David Tomás Sánchez Martínez
Lourdes García Rodríguez
(coordinadores)

Proceedings of the 7th International Seminar on ORC Power Systems

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ACHIEVING 45% MICRO GAS TURBINE EFFICIENCY THROUGH HYBRIDIZATION WITH ORGANIC RANKINE CYCLES

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ABSTRACT

The demand for affordable, secure, and sustainable energy storage solutions has grown significantly with the increasing focus on decarbonization and the adoption of renewable energy sources (RES). Power-to-Power (P2P) energy storage systems (ESS) have emerged as a promising solution, utilizing excess electricity from RES to produce hydrogen for future power generation. This document presents a study on increasing the round-trip efficiency of P2P ESS by improving the electric efficiency of micro gas turbines (mGT) and integrating waste heat to power (WHP) technology. The research investigates the potential of mGTs as prime movers in P2P ESS, aiming to break the 45% electric efficiency barrier that would make them competitive with other alternatives like internal combustion engines (ICE) and fuel cells (FC). Increasing the nominal electric efficiency of mGTs would lead to significant reductions in hydrogen consumption, system footprint, and overall capital expenditure. Thus, this research focuses on increasing the electrical efficiency of the mGT by proposing a hybridization between the recuperative Brayton cycle and bottoming organic Rankine cycles, reaching higher than 45% electrical efficiencies in a hybrid configuration. An exhaustive comparison of the main ORC systems hybridized with the recuperative Brayton cycles is presented. The results reveal that hybridizing an intercooling-recuperative Brayton cycle with a simple recuperated ORC has the potential to increase electrical efficiency to 46%. The work also presents a sensitivity analysis to assess how the design parameters influence the performance of the hybrid thermodynamic cycle.

1 INTRODUCTION

In the recent past, storing large amounts of energy was impossible and, even today, it poses many technical challenges. However, with the growing penetration of renewable energy sources (RES) and the push for decarbonization due to new regulations and societal concerns, finding affordable, secure, and sustainable energy storage solutions is crucial. Power-to-Power (P2P) energy storage systems (ESS) have gained significant attention recently, particularly in relation to national plans for developing hydrogen and other decarbonized fuel alternatives (FCH, 2019), (FCHEA, 2020). Additionally, governments are expediting the adoption of RES and energy storage options to ensure the security of supply whilst still in compliance with the Green Deal vision, given the significant uncertainty and volatility of the energy market. The European Commission has introduced the "Fit for 55" legislative package (EU, 2022), aiming to update and implement the regulatory framework necessary to achieve the decarbonization targets for 2030 and 2050.

A Power-to-Hydrogen-to-Power (P2P-ESS in the context of this paper) makes use of excess electricity generated from RES to power an electrolyzer, which breaks water into hydrogen and oxygen. The hydrogen generated is then stored to be used later to run a power generation system. This process enables utilizing initially non-dispatchable renewable electricity, effectively aligning production and consumption of electricity, thus ensuring that the power demand is met at any time. From a practical standpoint, the hydrogen stored can be used to operate fuel cells, gas turbines or other heat engines, although the former two are the main technologies proposed for power generation from hydrogen. Recently, the authors have extensively researched this concept, placing particular emphasis on decentralized and off-grid applications, and employing a micro-gas turbine (mGT) as the primary mechanism for power generation utilizing hydrogen (H2) (Escamilla, 2022) (Escamilla, 2023).

Past work by the authors on P2P-mGT concepts shows that the cost-effectiveness of these systems is compromised by the low efficiency of the prime mover (mGT). In particular, making use of the most efficient micro gas turbines in the market today (26.9% LHV efficiency for 30 kWe rated output) yields a very low round-trip efficiency of 15.5% only, which is not high enough to compensate for the high capital cost required to implement this solution (Escamilla, 2023). This highlights that the incorporation of much more efficient power generation devices into these P2P-EES systems is the most critical route towards the development of cost-effective, small-scale P2P-EES solutions based on green hydrogen.

Micro gas turbines have power outputs below 500 kWe, typically, a range where the main competing technologies are Internal Combustion Engines (ICE) and Fuel Cells (FC), technologies featuring higher efficiency than mGTs and, for ICEs, also lower capital cost (CapEx). Therefore, despite the visible advantages of mGTs (low NOx, high-grade heat, flexibility, fast-response capability), this does not suffice to emerge as a more interesting prime mover. It is hence essential for mGTs to increase their electric efficiency in order to gain market share in a future energy system transitioning towards decentralized energy solutions (Tilocca, 2023). The Aurelia A400 engine features the highest electric efficiency of all mGTs in the market: 40.2% (LHV) (Aurelia, 2023) (Escamilla, 2022). This efficiency is comparable to ICEs and FCs of similar power output but cannot be sustained at smaller outputs because of the need to adopt simpler cycles or due to the impact of scale effects on component efficiency.

In the foregoing context, the current study aims to increase the efficiency of mGTs for a wider output range in order to enable their utilization in P2P-mGT ESS. To this end, past work by the authors concluded that the efficiency of the power conversion unit must be, at least, 45% since this boosts the round-trip efficiency of the resulting solution to 26% (in lieu of 15.5% for an mGT with 26.9% efficiency). The consequence of this is an almost 45% reduction in hydrogen consumption of the mGT, which translates into a footprint reduction of all systems involved in a P2P-mGT ESS, largely reducing the CapEx of the overall system. Two options to enable such efficiency increase are considered: higher efficiency mGTs and combined mGT + waste heat to power bottoming system. In the latter case, the exhaust gas from the mGT is used to drive a thermomechanical energy conversion system to produce additional electric power from the mGT waste heat. The two options are typically considered for WHP: Steam Rankine Cycle (SRC) and Organic Rankine Cycle (ORC). Amongst the two, steam is not cost-effective at a small scale, given the very low performance and high cost of steam turbines of a few hundred kilowatts (Vanslambrouck, 2012). Therefore, this research investigates the thermodynamic feasibility of integrating ORCs with different recuperative Brayton Cycle layouts, used by microturbines, to boost the power-to-heat ratio, and thus, the electric efficiency. A short literature review on the topic is presented below.

Bao et al. (Bao, 2013) presented a review of organic working fluid and expander options for ORC systems, screening the most prominent Key Performance Indicators for the selection of these two elements. Bonolo de Campos et al. (Bonolo de Campos, 2019) presented a review of the combination of micro gas turbines and ORC systems, concluding that the efficiency of a 100 kWe mGT could increase from 30% to 35% when combined with an ORC system, even if at the expense of 48% higher capital cost; it is to note that the work cited is a review and does not rely on calculations by the authors. Mago et al. (Mago, 2013) examined the potential of using the exhaust gas from microturbines in ORC systems, considering microturbines with different power outputs and different fluids in the ORC system, and basing the analysis on electric and exergy efficiencies. For this, the authors considered a set isentropic efficiency for both the ORC turbine and pump, and also a fixed electric efficiency for the mGT (ranging from 25% to 31%, depending on power output). The work gives a good understanding of which fluids might perform better whereas the present paper goes into more detail about the assessment of potential configurations of Brayton cycles and ORC systems that could help raise global efficiency, and therefore, the round-trip efficiency of the P2P-mGT ESS that the authors have previously investigated. This is of course not a new concept, as the forecited works have studied it already, but the integration of the mGT within a P2P ESS with the objective to break the 45% efficiency barrier and the improvements that are needed are innovative, as deduced from the literature review carried out by the authors. For that, systems forming both cycles will need to be dealt with in detail in the forthcoming sections.

Furthermore, it is recognized that the input data and specifications of the cycle and components, especially for the turbomachinery parts, are strongly influenced by scale even though this is mostly not considered in the literature reviewed. Thus, to assess the relevance of this common assumption, the first part of this paper provides an analysis of the impact of scale effects on the performance of compressors and turbines, which is then used to set the appropriate input data to run simulations. This is aimed at ensuring the credibility of the results. Moreover, the study incorporates diverse configurations of the Brayton cycle and varying power outputs to encompass the entire design range of micro-gas turbines, spanning from 1 kW to 500 kW that could be integrated into the P2P ESS. It is worth noting that the primary fuel utilized in this study is natural gas.

The authors acknowledge that increasing the system's complexity will inevitably lead to higher CapEx and operational expenditures (OpEx) for the mGT. However, if the overall context is considered, integration of a mGT within a P2P ESS, the increase in CapEx and OpEx of the mGT will be hardly noted as the main source of CapEx and OpEx are the PV solar, electrolyser and H_2 storage systems.

The study is organized as follows: 1) introduction to the concepts of P2P-mGT ESSs and waste-heat-to-power applications and literature review of hybrid micro gas turbines and ORC systems. 2) description of the hybridization layouts considered. 3) discussion of the design parameters used for each mGT layout and ORC system, as well as of the list of organic fluids used in the simulations. 4) a discussion of the results from a sensitivity analysis assessing the impact of varying the evaporator pinch-point and the maximum pressure of the ORC system, 5) the presentation of the main conclusions and next steps.

2 HYBRIDIZATION OF THE BRAYTON CYCLE WITH A BOTTOMING ORGANIC RANKINE CYCLE

Gas turbines operate according to a Brayton cycle, comprised of gas compression, heating, expansion and (virtual) cooling; in a practical engine, this latter process involved direct heat and mass transfer between the engine and the environment. Organic Rankine cycles are Rankine cycles where the working fluid is organic, typically with high molar mass and molecular complexity, whose evaporation temperature is lower than that of steam at the usual operating pressures. Heavy-duty combined cycle power plants make use of use of a topping Brayton Cycle and a bottoming steam Rankine Cycle harvesting the available heat at the exhaust from the former. Gas turbines in these systems feature very high turbine inlet temperatures and pressure ratios of around 25:1. When micro gas turbines are used, the turbine inlet temperature is low (limited by the material melting point since blade cooling cannot be used) and so is the associated pressure ratio accomplished by radial turbomachinery. Therefore, these engines rely on recuperative Brayton cycles to increase gas turbine performance, which implies lower exhaust gas temperatures, typically not higher than 250 ºC. For this temperature level, ORCs are better suited than steam Rankine cycles. 517

Brayton cycles can adopt multiple configurations to increase either thermal efficiency, specific power, or both. Nevertheless, as thermal efficiency increases, the number of components and the complexity of system integration also increase. In the next sections, the different Brayton cycle layouts are discussed – a recuperative Brayton cycle and an intercooled-recuperative Brayton cycle –, the latter in a twin-spool arrangement. Though the added number of components and the complexity of the cycle becomes very visible, adopting the latter layout boosts thermal efficiency by 10 percentage points compared to the single spool recuperative Brayton cycle. Both configurations will be used in the current research.

The implementation of Brayton cycles in gas turbines renders an open-cycle engine (except on very rare occasions) whilst ORC power systems are closed-cycle systems incorporating a condenser for heat rejection. Figure 1 shows the configuration of the reference mGT-ORC system used in this research. The mGT module will adopt different configurations that will be introduced in the following section. The exhaust gases from the mGT are redirected to the evaporator where the organic fluid discharged from the pump undergoes heating and phase change. The resulting saturated vapour is then expanded across the turbine and then cooled down and condensed; these processes are then carried out cyclically. It is to note that, even though recuperative heat exchangers are typically used in other applications of ORC systems to use the available sensible heat at turbine exhaust to preheat the liquid working fluid upstream of the vapour generator.

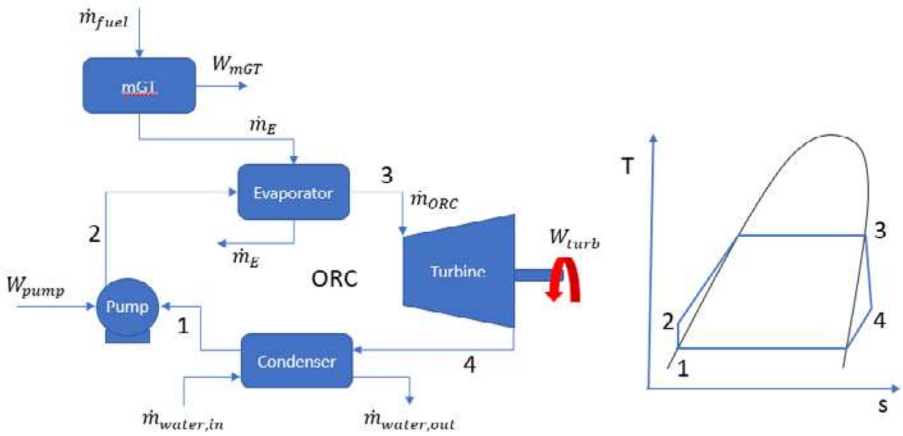

Figure 1. Hybridization of an mGT with a bottoming Organic Rankine Cycle system. The overall layout and T-s diagram of the bottoming cycle.

The selection of thermodynamic parameters for each system as well as the selection of the working fluid for the ORC will be discussed in the following sections.

3 SIMULATION OF BASECASE SCENARIO

3.1 Selection of thermodynamic cycle parameters and simulation

The hybridisation of the three layouts presented in figures 2, 3 and 4 with the bottoming ORC system in Figure 1 has been analysed using a simulation platform built in the Thermoflex environment (Thermoflex, 2022). 518

Out of all the equipment involved, the systems which are affected by scale effects the most are the compressor and turbine in the micro gas turbine, due to the aerodynamic and secondary loss effects; therefore, while carrying out the simulation, it is important to consider the power output (i.e, size) of the system under consideration. Three micro gas turbine options are assessed, combining system layout and power output: R-MGT for 5 and 100 kWe, and ICR-MGT for 400 kWe. The polytropic efficiencies given in Table 1 have been selected for each case, based on the considerations given in the work by Galanti *et al.* (Galanti, 2011). Table 1 presents the remaining boundary conditions and specifications of components.

Figures 2, 3, and 4 show the heat and mass balance of each simulation whilst the corresponding global performance parameters are presented in Table 2. Tables 1 and 2 along with figures 2, 3 and 4 show the validation of the model and allow for the reproduction of the results.

Electric efficiency for each base-case scenario is 26.5%, 29.2% and 40.2%. The electric efficiency increase comes from three different sources: upscale of turbomachinery, turbine inlet temperature, and thermodynamic cycle layout enhancement. Interestingly, each of these cases is intended to replicate existing commercial micro-gas turbines – MTT-EnerTwin (EnerTwin, 2023), Ansaldo-AE-T100 (Ansaldo, 2023), and Aurelia-A400 (Aurelia, 2023) -, even if the specifications reported in Table 1 deviate from the commercial specs announced by the Original Equipment Manufacturers.

Table 1. Input parameters for the simulation of the Brayton cycle for different layouts.

Parameter	Unit	Value		
		R-MGT-1	**R-MGT-2**	**ICR-MGT**
Ambient temperature and pressure	ºC / bar	15 / 1.013	15 / 1.013	15 / 1.013
Working fluid	-	Air	Air	Air
Fuel	-	Natural Gas	Natural Gas	Natural Gas
Exhaust gas flow	kg/s	0.0569	1.018	1.872
Gross Electric power	kW	5.08	101.5	401.0
Turbine inlet temperature	ºC	850	850	1005
Total pressure ratio	-	2.5	2.5	5.8
HP compressor polytropic efficiency	%	-	-	80.2
HP turbine polytropic efficiency	%	-	-	85.2
LP compressor polytropic efficiency	%	76.5	80.5	81.0
LP turbine polytropic efficiency	%	83.8	85.2	85.8
HE thermal effectiveness	%	85.0	85.0	90.5
Combustor efficiency	%	96.0	96.0	98.0
Compressor inlet pressure loss	%	1.0	1.0	1.0
HE pressure loss	%	1.0	1.0	1.0
Combustor pressure loss	%	2.0	2.0	2.0
Mechanical efficiency	%	98.5	98.5	98.5
Generator efficiency	%	96.0	96.0	96.0

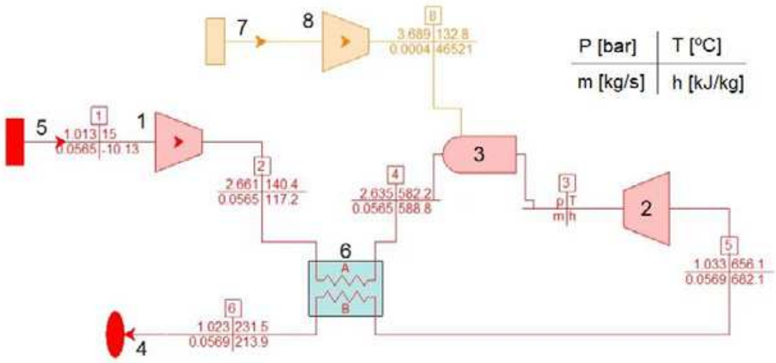

Figure 2. Simulation of R-MGT-1.

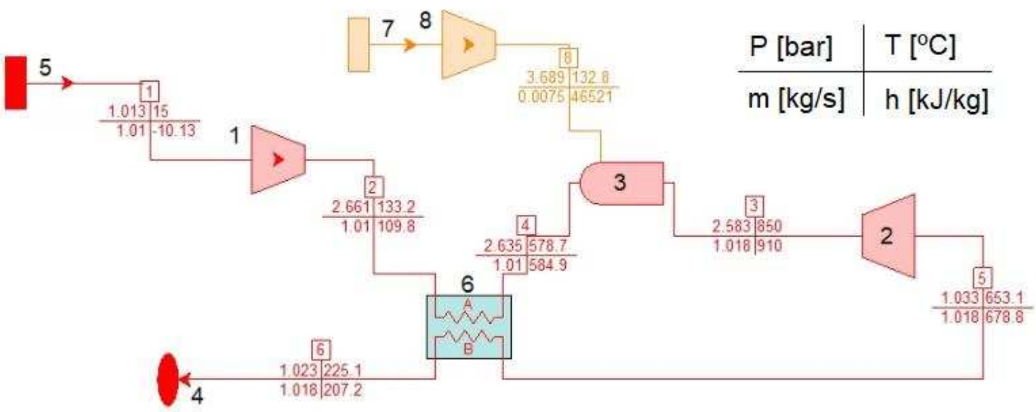

Figure 3. Simulation of R-MGT-2

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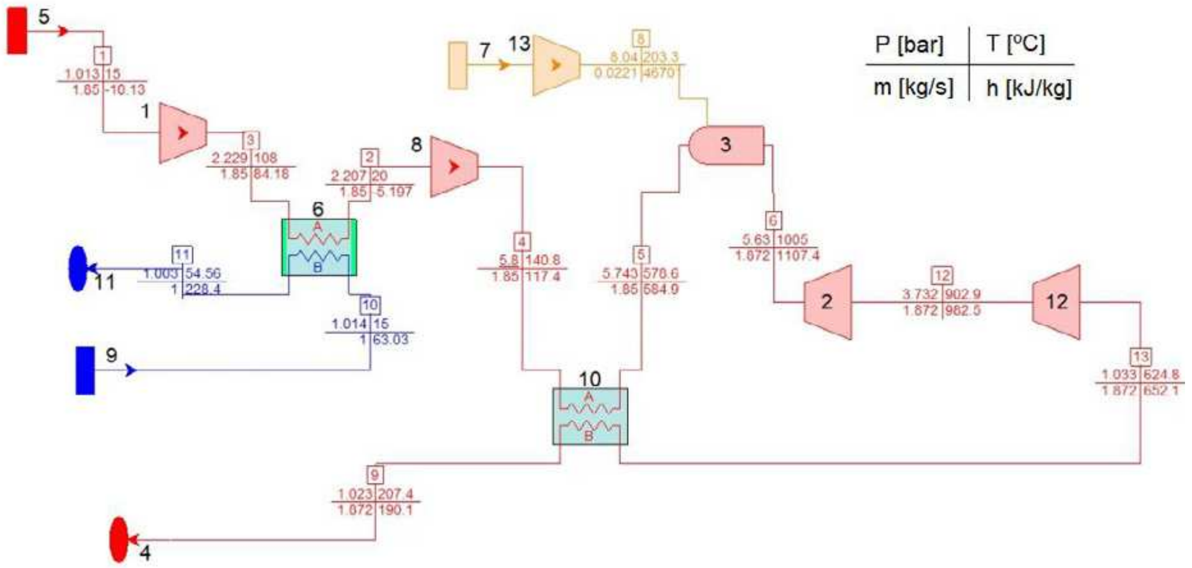

Figure 4. Simulation of ICR-MGT.

Table 2. Main output parameters of the simulated Brayton cycles. Input parameters are displayed in Table 1.

Parameter		Unit	Value		
			R-MGT-1	R-MGT-2	ICR-MGT
Thermal efficiency (LHV)		%	29.4	32.2	43.4
Electric efficiency (LHV)		%	26.5	29.2	40.3
Net electric output		kW	5.08	101.5	401.0
Exhaust gas temperature		ºC	231.5	225.1	204.5
Fuel Input (LHV)		kW	19.2	347.4	995.7
Exhaust gas flow		kg/s	0.0569	1.018	1.872
Exhaust Gas Composition	O_2	% mole	18.08	18.046	16.555
	CO_2	% mole	1.261	1.276	1.967
	H_2O	% mole	3.352	3.382	4.697
	AR	% mole	0.919	0.919	0.913
	N_2	% mole	76.387	76.376	75.868

3.2 Selection of organic working fluid and parameters of the ORC system

There is a wide range of organic fluids whose utilisation in ORC systems has been assessed. This selection of the working fluid is not only critical from a thermodynamic standpoint but also in terms of health and safety requirements and capital cost. Furthermore, the working fluid of choice must be tailored to the type and quality of heat available to drive the cycle, which adds another degree of freedom to the optimisation problem. Guoquan Qiu proposed a methodology, based on check steps, to decide which organic fluids could be suitable for certain applications (Qiu, 2012). The methodology is applied in this work, narrowing down the portfolio of organic fluids to be studied, and it is also complemented with information from similar works looking for the most suitable organic fluids for the application considered in this study: waste heat from small gas turbines (Bao, 2013) (Mago, 2012) (Clemente, 2013).

Table 3 shows the fluids and associated thermodynamic properties considered in the analysis whilst Table 4 lists other parameters needed for the simulation of the organic Rankine cycle whose layout was presented in Figure 1. It is worth noting that condenser pressure is different for each fluid as this comes determined by the saturation temperature at the condenser, which depends itself on ambient temperature (same for all cases). In practice, this translates into condenser pressures equal to 0.91 bar, 1.48, and 4.99

bar for R123, R245fa, and R1234ze, respectively. One of the noteworthy features of using organic fluids in the Rankine cycle is the avoidance of vacuum conditions in the condenser. This has several advantages, the most salient of which being that deaeration is no longer needed given that the entire system operates under pressure. This reduces the cost of the system and increases the useful life of components, thanks to the corrosion triggered by oxygen leaking into the system. Additional benefits related to the mechanical design of components. Based on this, and to avoid vacuum conditions in the condenser, it is decided to set the following condenser pressures for the three fluids considered: 1.25 bar, 1.5 bar, and 5 bar, respectively.

Table 3. Properties of the different organic fluids considered.

Parameter [Coolprop]	Unit	Fluid		
		R123	R245fa	R1234ze
Critical pressure	MPa	3.66	3.64	3.64
Critical temperature	ºC	183.7	157.5	109.4
Boiling temperature*[1]	ºC	27.8	15.3	-18.95
Molar mass	g/mol	153	134	114
GWP (AR5)	-	79.0	858.0	1.00
*[1]: at 1 bar.				

Table 4. Input parameters for the ORC layouts considered.

Parameter	Unit	Value		
		R-MGT-1	R-MGT-2	ICR-MGT
Condenser temperature	ºC	25	25	25
Pump isentropic efficiency	%	85.0	85.0	85.0
Pump motor efficiency	%	88.0	88.0	88.0
Turbine isentropic efficiency	%	83.8	85.2	85.8
Evaporator thermal effectiveness	%	85.0	85.0	85.0
Evaporator pinch point	ºC	5	5	5
Mechanical efficiency	%	98.5	98.5	98.5
Generator efficiency	%	96.0	96.0	96.0

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4 HYBRIDIZATION OF MGT AND ORC SYSTEM

Once the base case scenarios have been set, this section explores the benefits of using the exhaust gases from the different mGT layouts to drive an ORC system, considering several organic fluids. The analysis aims to understand how the global electric efficiency of the power generation system is impacted by the hybridization proposed, calculated as follows:

$$\eta_t(\mathrm{LHV}) = \frac{\text{useful power ouput}}{\text{energy input}} = \frac{P_{\mathrm{e,GEN1}} - P_{\mathrm{e,FUEL}} + P_{\mathrm{e,GEN2}} - P_{\mathrm{e,PUMP}}}{\text{Fuel Input (LHV)}} \tag{1}$$

Where P_e stands for electric power. Generator 1 (GEN1) refers to the generator of the mGT (electric output at generator terminals) whilst Generator 2 is driven by the expander of the ORC system. FUEL and PUMP refer to the electric motor driving the fuel compressor of the Brayton cycle and pump in the ORC unit. There is only one fuel input source: the fuel added in the combustor of the mGT.

The bottoming ORC system is coupled with the stream of exhaust gases from each mGT considered (Table 2) as shown in Figure 5, where stream 2 is the hot gas coming from the turbine. For each mGT layout, three different organic fluids used in the ORC are considered, yielding nine cases in total. In the first part of the study the bottoming system is designed considering a minimum evaporator's pinch point and a maximum pressure of 20 bar. Next, a sensitivity analysis on the maximum pressure of ORC system is carried out to understand the maximum potential of the ORC system to boost the total electric efficiency of the system. The upper limit of the maximum cycle pressure is set by the critical pressure of each organic fluid (Table 3).

Table 5 shows the results of the first analysis, considering a 5ºC minimum pinch point in the Heat Recovery Vapour Generator and a maximum pressure of the ORC system of 20 bar. The results are highly influenced by the condensation temperature of 25ºC since this directly affects the pressure ratio through modifications of condenser pressure from one case to another. This is reflected in the electric efficiency of the ORC unit, revealing that achieving 45% global efficiency is only possible if the ICR-MGT gas turbine layout is combined with an ORC system running on R245fa. Additionally, there is a clear trend in the contribution of the ORC unit to total power output. This is measured through the ORC Power ratio, (ORC System Power Output)/(Total Power Output), which decreases as the electric efficiency of the mGT increases, given the lower energy content of the exhaust gases from the turbine; i.e., the lower turbine exhaust temperature reduces the efficiency of the Heat Recovery Vapour Generator, meaning that a lower amount of heat is recovered from the turbine exhaust.

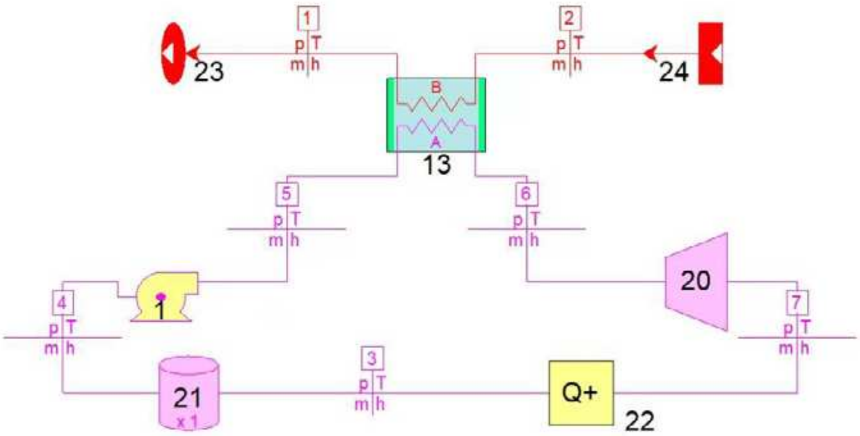

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Figure 5. The layout of the ORC (3-4-5-6-7-3) coupled with the exhaust gas stream of an mGT (1 – 2).

Table 5. Results of the hybridized system (Brayton + ORC) considering a maximum pressure of 20 bar. Input parameters are in Table 4.

Parameter	**Unit**	**Value (R-MGT-1/R-MGT-2/ICR-MGT)**								
		R123			**R245fa**			**R1234ze**		
ORC pressure ratio	-	16			13.3			4		
Total electric efficiency	%	35.8	37.9	44.3	35.7	38.2	45.5	32.9	35.5	43.9
ORC system efficiency	%	16.0	16.2	16.3	15.0	15.3	15.4	10.5	10.7	10.7
Total gross electric power	kW	6.88	131.6	441.3	6.85	132.8	453.1	6.32	123.3	437.4
ORC power ratio	-	0.26	0.23	0.09	0.26	0.24	0.12	0.20	0.18	0.08

The effect of maximum cycle pressure is studied next, assuming a pinch point of 5ºC in the vapour generator and a condensation temperature of 25ºC. Figure 6 shows how total electric efficiency is affected by the pressure ratio. The only configuration that achieves the 45% total electric efficiency target is the ICR-MGT with the R245fa organic fluid. In general, for the upper limit of the pressure ratio, it becomes clear that R245fa outperforms R123. For the lower limit of pressure ratio, on the contrary, R1234ze outperforms the other two fluids considered, regardless of the mGT configuration considered. It is worth noting that, due to the constraints set for condensation temperature, the maximum efficiency attainable by R1234ze is limited to 43.5%, corresponding to the ICR-MGT configuration.

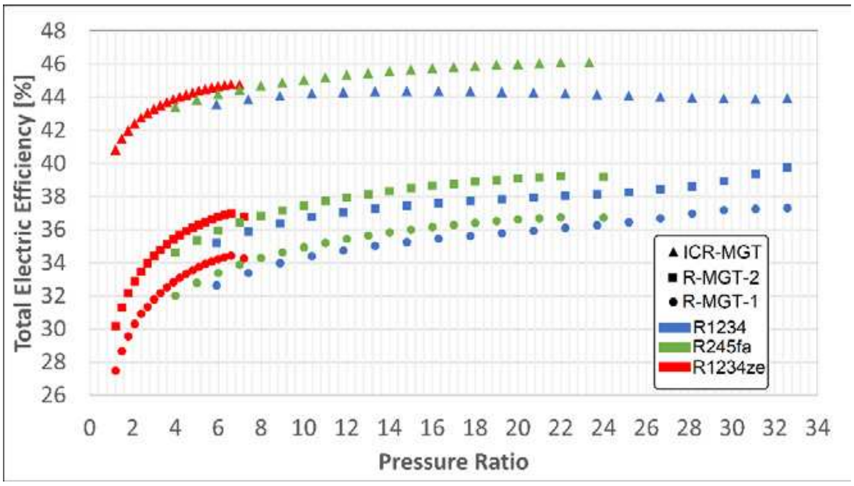

Figure 6. Total electric efficiency when varying the pressure ratio of the ORC system for the 3 mGT configurations and 3 organic fluids.

The results presented reveal that the utilization of a bottoming ORC unit running on R245fa enables achieving the target total electric efficiency of 45%, for a pressure ratio of 10. However, this comes at an environmental cost since, out of the three organic fluids, R245fa has the highest GWP (Table 3), whereas R1234ze presents the lowest value of this index.

Based on these latter results, the authors have conducted a sensitivity analysis to identify the conditions that would enable using an ICR-MGT engine bottomed by an ORC unit running on the least harmful working fluid (R1234ze), still attaining 45% global electric efficiency. The assessment is based on calculating the break-even condensation temperature that would yield 45% total electric efficiency for maximum bottoming cycle pressure of 20 bar and 35 bar. The results obtained suggest that the break-even pressure ratio is 5.8 for the former case (20 bar), for a condensation temperature of 13.3ºC, and these figures increase to a pressure ratio of 7.7 and condensation temperature of 22ºC in the latter case. Therefore, the adoption of R1234ze instead of R245fa in the bottoming system would enable 45% total electric efficiency if the condensation temperature could be reduced.

5 CONCLUSIONS

The rationale behind this study is to develop combined (hybrid) mGT-ORC systems that would help to increase the round-trip efficiency of hydrogen-based power-to-power energy storage systems. The authors estimate that breaking the 45% electric efficiency would make the mGT much more competitive and a more solid candidate against the internal combustion engine and fuel cells (Escamilla, 2022) (Escamilla, 2023). To this end, the study focused on three mGT layouts, including the regenerative Brayton cycle (R-MGT) and intercooling-regenerative Brayton cycle (ICR-MGT), and a bottoming ORC system with the simplest layout possible (evaporator, turbine, condenser, pump).

The results of the paper show that the 45% electric efficiency target can be achieved if the ICR-MGT layout is adopted. In particular, the total efficiency could theoretically be as high as 46.1%, with the bottoming ORC system adding 58 kWe to the 400 kWe produced by the mGT. The latter is achieved when the R245fa organic fluid is adopted for a pressure ratio of 10 and a condensation temperature of 25ºC. The 45% electric efficiency barrier can also be surpassed when using the organic fluid R1234ze, which has the lowest GWP value, but with a lower condensation temperature, 22ºC with a pressure ratio of 7.7.

The next steps of this research will look into the correction factors (<1) introduced by scaling effects in turbomachinery and into the economics of the system, in particular as a function of maximum ORC pressure. However, it is to highlight that the additional cost of adopting such a solution would not oppose any major concern as the solution would be integrated into a hydrogen-based power-to-power energy storage system that would dilute the additional cost.

REFERENCES

AE-T100, Ansaldo Energia, [Online]. Available: https://www.ansaldoenergia.com/offering/equipment/turbomachinery/microturbines/ae-t-100. [Accessed 16 04 2023].

Aurelia A400 Turbine, Aurelia, [Online]. Available: https://aureliaturbines.com/aurelia-a400. [Accessed 16 04 2023].

Bao, J., Zhao, L., 2013, A review of working fluid and expander selections for organic Rankine cycle, Renewable and Sustainable Energy Reviews, Elsevier, vol. 24(C), pages 325-342.

Bonolo de Campos, G., Bringhenti, C., Traverso, A., Tomita, J., 2019, A Review on Combining Micro Gas Turbines with Organic Rankine Cycles, SUPEHR19 SUstainable PolyEnergy generation and HaRvesting, E3S Web of Conferences, vol. 113, 03007.

Clemente, S., Micheli, D., Reini, M. Taccani, R., 2013, Bottoming organic Rankine cycle for a small scale gas turbine: A comparison of different solutions, Applied Energy, vol. 106, pp. 355-364.

EnerTwin, MTT, [Online]. Available: https://enertwin.com/. [Accessed 16 04 2023].

Escamilla, A., Sánchez-Martinez, D., García-Rodrgíguez, L., 2022, Assessment of power-to-power renewable energy storage based on the smart integration of hydrogen and micro gas turbine technologies, International Journal of Hydrogen Energy, vol. 47, no. 40, pp. 17505-17525.

Escamilla, A., Sánchez-Martinez, D., García-Rodrgíguez, L., 2023, Techno-economic study of Power-to-Power renewable energy storage based on the smart integration of battery, hydrogen, and micro gas turbine technologies, Energy Conversion and Management: X, vol. 18, p. 100368.

Fuel Cells and Hydrogen Joint Undertaking, 2019, Hydrogen roadmap Europe: A sustainable pathway for the European energy transition, *EU Comission.*

Fuel Cells and Hydrogen Energy Association, 2020, Road map to a US Hydrogen Economy.

Galanti, L., Massardo, A.F., 2011, Micro gas turbine thermodynamic and economic analysis up to 500kWe size, Applied Energy, vol. 88, issue 12, pp. 4795-4802.

Giuseppe, T., Sánchez, D., Torres-García, M., 2023, Applications of the Theory of constraints to unveil the root causes of the limited market penetration of micro gas turbine systems, Energy, vol. 278, pp. 127717.

Mago, P.J., Luck, R., 2013, Energetic and exergetic analysis of waste heat recovery from a microturbine using organic Rankine cycles. International Journal Energy Research, vol. 37, pp. 888-898.

Qiu, G., 2012, Selection of working fluids for micro-CHP systems with ORC, Renewable Energy, vol. 48, pp. 565-570.

Thermoflex, Thermoflow, Version 30, 2022 [Online]. Available: https://www.thermoflow.com/products_generalpurpose.html. [Accessed 16 04 2023].

U.S. Department of Energy's (DOE's) Advanced Manufacturing Office, 2022, 2022 Combined Heat and Power & District Energy System Portfolio Meeting, [Online]. Available: https://www.energy.gov/eere/amo/events/2022-combined-heat-and-power-district-energy-system-portfolio-meeting. [Accessed 31 03 2022].

Vanslambrouck, B., Vankeirsbilck, I., van den Broek, M., Gusev, S., & De Paepe, M., 2012, Efficiency comparison between the steam cycle and the organic rankine cycle for small scale power generation, Renewable Energy World Conference and Expo North America, Proceedings. Presented at the Renewable Energy World Conference & Expo North America, Long Beach, CA, USA.

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This book contains the compilation of works contributed to the *7th International Seminar on Organic Rankine Cycle Power Systems* (ORC 2023), held in Seville between the 4th and 6th of September 2023. The event was hosted by Universidad de Sevilla on behalf of the Knowledge Centre on Organic Rankine Cycle Technology (KCORC), incorporated in The Netherlands.

The ORC conference, organized biennially, stems as the only conference that is specific to ORC technology, therefore gathering a diverse community whose affiliation spans across all the interested stakeholders, not only in this particular technology but also and in a broader context, in the energy transition. Original equipment manufacturers, professional associations, end-users, investors, policy makers, academics, scientists feel at home at ORC 2023.

The almost 100 proceedings in this book cover a wide variety of topics, from fundamentals to system integration through component design, accounting for thermodynamic performance as well as component design. In addition to this, and as a new track in 2023, works on heat pump technology were also accepted in order to raise awareness of the strong ties between both technologies, specifically in energy storage applications.

This book provides an excellent overview of the current maturity of power systems based on Organic Rankine Cycle technology for applications as diverse as geothermal and waste heat recovery in industry or downstream of other prime movers (e.g., marine applications). It is also an excellent source of information to understand the current challenges faced by the technology, stemming from a very competitive market and increasingly stringent environmental regulations.

The organizers of ORC 2023 hope that the reader finds this work as exciting as the attendees to the conference and, maybe, make the decision to join the 8th edition to the conference in 2025.

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