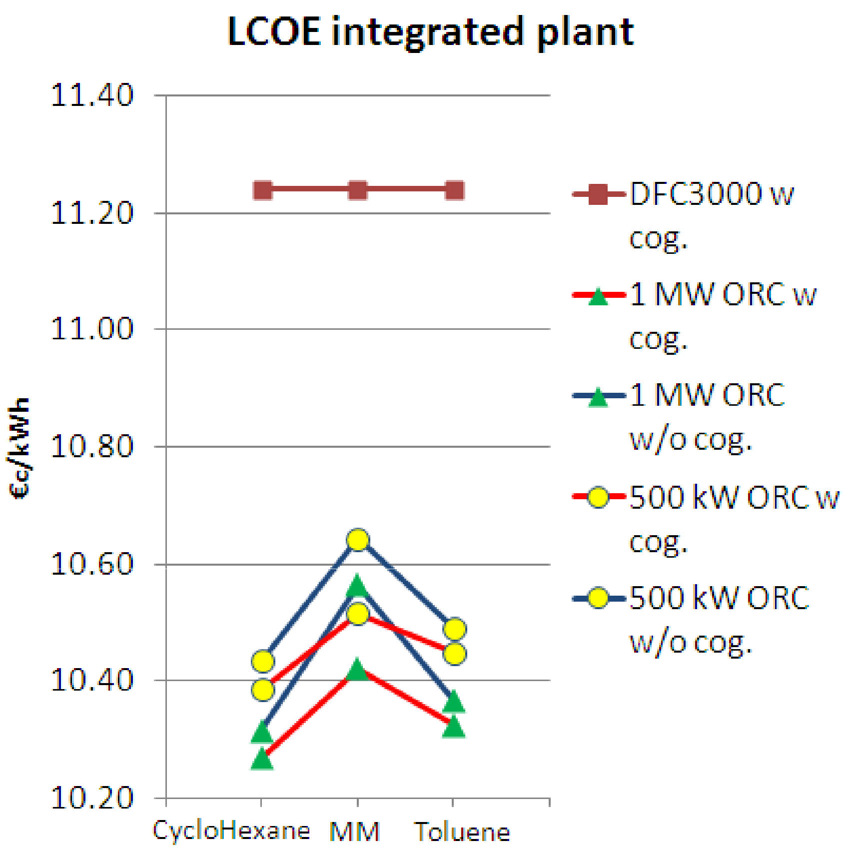
Economical Analysis

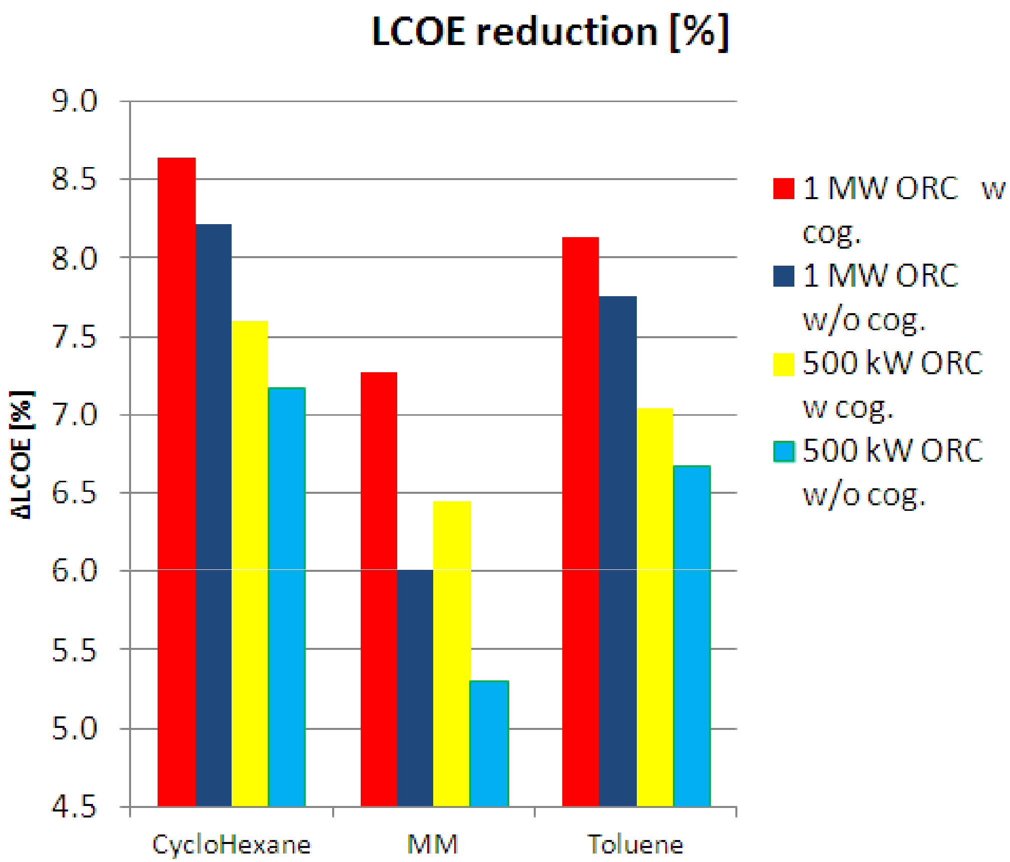
Costs of ORC were estimated by Turboden assuming a turnkey supply



Although the net power obtained with cyclohexane is greater than that of the other working mediums, the specific cost of the plant implementing such a fluid is the highest. This is due to the high evaporation pressure of the cycle.

Economical Analysis

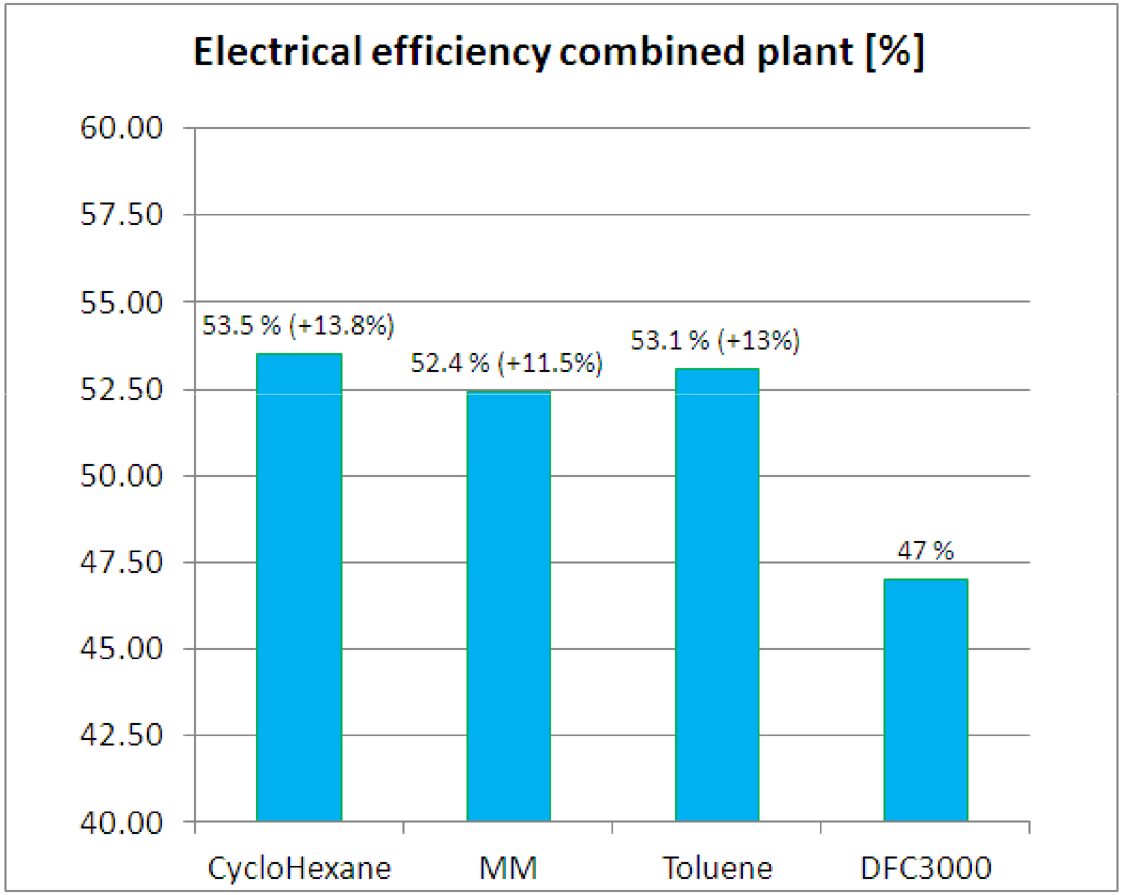




- **Since the specific cost of the ORC is significantly lower than that of fuel cell unit, the LCOE of combined plant is more influenced by the energy production of the bottoming cycle than by its cost.**
- **Thanks to cogeneration and the implementation of the regenerator, MM cycle performance approaches the economical results of the ORC with hydrocarbons as working medium**

Conclusions

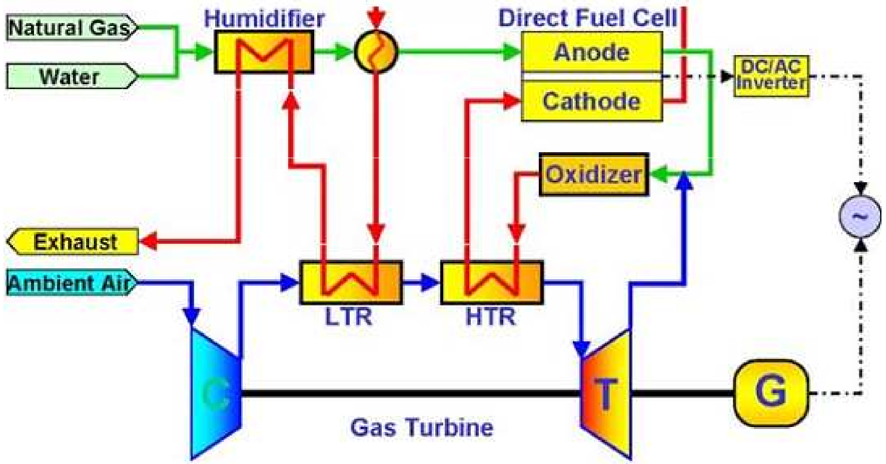
1. **Thanks to the ORC cycle, it's possible to increase the electrical efficiency of the plant from 47% to more than 53% (52.4% in the case with MM as working fluid).**



2. **The highest performance of the ORC cycle are achieved implementing hydrocarbons as working medium.**

Conclusions

3. However, similar results are obtained with linear siloxane MM. For such a fluid, the cycle has to be equipped with a regenerator (even if the cogeneration option is not considered) to improve the matching between the hot and cold streams in the steam generator
4. This efficiency improvements, realistically estimated, could be achieved implementing already well established technology.



DFC/T Ultra-High Efficiency System Concept

On the contrary, the integration of MCFC plant with externally fired gas turbine cycle, as proposed by the manufacturer, could achieve greater efficiency (58-60%), but still requires technological developments.

Conclusions

5. **The ORC implementation could also counteract the efficiency decay of the fuel cell unit that occurs during its lifetime.**
6. **The economical feasibility of the combined plant is demonstrated also for relative small size (~500 kW_{el}) of the ORC. Therefore it's an attractive solution for multi-MW plant, implementing at least 2 DCF3000 modules (P_{el} FC > 4.8 MW; FuelCell Energy already supplied one plant with this size)**

4.8 MW Fuel Cell – Pohang, Korea

Grid Support,
10 MW +

Thank you for your attention

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