HIGH TEMPERATURE ORC SYSTEMS

Riccardo Vescovo

Sales & Business Development Leader

Milan, 14 September 2017

AGENDA

1. STATE OF THE ART ORC SYSTEMS
2. VERY HIGH TEMPERATURE ORC SYSTEMS
3. APPLICATIONS OF VERY HIGH TEMPERATURE ORC SYSTEMS
4. STEAM & POWER ORC – ST&P ORC
5. ECONOMICS
6. CONCLUSIONS

STATE OF THE ART ORC SYSTEMS

- Most of the commercially available ORC systems use as working fluids Hydrocarbons, Siloxanes and Refrigerants [1]
- Typically Hydrocarbons and Siloxane are used to exploit Medium and High Temperature heat source applications [1]
- High Temperature ORC systems are used in Biomass, Heat Recovery and Waste to Energy applications at maximum working fluid temperature below 300 °C

Table 1. Common use working fluid for MT and HT heat source ORC application

Working Fluid	Max Operating Temperature [°C]	Evaporation Temperature Range [°C]	Condensation temperature Range [°C]
Octamethyltrisiloxane (MDM)	290	250 - 280	80 – 150
Hexamethyldisiloxane (MM)	290	180 - 250	30 – 60
Cyclopentane	300	200 - 230	> 0

Table 2. Typical Performances of medium and high temperature ORC cycles.

	Electrical efficiency		Thermal efficiency	
	Heat Source Temperature		Heat Source Temperature	
	HT / VHT	MT	HT / VHT	MT
Power only	25 – 28 %	20 – 22 %	0 %	0 %
LT CHP	20 – 22 %	15 – 18 %	77 – 79 %	81 – 84 %
MT CHP	15 – 18 %	12 – 15 %	81 – 84 %	84 – 87 %

LT: Low Temperature (< 200 °C)
MT: Medium Temperature (> 200 °C and < 250 °C)
HT: High Temperature (> 250 °C and < 500 °C)
VHT: Very High Temperature (> 500 °C)

VERY HIGH TEMPERATURE ORC SYSTEMS

- Potential Organic fluids stable above 300 °C : toluene, biphenyl, diphenyl oxide, terphenil, quadriphenil, linear hydrocarbons, alkylated aromatic hydrocarbons, phenilcycloesane, bicyclohexyl, perfluoropolyether
- Turboden identified the mixture diphenyl - diphenyl oxide as the most promising working fluid

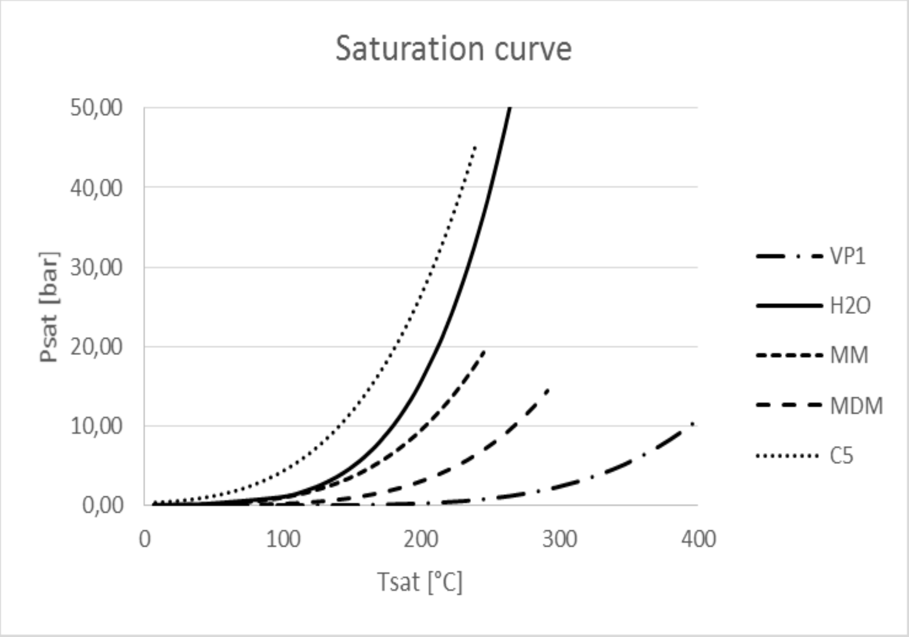


Figure 1: Saturation curves of different ORC working fluid vs. water steam

Table 3. Diphenyl and diphenyl oxide mixture working temperature ranges

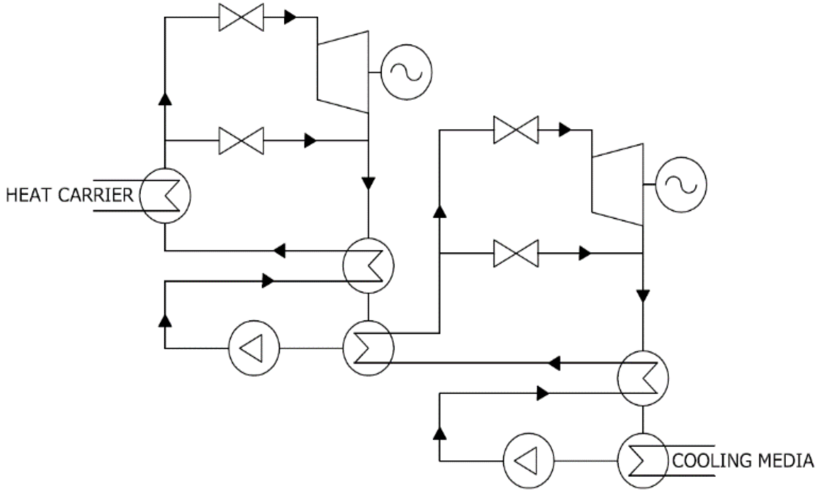
Working Fluid	Max Operating Temperature [°C]	Evaporation Temperature Range [°C]	Condensation temperature Range [°C]
Diphenyl - Diphenyl oxide mixture	400	390 - 350	250 – 160

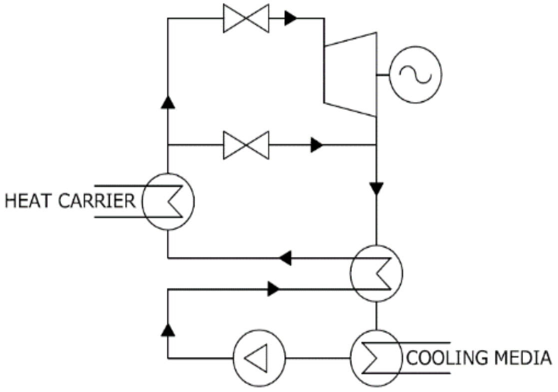
APPLICATIONS OF VERY HIGH TEMPERATURE ORC SYSTEMS

- There are many studies on ORC system operating above 300 °C reporting theoretical **very high efficiencies, improved heat source utilizations and enlarged range of application** [2]-[4]
- **Considering** diphenyl - diphenyl oxide as working fluid and its saturation curve [5]:
  - In **Power Only Configuration** a cascade cycle must be employed, achieving a gross efficiency > 30%
  - A **CHP configuration** can be done assuming a **cooling sink above 150 °C**

Table 4. Indicative Performances of Very High temperature ORC cycles.

	Electrical efficiency	Thermal efficiency
	VHT heat source	VHT heat source
Power only	30 – 34 %	0 %
HT CHP	15 – 20 %	79 – 84 %





A CHP SOLUTION WITH STEAM GENERATION FOR THE INDUSTRY

- **Power only solutions** could be of interest only for where primary fuel cost is relatively low and energy value is relatively high. This configuration is **not the subject of this study**
- Many **manufacturing facilities** require **large amount of electricity and valuable heat sources** as medium pressure steam [6]: the **CHP configuration with Steam Generation is the subject of this study**
- Most interesting Industries with large steam demand are [6]
  - Pulp & Paper
  - Chemical and Pharmaceutical
  - Food & Beverage
  - Textile

		Capacity range	Average Electricity	Average Steam	Ratio
		[ktons/year]	[MWe]	[MWt]	[MWt]/[MWe]
Paper	Specialties	6-948	8,9	16,7	1,9
Paper	Packaging	10-1214	18,5	42	2,3
Paper	Tissue	8-1115	10,4	18,7	1,8
Chemical	Organic Chemical	1-420	5,4	55,5	10,3
Chemical	Petrochemical	20-1100	8,2	44,7	5,5
Chemical	Plastic materials and Resins	20-430	2,6	13	5,0
Food & Bev	Sugar	42-546	7,7	46,2	6,0
Food & Bev	Diary	20-720	3,3	11,8	3,6
Food & Bev	Oils	0,4-150	9,9	14,3	1,4

TECHNOLOGY BENCHMARK

- Different natural gas fired CHP systems are available on the market, with specific characteristics in terms of electric and thermal production, temperature levels and efficiencies
- **Steam & Power (ST&P) ORC** is a **Very High Temperature ORC** system developed by Turboden combined with a **natural gas fired** thermal oil boiler

Table 6. CHP system efficiency parameter for a 2 MW unit. Performance based on OEM datasheet and Poyry market study [6]

CHP system		RE	GT	CP-SRC	ST&P
η_{el} [1]	%	44%	27%	8% [2]	16% [3]
Electrical output	MW	2,0	1,85	1,8	2,1
% captive consumption [4]	%	3%	5%	5%	8%
η_{th}	%	18%	55%	84%	76%
η_{I}	%	64%	82%	92%	92%
η_{II}	%	52%	47%	38%	43%

Heat Media: 12 bar(g). Feed water return temperature at 90°C

For RE: jacked water was considered as a loss

RE: Reciprocating Engines

GT: Gas Turbine

CP-SRC: Counter Pressure Steam Rankine Cycle

ST&P: Steam & Power ORC

[1] Gross electrical efficiency

[2] Considering steam generation at 50 bar 400°C

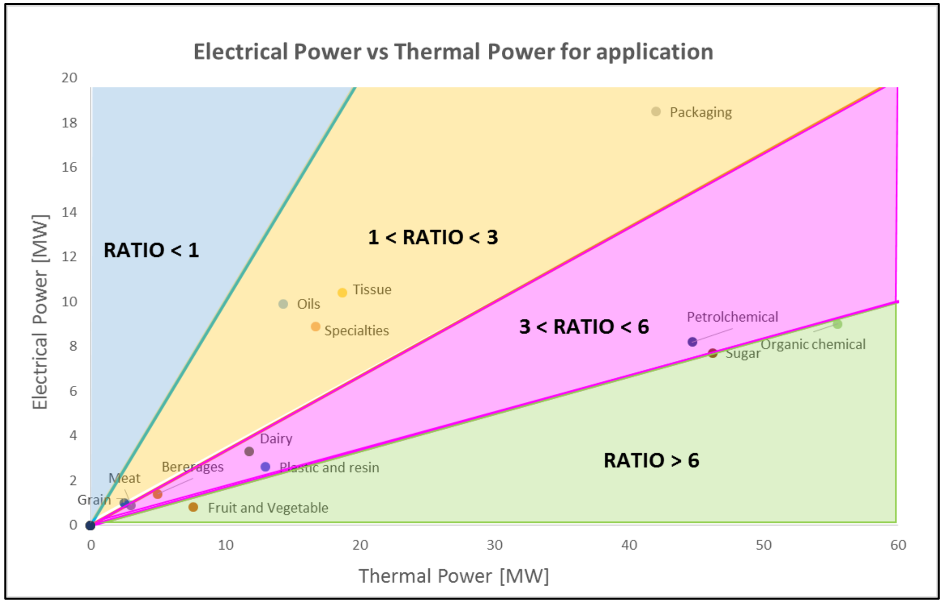
[3] ORC efficiencies as per Table 4 multiplied by thermal oil boiler efficiency equal to 90%

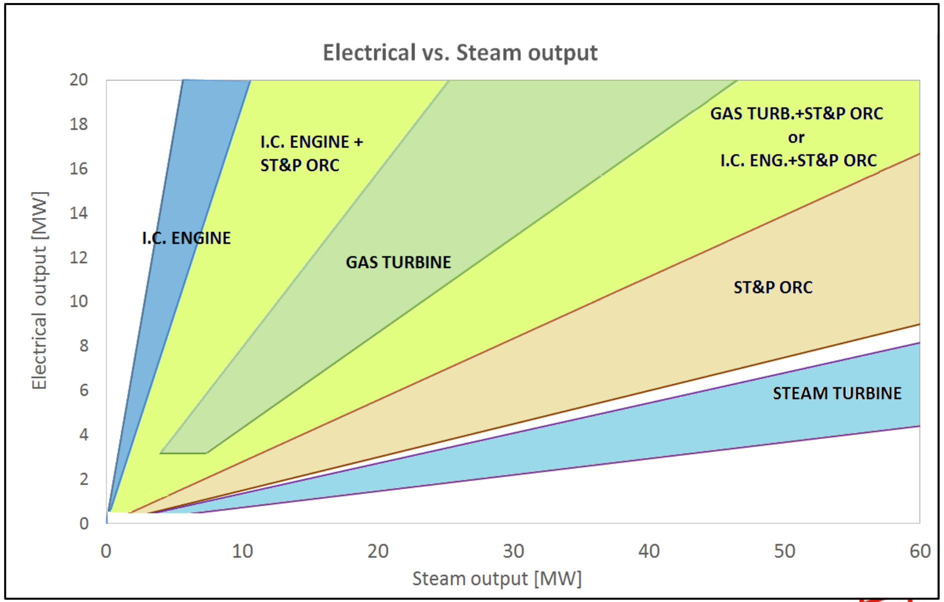
[4] On gross electric output

STEAM TO ELECTRICITY RATIO: PROCESS AND TECHNOLOGY BENCHMARK

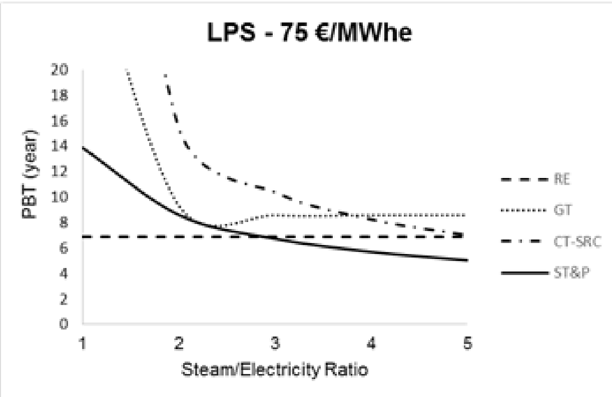
Steam to Electricity ratio: it's the ratio between the energy *required* (or *generated*) in the form of steam divided by the energy *required* (or *generated*) in form of electricity

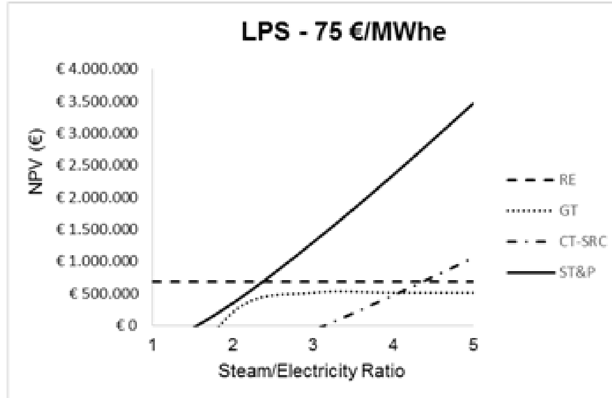
- *Required*: each **manufacturing facility has specific energy requirements** in terms of steam and electricity requirements (e.g. yearly consumptions, average values, etc.)
- *Generated*: each **CHP technology** (e.g. reciprocating engines, gas turbines, Steam&Power ORC, etc.) **has its own specific production characteristics** in terms of steam and electricity productions

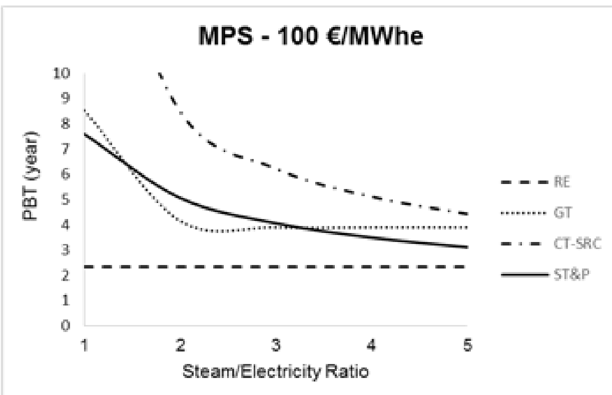


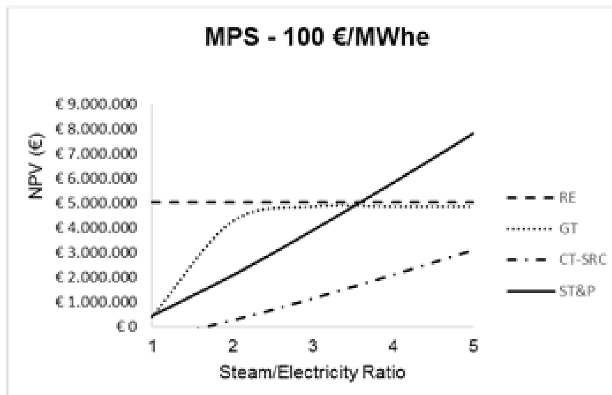


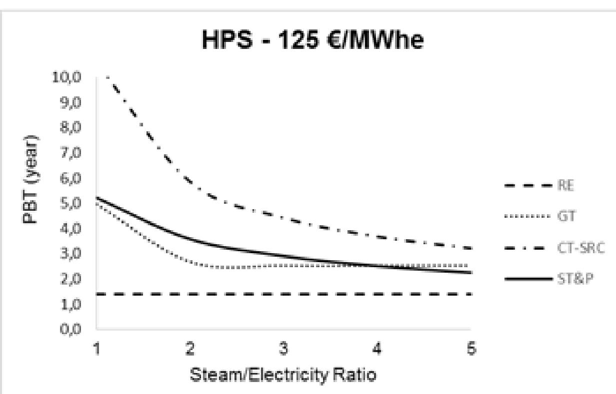
ECONOMICS: FEASIBILITY STUDY

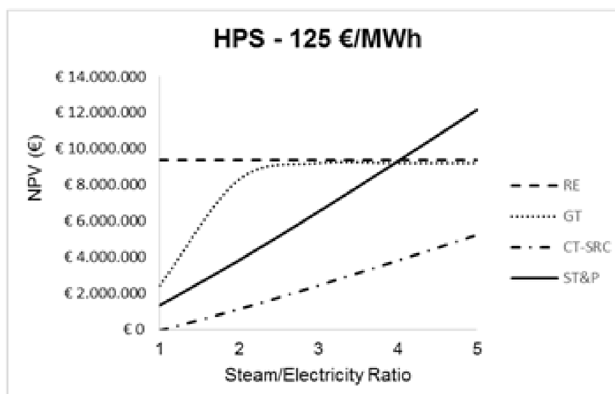












Notes and assumptions:

Reference Electric Power Output: **3 MWe** (or lower)
Natural Gas Price: **25** €/MWh
LPS: Low electricity Price Scenario, **75** €/MWh
MPS: Medium electricity Price Scenario, **100** €/MWh
HPS: High electricity Price Scenario, **125** €/MWh
Actualization Rate: **3%**
NPV: @ 10 years

CONCLUSIONS

- **Commercially available** ORC units use maximum working fluid temperature **below 300 °C,**
- **Exceeding this limit is possible** with the proper working fluids and
- It Allows to design a **High Temperate CHP** unit generating **medium pressure steam** from natural gas (and other primary energy sources), called **Steam & Power ORC – ST&P ORC**
- **ST&P ORC** can be employed in many **steam-demanding manufacturing processes**
- **ST&P ORC** has a characteristic **steam-to-electricity ratio** of about **4**: in those manufacturing facilities with a ratio greater than it, employing **ST&P ORC instead of other traditional CHP technologies leads to better economic results**
- **ST&P ORC** can be combined to other traditional CHP technologies to maximize primary energy savings and economic results
- **ST&P ORC is the first economically viable ORC solution using traditional fuels for non-subsidized markets**

Riccardo Vescovo

Sales and Business Development Leader

REFERENCES

[1] Macchi E., Astolfi M., 2016.Organic Rankine Cycle (ORC) Power System: Technologies and Applications. Woodhead Publishing Series in Energy, Cambridge (UK)

[2] Silvia Lasala, Costante Invernizzi, Paolo Iora, Paolo Chiesa, Ennio Macchi, Thermal stability analysis of perfluorohexane, Energy Procedia

[3] Invernizzi C.M., Iora P., Bonalumi, Macchi E., Roberto R., Caldera M., 2016. Titanium tetrachloride as novel working fluid for high temperature Rankine Cycles: Thermodynamic analysis and experimental assessment of the thermal stability. Applied Thermal Engineering

[4] Pasetti M., Invernizzi C.M., Iora P., 2014. Thermal stability of working fluids for organic Rankine Cycles: An improved survey method and experimental results for cyclopentane, isopentane and n-butane. Applied Thermal Engineering

[5] Author's processing

[6] Poyry Italy, 2016, Market and technology assessment for a new product. Commissioned by Turboden