ORC DEPLOYMENT OPPORTUNITIES IN GAS PLANTS

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ABSTRACT

Gas processing plants are characterized by large energy flows. Therefore it is key to maximize energy efficiency and to optimize utility balances. In the gas to liquid (GTL) complexes operated by Shell in Malaysia and Qatar, the highly exothermic Fischer Tropsch process is applied to convert gas into liquid hydrocarbon products. Most of the available thermal energy is used to cogenerate steam and to preheat feed streams, but still substantial additional cooling is required to reduce the temperature of intermediate streams for further processing. In the Qatar GTL plant this duty is in the order of 600 MW_{th}.

By means of a detailed investigation that included simulations and cost evaluation of both commercial ORC systems and dedicated advanced ORC concepts, it could be established that heat recovery by means of low-temperature ORC units is a feasible option. Prerequisite is that the ORC unit is directly coupled to the process, without an intermediate thermal fluid loop.

A parallel study focused on application of ORC systems in Liquefied Natural Gas plants. These plants waste large quantities of thermal energy in the form of high temperature exhaust gas from gas turbines used for power generation and gas compression. A similar evaluation of current ORC technology for the recovery of this high-temperature heat led to the conclusion that ORC systems can be more attractive than steam cycles for waste heat recovery from both mid-range gas turbine installations and a feasible option for larger systems in remote or arid locations where steam power plants are impractical. This still is a large scope of deployment, which is expected to increase given the potential for further developments in ORC technology, cost prices and market.

1. INTRODUCTION

Gas processing plants are characterized by large energy flows. In the gas to liquid (GTL) complexes operated by Shell in Malaysia and Qatar, the highly exothermic Fischer Tropsch process is applied to convert gas into liquid hydrocarbon products. Most of the available thermal energy is used to cogenerate steam and to preheat feed streams, but still substantial additional cooling is required. In the Qatar GTL plant, an amount of 600 MW_{th} has to be cooled away from temperatures between 130 and 185 °C. Another large currently wasted energy source is the hot exhaust from gas turbines in LNG plants, released at temperatures of 450-550 °C. Appropriate technology is sought to recover this energy and increase the energy efficiency of the plants, and Organic Rankine Cycle (ORC) power generation has been identified as a promising option.

Process simulations and cost evaluations have been performed to evaluate the power generation potential and economic feasibility of commercial as well as more innovative configurations for ORC units, when integrated in gas plants. The main results and conclusions of these studies are presented in Section 2 (GTL) and 3 (LNG) of this paper. Related studies and literature are, for instance, found in Stijepovic *et al.*, 2012, Jung *et al.*, 2014 and Chacartegui *et al.*, 2009.

2. LOW GRADE PROCESS WASTE HEAT RECOVERY

2.1 Specification of heat sources, sinks and assumptions

Figure 1 shows part of the heat recovery and cooling equipment in the syngas treating and separation train of a GTL plant of the size of Pearl. The specifications of the relevant streams are listed in Table 1.

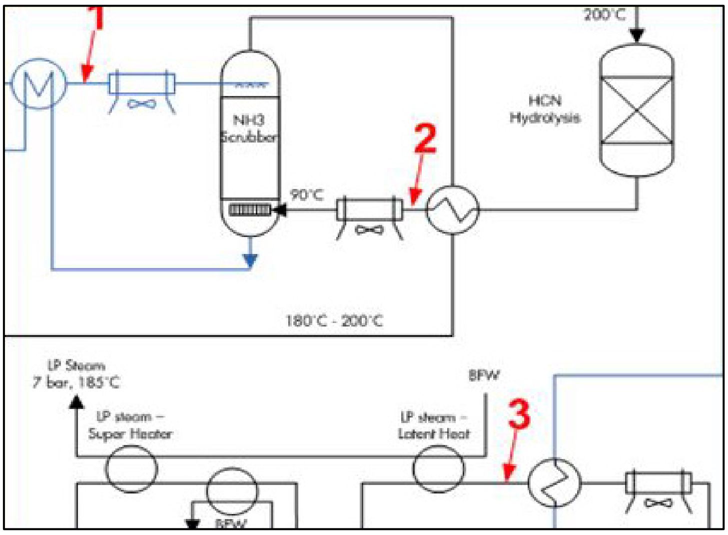

Figure 1: Process flow diagram representing the heat recovery and cooling equipment in the syngas treating and separation train of a GTL plant of the size of Pearl.

Table 1: Specification of process stream heat sources and ambient conditions.

Process stream		1	2	3
Medium		Water	Syngas mixture	Syngas mixture
Phase		Liquid, superheated	Gas, partially condensing	Gas, partially condensing
Pressure	bar	45	26.9	22
Pressure drop, assumed	bar	0.3	0.1	0.3
Temperature, inlet	°C	185	134	168
Temperature, outlet	°C	90[a]	90[a]	40[a]
Heat available, based on specified outlet temperature	MW_{th}	30.6	208	269
Ambient temperature, dry bulb, daily maximum, seasonal/annual averages	°C	27 (winter), 43 (summer), 27 (annual mean)		
Ambient temperature, dry bulb, daily minimum, seasonal/annual averages	°C	10 (winter), 27 (summer), 27 (annual mean)		

[a] Maximum allowed temperature limit for process stream outlet; lower return temperatures are preferred also for the downstream process operation.

Process stream 2 and 3 are syngas mixtures that partially condense in the stated temperature range, resulting in a curved temperature profile. This is an important characteristic for the determination of the optimal waste heat recovery (WHR) technology and configuration. The temperature profiles, i.e., the relation between the temperature and the thermal power during the cooling, are used to determine the match in temperatures between the process streams and the heat recovery system. The temperature profiles of process streams 2 and 3 are modeled using the PCPSAFT thermodynamic model (Gross and Sadowski, 2001) so as to take into account the effect of condensation and for stream 1 using RefProp (Lemmon *et al.*, 2010). These models, which are respectively implemented and accessed via FluidProp, an in-house program (Van der Stelt and Colonna, 2004), have been verified to represent the temperature profile of the source data to a sufficient accuracy for preliminary engineering evaluation.

The study is based on the following assumptions and considerations:

- A very important requirement is that, in order not to compromise plant operation, the process streams need to be cooled down to the maximum outlet temperatures indicated in Table 1.
- The process stream conditions do not vary significantly, so that the temperature and thermal energy flows, as specified in Table 1, are constant in time. Therefore, process stream part-load and transient operation were not considered in the waste heat recovery analysis.
- The seasonal and daily variation of the ambient temperature indicated in Table 1 is relatively large with respect to the average temperature, which is likely to have a large impact on the ORC power plant performance. This large variation also needs to be taken into account in the sizing of the air-cooled condenser of the ORC units. In this study, the performance evaluation and dimensioning of the air-cooled condensers of the envisaged ORC power plants are based on a design-point ambient temperature of 32 °C. At some locations, cooling water may be available in sufficient quantities for the ORC condensers, providing several advantages. For this case, cooling water conditions of 32 °C and 4.5 bar (supply flow) and 42 °C and 3 bar (return flow) are assumed.

2.2 Comparison of heat recovery configurations and full integration with process cooling

Various options exist for the integration of the waste heat recovery unit, using either Intermediate Heat Transfer Fluid (IHTF) loops and Direct Heat Exchange (DHE). IHTF loops offer control advantages, whereas DHE offers cost savings and higher efficiency (higher maximum cycle temperature). Process heat recovery configurations have been compared, and a preliminary evaluation led to the selection of the most interesting configuration with respect to feasibility, performance, cost and reliability for both greenfield and retrofit applications.

An important requirement is that the process streams need to be cooled down in order not to compromise the operation of the process plant. It is technically possible for ORC power plants to cool the process streams to the temperatures indicated in Table 1, except in very hot periods. Currently, a backup cooling system is still assumed to be installed. However, to minimize cost and plot space requirements, complete integration of the ORC power plants with the backup cooling system will be required. This is illustrated in Figure 2. This also depends on the degree of redundancy (parallel units) that is enforced.

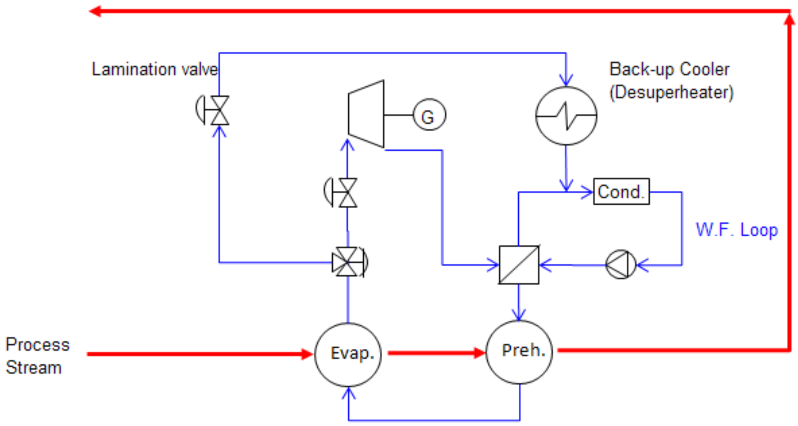

Figure 2: Example of integrated heat recovery: Direct Heat Exchange with back-up cooling on ORC low-pressure side.

The scheme of Figure 2 may be the preferred option in case DHE is applied. This implies that the process cooling becomes dependent on several ORC plant components, so availability of these components becomes a critical requirement for fail-safe process cooling. Careful heat exchanger dimensioning is required to avoid ending up with larger heat transfer surface and fan loads due to lower average rejection temperatures.

The scale up of ORC units beyond the current commercially available maximum unit power output may offer further advantages with respect to cost. The reduced parallelization associated with larger units, however, will affect the degree of redundancy and therefore availability.

2.3 Commercial ORC power plant solutions

This section presents the performance evaluation, based on thermodynamic cycle models, of the technical solutions proposed by various ORC vendors, for the recovery of waste heat from the processes specified in Table 1. These solutions are considered to be representative references for commercial and mature low-temperature ORC power plants of the required large capacity.

Thermodynamic cycle models were developed and validated based on the specifications of the technical proposals supplied by the ORC vendors for the three process heat sources. Conservative assumptions and values typically found for state-of-the-art ORC power plants were used for the isentropic efficiencies of the turbine and feed pump, pinch points and pressure drops of the components and degree of superheating. The models were developed in Cycle-Tempo, an in-house flow sheeting program for the steady-state simulation, design and verification of energy conversion systems (Van der Stelt *et al.*, 2002) marketed by Asimptote. All thermodynamic cycle simulations and coordination were done by Gensos, partner of Asimptote.

The steady-state operations of commercial ORC systems were simulated under various conditions, using these models. Given the assumed steady state environment of heat streams, the influence of ambient temperatures was investigated assuming a constant overall thermal conductance (UA-value) as calculated from the design-point condition (32 °C). The turbine and pump efficiency were assumed to remain constant at off-design conditions, which mainly refers to the varying condensation temperature.

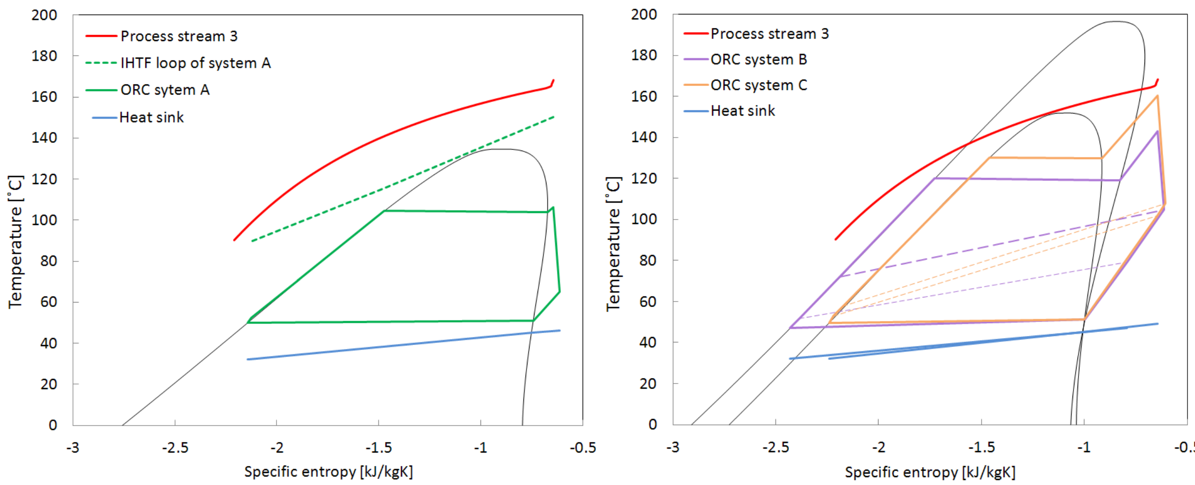

Figure 3: The thermodynamic cycles of three ORC systems using IHTF loop (left) and DHE (right) proposed by vendors, modeled with Cycle-Tempo at design-point conditions, shown in the temperature-entropy of the heat source. The entropy of the working fluids and heat sink medium is linearly scaled to that of the heat source. The dashed lines connect the heating and cooling temperature profiles that occur in the regenerator. Note the strongly curved temperature profile of the heat source due to partial condensation.

The results are summarized in Table 2. The ambient temperature variation reflects typical conditions for a location in the Middle East. As shown, the ambient temperature variation strongly determines net power output; at low ambient temperatures, the ORC power plants can deliver a significantly higher net power output.

Ambient temperature also affects the available cooling capacity. Process stream 1 and 2 can be cooled down to the required temperature of 90 °C using currently commercially available ORC power plants for almost all ambient conditions. Process stream 3 should be cooled down to 40 °C, which is not feasible using commercial ORC power plants, due to dependence on the comparatively high and varying ambient temperature that is offset by pinch point temperature differences in the ORC system. An additional air-cooled process stream cooler is therefore required for this process stream. If water cooling were an option, then also this process stream can be cooled down to almost the required temperature.

Given the large thermal power available (Table 1) in comparison to the current maximum rating of commercial ORC power plants, an arrangement of two to three ORC units in parallel is required for process stream 2 and 3. The modularity offered by several units in parallel will be required anyway, to provide sufficient operational flexibility, redundancy/continuity and ease of maintenance.

Table 2: Performance predictions for current-technology ORC power plants recovering thermal energy from the process streams for a range of ambient temperatures (assuming air-cooled condensers) and water cooling. Results are also shown in case that sufficient cooling water were available to reject the heat through shell-and-tube condensers. Remaining auxiliary power consumptions other than fan and pump loads are necessarily excluded.

Process stream		1				
Ambient temperature	°C	10	27	32	43	Water cooling
Corresponds to		winter min.	annual mean	design	summer max.	-
Net electric power output	MW_e	4.86	3.71	3.34	2.78	4.25
Heat recovered	MW_{th}	34.3	31.4	30.6	29.2	35.4
Temperature, process outlet	°C	78	87	90	94	75
Water cooling duty	MW_{th}	-	-	-	-	30.8

Process stream		2					3				
Ambient temperature	°C	10	27	32	43	Water cooling	10	27	32	43	Water cooling
Corresponds to		winter min.	annual mean	design	summer max.	-	winter min.	annual mean	design	summer max.	-
Net electric power output	MW_e	27.1	17.6	15.1	10.8	21.1	37	27.9	25.0	20.3	31.7
Heat recovered	MW_{th}	246	212	201	195	224	253	234	201	218	265
Temperature, process outlet	°C	72	86	90	92	82	61	82	90	95	45
Water cooling duty	MW_{th}	-	-	-	-	201	-	-	-	-	231

2.4 Cost evaluation of ORCs for waste heat recovery in a GTL process

To assess the economic feasibility of ORC power recovery a P50[1] cost estimate has been developed for an ORC unit for syngas cooling in an actual GTL project. The project premises were taken from a study for a GTL plant with the size of Pearl in Qatar under development for realization in the US Gulf Coast area (Oil & Gas Journal, 2013).

Attention was restricted to the syngas cooler on process stream 3. The available heat is 269 MW_{th}, at a temperature of ≅ 170 °C. Based on air cooling and the ambient temperature frequency distribution of Baton Rouge the yearly average recoverable electric power is estimated at 29.6 MW_e, see Figure 4. The pre-tax Net Present Value (NPV) of the electricity, at $70 per MWh, including avoided CO_2 costs, would be of the order of 240 mlnUS$. The project cost was estimated at 155 mlnUS$. This figure is based on the detailed material take off cost calculation provided by the Asimptote

[1] A P50 cost estimate has a 50% probability of either underrunning or exceeding the final actual cost.

subcontractor Austex, complemented by Shell with further allowances, contingencies, premiums and costs, based on the Gulf Coast GTL premises. The resulting NPV would be 85 mlnUS$, with a Value over Investment Ratio (VIR) of 0.55. In case water cooling can be applied, the value could be still somewhat higher, with an NPV of 100 mlnUs$ and a VIR of 0.65. For a system with an ITHF loop the recoverable power is reduced to 19.3 MW_e, and the estimated cost increases to 181 mlnUS$, resulting in a negative VIR.

For the evaluation the full cost of the secondary cooling was attributed to the ORC loop, i.e. no credit was taken for redundancy of the original air coolers. A substantial further economic optimization will be achieved by integrating the ORC condensors with the existing GTL air coolers.

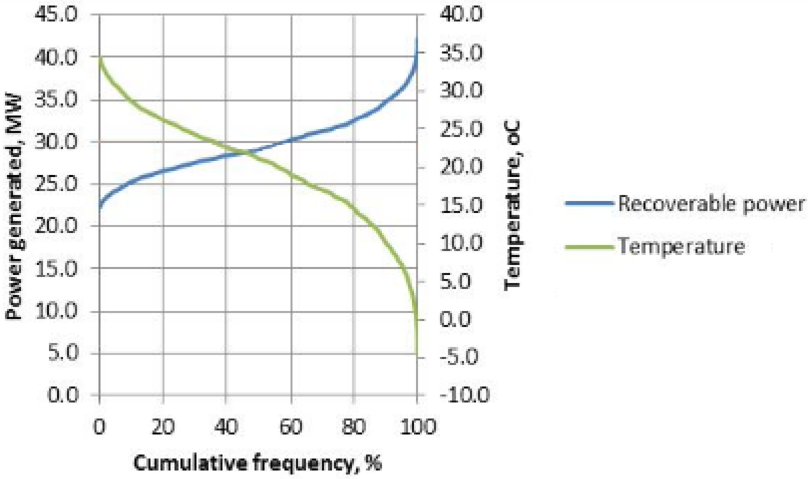

Figure 4: Temperature distribution and accompanying ORC power output. The yearly average recoverable electric power is estimated at 29.6 MW_e

2.5 Dedicated and advanced ORC power plant configurations

In contrast to current commercial ORC power plants, future ORC systems dedicated to the considered process streams could be developed, given the very large drive that such a market could have. These future ORC systems may also include advanced cycle concepts such as novel working fluids, supercritical cycle pressures, and binary or ternary mixtures as working fluids. The potential performance gains of such dedicated and advanced cycle concepts has been investigated for the process streams in question (Table 1). The pinch point temperature differences and pressure drops used were as determined in the validation of the thermodynamic cycle models for the current state of the art.

The results indicate that optimal pure fluids and optimal cycle conditions would allow for performance gains in terms of net electric power output of approximately 20-35% and a 25-30 °C lower process outlet temperature, depending on the condensation behavior of the process stream. For process streams with limited or no condensation, working fluids with a critical temperature just below the process stream inlet temperature, leading to supercritical cycle conditions appear to provide the highest performance. For process streams with substantial (partial) condensation, working fluids with a critical temperature close to the process stream inlet temperature appear to yield the highest net power output and cooling capacity; in this case supercritical and subcritical evaporative cycle conditions result in equally good performance.

Zeotropic mixture fluids allow for potential performance gains, due to their non-isothermal isobaric condensation and evaporation. Preliminary cycle studies for the heat sources in Table 1 indicate potential gains of 30-35% in gross power output and 36-40 °C lower process outlet temperature (down to 20 °C above ambient conditions). This potential gain may however only be possible if, through careful expert heat exchanger design, a counter-current flow arrangement can be implemented and working fluid fractionation risks can be minimized. Furthermore, zeotropic mixtures may require more costly heat exchanging equipment and higher fan loads.

3. HIGH GRADE GAS TURBINE EXHAUST HEAT RECOVERY

The feasibility and performance of ORC systems for gas turbine heat recovery in LNG sites was investigated and compared to that of conventional steam bottoming cycles. This part of the study aimed at identifying an application window for which current ORC systems can be more attractive than steam systems, as well as investigating performance gains that future, advanced ORC power plant configurations can potentially bring with continued technology developments and market sector penetration.

3.1 Specification of heat sources, sinks and assumptions

LNG facilities operated by Shell employ gas turbines (GTs) and conventional combined cycles (CCGTs) in various locations. This study focused more specifically on aeroderivative gas turbines (LM2500 and LM6000). A typical LNG site has 4-6 such turbines with a load percentage varying between 60-80%, with common operation at 80%.

To allow for generic conclusions for all LNG operations, a conceptual approach has been adopted. In this approach, the performance of ORC bottoming cycles is evaluated, using validated thermodynamic cycle models, for a range of exhaust temperatures between 400^{o}C to 600^{o}C, while the GT exhaust mass flow rate is set at 100 kg/s, for a range of ambient temperatures. The GT exhaust temperature ranges includes the GTs at both full load and part-load conditions. The reference GT exhaust mass flow rate of 100 kg/s is consistent with a medium-scale GT operating at full load (see, e.g., Del Turco *et al.*, 2011) and also allows for convenient scaling to different GT types and varying numbers of GT units. Like in the GTL case, the performance evaluation of the envisaged ORC power plants is based on a design-point ambient temperature of 32 °C. Using this approach, preliminary conclusions can be drawn for the various GT types, part-load operation, number of gas turbines in a set and the specific (ambient) location conditions relevant for LNG operations.

3.1 Commercial ORC power plant solutions

Thermodynamic cycle models of three ORC power plants, considered to be representative references for commercial and mature ORC power plant technology for GT waste heat recovery, and a conventional single-pressure, unfired, steam-based combined cycle power plant (CCGT) system were developed using the conservative assumptions stated in Section 2.3. The models were validated based on specifications of datasheets and technical proposals supplied by ORC vendors and literature (Gas Turbine World, 2012). The steady-state operation of the ORC systems and CCGT system were then simulated under the aforementioned condition ranges. For the off-design simulations, the sizes of all heat transfer equipment were fixed to the design value.

The results shown in Table 3 indicate that for this application CCGT systems currently still provide approximately 30%-45% more power output, on an equal specific capacity base, at gas exhaust temperatures of 450-550 °C (representative of the aeroderivative LM6000 PD) and nominal conditions. At higher temperatures, typical of heavy duty gas turbines, the gain in power output increases. If gas turbine load variations are frequent or large, the spread is smaller, since ORC systems are more flexible and tolerant to off-design conditions. DHE did not result in considerably higher power outputs as compared to the adoption of IHTF loops. IHTF loops were therefore assumed for subsequent simulations of commercial ORC solutions and DHE for advanced ORC power plant configurations.

The main reason for the lower output of ORC systems at high exhaust temperatures is the thermal stability limit of currently adopted working fluids (at most, approximately 350 to 400 °C, depending on the fluid), which imposes a limitation on the maximum turbine inlet temperature and thus power output. Water/steam does not have this limitation and CCGT systems can operate at much higher turbine inlet temperatures and thus provide generally higher power outputs. The development of suitable organic fluids with higher thermal stability limits (and higher critical temperature while maintaining their low critical pressure) is therefore desirable. The ambient temperature appears to equally influence the power output for both ORC and CCGT systems.

Table 3: Main performance results based on thermodynamic cycle simulations for current state-of-the-art ORC systems compared to a (single-pressure) CCGT system, if coupled in a 1:1 mode to an LM6000 PD at 80% load (corresponding to an exhaust gas flow rate and temperature 94 kg/s and 503 °C, respectively) and air-cooled condenser with ambient temperature of 32 °C.

System	Gross power Output (MW_e)	Pump power (MW_e)	Fan Power (MW_e)	Net Power Output (MW_e)	Heat Recovered (MW_{th})
ORC system D	7.46	0.60	0.11	6.75	34.3
ORC system E (IHTF)	7.43	0.44	0.31	6.68	32.8
ORC system E (DHE)	7.61	0.36	0.35	6.90	33.5
CCGT	10.3	0.07	0.81	9.44	35.5

Application of ORC technology to GT WHR focuses on smaller installations, though a trend towards larger installations is noticeable. Figure 5 presents an indicative graphical representation of heat source temperatures and power outputs for which ORC and CCGT systems are considered viable. The feasibility limits shown for ORC and CCGT systems are based on current reference plants and therefore are merely an indicative representation of their current respective techno-economic viability. These limits may change due to progressing technological developments, reductions in cost prices, changes in the value of power or local regulations requirements. The thermal stability limit shown refers to the maximum temperature of currently adopted organic working fluids of ORC systems. The organic working fluids in ORC systems do not reach the heat source temperature, due to heat transfer surfaces (DHE) or the adoption of IHTF loops. Hence, heat sources with temperatures higher than the thermal stability limit can be recovered, although generally they will not lead to higher ORC system conversion efficiency and power output.

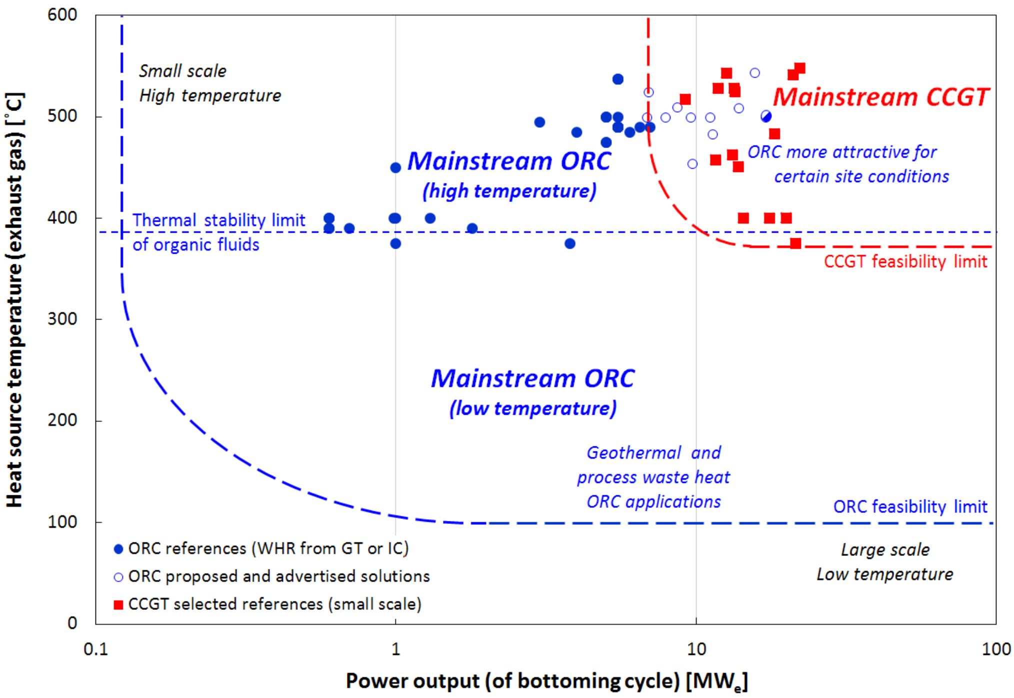

Figure 5: Heat source temperatures and power outputs for which ORC and CCGT systems are considered viable. This figure should only be used as an approximate indication; it was inspired by the figure from (Gaia,

2011) and constructed based on expert knowledge and experience, includes reference plants for ORC systems and CCGT systems and proposed solutions.

ORC systems can have a decisive advantage over CCGT systems in case of locations where water is not available, freezing conditions may be an issue, gas turbine load variations are frequent or large, or remote locations with limited operations support. ORC plants are fully automated and can sustain unattended operation (requiring no on-site supervision or qualified operator nor periodic manual checks or analyses of the working fluid), have zero water consumption, and automatically adapt to load variations without excessive penalties on turbine efficiency.

Given the potential for further performance improvement (up to 30%, see Section 3.2), standardization of manufacturing and economies of scale with increasing market adoption, cost price reductions are expected for ORC systems in the coming years, similarly to reductions that occurred for CCGT systems in previous decades. This would considerably enlarge the range of applications where ORC systems are more attractive than CCGT systems.

Although the state of the art in ORC systems does not provide the same power output as CCGT systems, it offers important operational and cost advantages with respect to simplicity and reliability of plant configuration, as well as safety aspects and requirement for skilled operators. These advantages lead to lower life cycle costs and, for small power output applications, may outweigh the (currently) higher specific investment costs as compared to CCGT systems.

3.2 Developments and advanced ORC power plant configurations

From the thermodynamic optimization point of view, opportunities exist to improve the performance of current ORC systems. These include (new) optimal working fluids with higher thermal stability and critical temperatures, the adoption of novel cycle configurations such as supercritical cycles (including CO_2 as fluid) and cascade ORC systems.

The results of a preliminary study, shown in Table 4, indicate that by employing more suitable fluids, optimized cycle conditions and more advanced ORC system concepts, the net output of ORC power plants could be increased up to 30% with respect to the current state of the art ORC systems at their (conservative) design cycle conditions. For the LNG application, this would make ORC systems comparable to CCGT with respect to performance. It should be noted that these results are demonstrational and do not necessarily represent the optimized solution for these concepts.

Table 4: Main performance results based on thermodynamic cycle simulations of (single-pressure) Rankine cycles for various high-temperature working fluids at optimized cycle parameters recovering heat, using Direct Heat Exchange, from an LM6000 gas turbine operating at 80% load (corresponding to an exhaust gas flow rate and temperature 94 kg/s and 503 °C, respectively, at a design ambient temperature of 32 °C).

Working Fluid	P_c (bar)	T_{max} (°C)	Gross Power Output (MW_e)	Pump Load (MW_e)	Fan Load (MW_e)	Net Power Output (MW_e)	Stack Tempe rature (°C)	Heat Recovered (MW_{th})	Gain[a] (%)
Cyclopentane	45.2	232	9.05	0.6	0.3	8.14	110	40.4	18%
Toluene	41.3	313	9.55	0.41	0.12	9.02	139	37.4	31%
Cyclohexane	40.8	274	9.58	0.49	0.16	8.93	136	37.8	29%
Pentane	33.7	190	7.74	0.6	0.62	6.53	110	40.4	-5%
MM	19.4	240	7.28	0.39	0.14	6.75	160	35.4	-2%
Steam	220	478	10.5	0.07	0.82	9.62	154	36.1	n/a

[a] Gain is defined as the percentage increase in the net power output as compared to current state of the art ORC systems at their (conservative) design cycle conditions.

4. CONCLUSIONS

By means of a detailed investigation that included simulations of both commercial ORC systems and dedicated advanced ORC concepts, allowed to establish that the recovery of waste heat from gas to liquid (GTL) complexes operated by Shell by means of ORC systems is a feasible option. Prerequisite is that the ORC unit is directly coupled to the process, without an intermediate thermal fluid loop.

The similar evaluation of current ORC technology for the recovery of high-temperature heat from gas turbines exhausts in Liquefied Natural Gas (LNG) plants, led to the conclusion that ORC systems can be more attractive than steam power plants for waste heat recovery from both mid-range gas turbine installations and a feasible option for larger systems in remote or arid locations where steam cycles are impractical. This still is a large scope of deployment, which is expected to increase given the potential for further developments in ORC technology, cost prices and market.

REFERENCES

Chacartegui R., Sanchez D., Munoz J.M., Sanchez T., Alternative ORC bottoming cycles FOR combined cycle power plants, 2009, *Applied Energy*, 86 (10) , pp. 2162-2170.

Gaia, M., 2011, 30 Years of Organic Rankine Cycle Development, *First International Seminar on ORC Power Systems*, September 22-23, 2011, Delft University of Technology, keynote.

Gas Turbine World, 2012, *Gas Turbine World Handbook*, Pequot Publishing Inc. Fairfield, CT, United States.

Gross, J. and Sadowski, G., Perturbed-Chain SAFT: An Equation of State Based on a Perturbation Theory for Chain Molecules, 2001, *Industrial & Engineering Chemistry Research*, 40 (4), pp. 1244-1260.

Jung H.C., Krumdieck S., Vranjes T., Feasibility assessment of refinery waste heat-to-power conversion using an organic Rankine cycle, 2014, *Energy Conversion and Management*, 77 , pp. 396-407.

Lemmon, E.W., Huber, M.L., McLinden, M.O., 2010, *NIST Standard Reference Database 23: Reference Fluid Thermodynamic and Transport Properties-REFPROP*, Version 9.0, National Institute of Standards and Technology, Standard Reference Data Program, Gaithersburg, United States.

OGJ Editors, Shell selects Louisiana site for $12.5 billion, world-scale GTL facility, *Oil & Gas Journal Online*, September 24, 2013.

Stelt, T.P. van der, and Colonna, P., 2004, Fluidprop: a program for the estimation of *thermophysical properties of fluids*. Energy Technology Section, Delft University of Technology, The Netherlands.

Stelt, T.P. van der, Woudstra, N., Colonna, P., 2002, *Cycle-Tempo: a program for the thermodynamic analysis and optimization of systems for the production of electricity, heat and refrigeration*, Energy Technology Section, Delft University of Technology, The Netherlands.

Stijepovic M.Z., Linke P., Papadopoulos A.I., Grujic A.S., On the role of working fluid properties in Organic Rankine Cycle performance, 2012, *Applied Thermal Engineering*, 36 (1) , pp. 406-413.

Turco, P. Del, Asti, A., Del Greco, A.S., Bacci, A., Landi, G., Seghi, G., 2011, The ORegen waste heat recovery cycle: Reducing the CO2 footprint by means of overall cycle efficiency improvement, *Proc. ASME Turbo Expo*, GT2011, June 6-10, 2011, ASME, 1-10.

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