

David Tomás Sánchez Martínez  
Lourdes García Rodríguez  
(coordinadores)

Proceedings of the 7th International Seminar on

# ORC

## Power Systems

Editorial Universidad de Sevilla



Proceedings of the 7th International Seminar on

# **ORC**

Power Systems



David Tomás Sánchez Martínez

Lourdes García Rodríguez

(coordinadores)

Proceedings of the 7th International Seminar on

**ORC**

**Power Systems**

**(ORC2023)**

**4<sup>th</sup> to 6<sup>th</sup>**

**SEPTEMBER**

**SEVILLE 2023**

 **EDITORIAL**  
**UNIVERSIDAD DE SEVILLA**

Sevilla, 2024

## Colección Actas

Núm.: 91

Comité editorial de  
la Editorial Universidad de Sevilla:

Araceli López Serena  
(Directora)

Elena Leal Abad  
(Subdirectora)

Concepción Barrero Rodríguez  
Rafael Fernández Chacón  
María Gracia García Martín  
María del Pópulo Pablo-Romero Gil-Delgado  
Manuel Padilla Cruz  
Marta Palenque  
María Eugenia Petit-Breuilh Sepúlveda  
Marina Ramos Serrano  
José-Leonardo Ruiz Sánchez  
Antonio Tejedor Cabrera

Review chairs of the 7<sup>th</sup> International Seminar on ORC Power Systems

Prof. Christoph Wieland (University of Duisburg-Essen) - *Review Chair*

Prof. Sotirios Karellas (National Technical University of Athens) - *Review Co-Chair*

Prof. Teemu Turunen-Saaresti (LUT University) - *Review Co-Chair*

Dr. Diego-César Alarcón-Padilla (Plataforma Solar de Almería - CIEMAT) - *Review Co-Chair*

Dr. Francesco Crespi (Universidad de Sevilla) - *Review Co-Chair*

Esta obra se distribuye con la licencia

Creative Commons Atribución-NoComercial-SinDerivadas 4.0 Internacional ([CC BY-NC-ND 4.0](https://creativecommons.org/licenses/by-nc-nd/4.0/))



Usted es libre de:

**Compartir** — copiar y redistribuir el material en cualquier medio o formato

La licenciate no puede revocar estas libertades en tanto usted siga los términos de la licencia

**Bajo los siguientes términos:**

**Atribución** — Usted debe dar crédito de manera adecuada, brindar un enlace a la licencia, e indicar si se han realizado cambios .  
Puede hacerlo en cualquier forma razonable, pero no de forma tal que sugiera que usted o su uso tienen el apoyo de la licenciate.

**NoComercial** — Usted no puede hacer uso del material con propósitos comerciales .

**SinDerivadas** — Si remezcla, transforma o crea a partir del material, no podrá distribuir el material modificado.

**No hay restricciones adicionales** — No puede aplicar términos legales ni medidas tecnológicas  
que restrinjan legalmente a otras a hacer cualquier uso permitido por la licencia.

© Editorial Universidad de Sevilla 2024

c/ Porvenir, 27 - 41013 Sevilla.

Tlfs.: 954 487 447; 954 487 451; Fax: 954 487 443

Correo electrónico: [info-eus@us.es](mailto:info-eus@us.es)

Web: <https://editorial.us.es>

© [David Tomás Sánchez Martínez](#) y [Lourdes García Rodríguez](#)  
(coordinadores)

© De los textos, los autores 2024

ISBN 978-84-472-2745-7

DOI: <https://dx.doi.org/10.12795/9788447227457>

Diseño de cubierta y maquetación: los autores

## INDEX OF CONTRIBUTIONS

ID3 - Additive manufacturing for fast prototyping of a velocity compounded radial re-entry turbine Authors: Dominik Stümpfl, Karel Ráž, Philipp Streit, Andreas P. Weiß . . . . .	13
ID4 - Thermodynamic concept of a novel recuperative two-phase power cycle process Authors: Benedikt G. Bederna, Riley B. Barta, Christiane S. Thomas . . . . .	23
ID7 - Performance analysis of a 1.5 MW Organic Rankine Cycle in a Carnot battery system for grid balancing services Authors: Robin Tassenoy, Hannes Van De Velde, Kenny Couvreur, Michel De Paepe, Steven Lecompte . . . . .	33
ID8 - Calibration of multi-hole probes for measurements in compressible organic vapor flows Authors: Leander Hake, Stephan Sundermeier, Stefan Aus Der Wiesche, Maximilian Passmann . . . . .	43
ID9 - pocketORC: A browser-based calculator for teaching organic Rankine cycle power systems Authors: Martin White . . . . .	53
ID10 - Evaluation of existing supercritical heat transfer correlations for designing the vapor generator in low-temperature transcritical Organic Rankine Cycle systems Authors: Jera Van Nieuwenhuyse, Anastasios Skiadopoulos, Dimitris Manolakos, Steven Lecompte, Michel De Paepe . . . . .	61
ID12 - A novel combined cooling and power cycle integrated ejector refrigeration and composition adjustment for stationary engine waste heat recovery Authors: Xiaocun Sun, Lingfeng Shi, Hua Tian, Gequn Shu . . . . .	71
ID14 - Design and construction of a reversible ORC test rig for geothermal CHP applications Authors: Florian Kaufmann, Christopher Schiffler, Christoph Wieland, Hartmut Spliethoff . . . . .	81
ID15 - Robust and fast meanline methodology for radial inflow turbines with non-ideal gases for system level optimisation of organic Rankine cycles Authors: Carola Freytag, Eva Alvarez-Regueiro, Pablo Ale-Martos, Esperanza Barrera-Medrano, Ricardo Martinez-Botas . . . . .	91
ID16 - Shape optimization of a sCO <sub>2</sub> centrifugal compressor stage Authors: Alessandro Romei, Paolo Gaetani, Giacomo Persico . . . . .	101
ID17 - Optimizing the performance of a hybrid solar-biomass micro-CHP system with a TFC engine as the prime mover for domestic applications Authors: Anastasios Skiadopoulos, Xander Van Heule, Steven Lecompte, Michel De Paepe, Dimitrios Manolakos . . . . .	109
ID19 - Systematic and multi-criteria optimisation of subcritical thermally integrated Carnot batteries (TI-PTES) in an extended domain Authors: Antoine Laterre, Olivier Dumont, Vincent Lemort, Francesco Contino . . . . .	119



ID20 - ORC technology used in a heat removal system for an advanced nuclear power plant Authors: Guillaume Lhermet, Benoit Payebien, Nicolas Tauveron, Nadia Caney, Franck Morin . . . . .	130
ID22 - Assessment of trilateral Organic Rankine Cycle for solar applications with innovative turboexpander concept Authors: Alessandro Romei, Andrea Giotri, Andrea Spinelli. . . . .	140
ID25 - Evaluation of the performance of an axial one-stage 10kW turbogenerator through experimental testing Authors: Piotr Klimaszewski, Piotr Klonowicz, Lukasz Witanowski, Tomasz Suchocki, Piotr Lampart, Eugeniusz Ihnatowicz, Lukasz Antczak, Dawid Zaniewski, Lukasz Jedrzejewski . . . . .	149
ID26 - Investigation of the turbulence level and the vortex shedding in a turbine cascade working with an organic vapor at subsonic Mach numbers Authors: Leander Hake, Stephan Sundermeier, Stefan Aus Der Wiesche, Camille Matar, Paola Cinnella, Xavier Gloerfelt . . . . .	159
ID27 - A novel approach to district heating: using a two-phase expander in a reversible heat pump-Organic Rankine Cycle system Authors: Sindu Daniarta, Attila R. Imre, Piotr Kolasinski . . . . .	169
ID28 - Optimization of a partially evaporating Organic Rankine Cycle with thermal non-equilibrium expansion Authors: Xander Van Heule, Tasos Skiadopoulos, Dimitris Manolakos, Michel De Paepe, Steven Lecompte . . . . .	176
ID29 - Cost-effective option of cold energy utilization in pharmaceutical industry Authors: Sindu Daniarta, Dawid Sowa, Ádám Havas, Attila R. Imre, Piotr Kolasinski . . . . .	184
ID30 - Numerical investigation of a transonic dense gas flow over an idealized blade vane configuration Authors: Aurelien Bienner, Xavier Gloerfelt, Paola Cinnella, Leander Hake, Stefan Aus Der Wiesche . . . . .	193
ID31 - Comprehensive analysis of ORC-VCC system for air conditioning from low-temperature waste heat Authors: Lukasz Witanowski . . . . .	203
ID33 - Pareto front analysis for the design and the working fluid selection in ORC-based pumped thermal energy storage technology in both pure electric and cogenerative applications Authors: Marco Astolfi, Dario Alfani, Andrea Giotri . . . . .	214
ID36 - Evaluating the waste heat sources in a very large crude carrier and the potential integration of Organic Rankine Cycle configurations Authors: Amalia Stainchaouer, Christopher Schiffler, Christoph Wieland, Hartmut Spliethoff . . . . .	224
ID37 - Investigating R1234ze and R1234yf as replacements to R134a in waste heat recovery ORC applications Authors: James Bull, James Buick, Jovana Radulovic . . . . .	234



ID38 - Performance and economic assessment of a thermally integrated reversible HP/ORC Carnot battery applied to data centers Authors: Chiara Poletto, Andrea De Pascale, Saverio Ottaviano, Olivier Dumont, Maria Alessandra Ancona, Michele Bianchi .....	244
ID39 - Evaluation of the performance of multiple supercritical CO <sub>2</sub> power cycles in Waste Heat Recovery applications Authors: Hicham Chibli, Matthew Read, Abdalnaser Sayma .....	254
ID40 - Design and modeling of a demonstration-scale ORC cycle for the Liquid Air Combined Cycle Authors: Owen Pryor, William Conlon, Aaron Rimpel, Milton Venetos.....	264
ID41 - Guidelines and optimization criteria of a machine learning-based methodology for mixture design in ORC systems Authors: Valerio Mariani, Saverio Ottaviano, Andrea De Pascale, Giulio Cazzoli, Lisa Branchini, Gian Marco Bianchi .....	273
ID45 - Potential of trigenerative Waste Heat Recovery CO <sub>2</sub> -mixture transcritical power plants for increasing the sustainability of district heating and cooling networks Authors: Mattia Baiguini, Michele Doninelli, Ettore Morosini, Dario Alfani, Gioele Di Marcoberardino, Paolo Giulio Iora, Giampaolo Manzolini, Costante Mario Invernizzi, Marco Astolfi .....	282
ID46 - Thermodynamic analysis of a novel pumped thermal energy storage system with waste heat integration Authors: Meiyang Zhang, Lingfeng Shi, Peng Hu, Gang Pei, Gequn Shu .....	294
ID48 - Pressure profile optimisation of a nozzle for wet-to-dry expansion Authors: Pawel Ogrodniczak, Abdalnaser Sayma, Martin T. White .....	304
ID51 - Thermodynamic modification of CO <sub>2</sub> -based combined cooling and power cycle with ejector Authors: Yonghao Zhang, Lingfeng Shi, Gequn Shu .....	313
ID53 - Selection of suitable working fluid and storage material for ORC coupled with Thermal Energy Storage Authors: Dawid Sowa, Sindu Daniarta, Piotr Kolasinski .....	323
ID54 - Influence of dopant fluorination on the heat transfer behaviour of CO <sub>2</sub> -based mixtures in transcritical power cycles Authors: Michele Doninelli, Gioele Di Marcoberardino, Costante Mario Invernizzi, Paolo Giulio Iora .....	333
ID57 - On air-cooled condensers for ORC systems operating with zeotropic mixtures Authors: Lorenzo Galieti, Carlo De Servi, Dario Alfani, Paolo Silva, Paola Bombarda, Piero Colonna .....	344
ID58 - Experiments on supersonic ORC nozzles in linear cascade configuration Authors: Marco Olivetti, Marco Manfredi, Giacomo Persico, Andrea Spinelli, Paolo Gaetani, Vincenzo Dossena .....	354
ID59 - Numerical analysis of aerodynamics and performance of a radial-inflow micro-ORC turbine Authors: Fatemeh Ardaneh, Marta Zocca, Antti Uusitalo, Teemu Turunen-Saaresti. ....	363

ID61 - ORC system using R1233zd(E) for waste heat recovery from the upstream process Authors: Meng Soon Chiong, Bemgba Nyakuma, Nur Izwanne Mahyon, Srithar Rajoo, Eva Alvarez-Regueiro, Maria Esperanza Barrera-Medrano, Ricardo F. Martinez-Botas, Yossapong Laonual .....	373
ID63 - Experimental investigation of a small-scale reversible high temperature heat pump – Organic Rankine Cycle system for industrial Waste Heat Recovery Authors: Rahul Velanparambil Ravindran, Donal Cotter, Christopher Wilson, Ming Jun Huang, Neil Hewitt. ....	381
ID64 - Technical comparison and evaluation of a Pumped Thermal Energy Storage with two different designs Authors: Márcio Santos, Jorge André, Ricardo Mendes, José Ribeiro. ....	391
ID68 - The potential of CO <sub>2</sub> -Plume Geothermal (CPG) Systems for CO <sub>2</sub> component manufacturers: opportunities and development needs Authors: Christopher Schiffler, Jasper De Reus, Hartmut Spliethoff, Martin O. Saar, Sebastian Schuster, Dieter Brillert .....	400
ID69 - Development of a generalised low-order model for twin-screw compressors Authors: Florian Kaufmann, Ludwig Irrgang, Christopher Schiffler, Hartmut Spliethoff. ....	410
ID71 - Decision-making matrix for the selection of mixture in ORC applications Authors: William Combaluzier, Nicolas Tauveron, Michel Beaughon, Aldo Serafino. ....	420
ID72 - Reversible heat pump-ORC pilot plant – Experimental results and fluid charge optimization Authors: Maximilian Weitzer, Sebastian Kolb, Dominik Müller, Jürgen Karl .....	430
ID73 - Performance of Organic Rankine Cycle system in combination with residual municipal solid waste gasification: a simulation analysis Authors: Luca Cioccolanti, Giovanni Biancini, Ramin Moradi, Luca Del Zotto, Matteo Moglie .....	439
ID74 - Enhancing knowledge of engineering students at all levels on organic rankine cycle systems for their application in the built environment Authors: Luca Cioccolanti, Ramin Moradi, Ermira Abdullah, Syamimi Saadon, Mohamad Yusof Idroas, Teoh Yew Heng, Kwanchai Kraitong .....	449
ID75 - Studying carbon dioxide and acetone mixtures in a single-stage absorption-compression cycle for heating and cooling applications Authors: Jesús Gómez-Hernández, Ali Kholghi, Mercedes De Vega, Javier Villa, Ronan Grimes .....	458
ID77 - Valorising thermal composite recycling processes using Organic Rankine Cycles for combined heat and power applications Authors: Ramin Moradi, Liu Yang .....	466
ID80 – Prediction of the ideal maximum operational temperature of hydrocarbon and HFCs as working fluids of Organic Rankine Cycle power plants based on transition state theory Authors: Wei Yu, Chao Liu, Xijie Ban, Zhirong Li, Tianlong Yan .....	476
ID82 - Comparison of different evaporator topologies for industrial heat pumps Authors: Sanjay Vermani, Nitish Anand, Johan Van Bael, Evgueni Touliankine, Aldo Serafino, Carlo De Servi. ....	486

ID83 - On the plant improvement of Solar-driven ORC based power unit for domestic microcogeneration Authors: Fabio Fatigati, Marco Di Bartolomeo, Arianna Coletta, Diego Vittorini, Giammarco Di Giovine, Davide Di Battista, Roberto Cipollone. . . . .	496
ID84 - Mapping the techno-economic potential of next-generation CSP plants running on transcritical CO <sub>2</sub> -based power cycles Authors: Pablo Rodríguez-deArriba, Francesco Crespi, Sara Pace, David Sánchez . . . . .	505
ID86 - Achieving 45% micro gas turbine efficiency through hybridization with Organic Rankine Cycles Authors: Antonio Escamilla, David Sánchez Martínez, Lourdes García-Rodríguez . . . . .	515
ID88 - Operational optimisation of the main heat rejection unit of CSP plants based on carbon dioxide mixtures Authors: Francesco Crespi, Pablo Rodríguez-deArriba, Lourdes García-Rodríguez, David Sánchez. . . . .	525
ID89 - Mechanical design and rotor-dynamic analysis of the ORCHID turbine Authors: Matteo Majer, Steven Chatterton, Ludovico Dassi, Alessio Secchiaroli, Edoardo Gheller, Carlo De Servi, Paolo Pennacchi, Piero Colonna, Matteo Pini. . . . .	535
ID91 - Thermodynamic feasibility of a pumped thermal energy storage driven by ocean temperature gradient Authors: Alessandra Ghilardi, Andrea Baccioli, Guido Francesco Frate, Lorenzo Ferrari . . . .	545
ID92 - Exergy-based methods for heat pumps Authors: Mathias Hofmann, Jonas Freißmann, Malte Fritz, Jeremias H. Alexe, Francesco Witte, George Tsatsaronis . . . . .	553
ID93 - Reduced order modelling of optimized heat exchangers for maximum mass-specific performance of Airborne ORC Waste Heat Recovery units Authors: Fabio Beltrame, Dabo Krempus , Piero Colonna, Carlo De Servi. . . . .	563
ID97 - Basic design of an ORC demonstrator system for implementation in an Iron & Steel plant through the DECAGONE project Authors: Magnus Windfeldt, Han Deng, Trond Andresen, Christopher Schiffler . . . . .	574
ID98 - Analytical estimation of the presence of non-condensable gases in the condensate tank of an Organic Rankine Cycle Authors: Radheesh Dhanasegaran, Antti Uusitalo, Juha Honkatukia, Teemu turunen-Saaresti	584
ID101 - Advanced control of compressor inlet temperature in supercritical CO <sub>2</sub> Brayton cycle Authors: Rui Wang, Xuan Wang, Hua Tian, Gequn Shu. . . . .	596
ID103 - Potential for surplus-heat-to-power conversion in current and future aluminium production processes with off-gas recycling Authors: Jonas Bueie, Magnus Windfeldt, Trond Andresen. . . . .	605
ID104 - Investigating the application range of ORC power plants for the exploitation of two-phase geothermal resources Authors: Tristan Merbecks, Claudio Pietra, Paola Bombarda, Martin O. Saar, Paolo Silva, Dario Alfani. . . . .	615
ID109 - Cold Energy Recovery in LNG plants with Organic Rankine Cycle Authors: Gabriele Marchiori, Marta Giudici, Giorgia Ruffato, Marco Astolfi . . . . .	626

ID110 - Numerical investigation of organic vapor flow effects on a micro-scale radial turbocompressor Authors: Andrés Sebastián, Rubén Abbas, Manuel Valdés . . . . .	636
ID112 - Design, modeling and simulation of an experimental Rankine PTES system Authors: Mario Petrollese, Giorgio Cau, Matteo Marchionni, Marcello Lorenzo Marroccu, Rosa Merchan . . . . .	645
ID113 - Small-scale turbopumps for Waste Heat Recovery applications based on an Organic Rankine Cycles, modeling, analytical and experimental investigation Authors: Sajjad Zakeralhoseini, Jürg Schiffmann . . . . .	655
ID116 - Double-stage ORC system based on various temperature waste heat sources of the negative CO2 power plant Authors: Kamil Stasiak, Pawel Ziólkowski, Dariusz Mikielewicz . . . . .	665
ID117 - Optimization of organic Rankine cycle in ocean thermal energy conversion based on NSGA-II Authors: Zheng Hu, Jiufa Chen, Bing Guo, Chengbin Zhang . . . . .	679
ID118 - TES4Trig: Development of a demonstrator for the production of electricity, heating and cooling based on an Organic Rankine and an Ejector Cooling Cycle driven by high-temperature parabolic trough collectors with thermal energy storage Authors: Konstantinos Braimakis, Dimitrios Tziritas, George Stavrakakis, Julio Terrón Gutiérrez, Siddhart Dutta, Christos Xynos, Panagiotis Zervas, Sotirios Karellas . . . . .	689
ID119 - Simulation and operation of a CSP that works with a HRB Cycle Authors: Antonio J. Subires, Antonio Rovira . . . . .	701
ID123 - Towards a green energy community: integration of micro-ORCs combined with renewable energy technologies in buildings Authors: Diego Antonio Rodríguez Pastor, Víctor Manuel Soltero Sánchez, Elisa Carvajal Trujillo, José Antonio Becerra, Ricardo Chacartegui . . . . .	713
ID129 - Assessment of high temperature heat pump layouts equipped with a bladeless turboexpander Authors: Matteo Passalacqua, Simone Maccarini, Stefano Barberis, Alberto Traverso . . . . .	723
ID133 - Selection of the optimal working fluid in an Organic Rankine Cycle for Waste Heat Recovery through multi-objective optimization and decision making Authors: Bipul Krishna Saha, El Mouatez Billah Messini, Syed J. Hoque, B Aneesh Bhat, Pramod Kumar . . . . .	733
ID139 - Dual condensing pressure ORC for cryogenic energy storage Authors: William M. Conlon, Milton J. Venetos . . . . .	743
ID141 - Optimum coupling of thermal energy storage and power cycles for Carnot batteries Authors: Salvatore Guccione, Rafael Guedez . . . . .	751
ID142 - Aerodynamic design and numerical analysis of a counter-rotating centrifugal compressor Authors: Cheikh Brahim Abed, Arthur Leroux . . . . .	761

# POTENTIAL OF TRIGENERATIVE WASTE HEAT RECOVERY CO<sub>2</sub>-MIXTURE TRANSCRITICAL POWER PLANTS FOR INCREASING THE SUSTAINABILITY OF DISTRICT HEATING AND COOLING NETWORKS

Mattia Baiguini<sup>1,2\*</sup>, Michele Doninelli<sup>1</sup>, Ettore Morosini<sup>3</sup>, Dario Alfani<sup>3</sup>, Gioele Di Marcoberardino<sup>1</sup>, Paolo Giulio Iora<sup>1</sup>, Giampaolo Manzolini<sup>3</sup>, Costante Mario Invernizzi<sup>1</sup>, Marco Astolfi<sup>3</sup>

<sup>1</sup> *Università degli studi di Brescia, Dipartimento di ingegneria meccanica e industriale, Via Branze 38, 25123 Brescia, Italy*

<sup>2</sup> *Scuola Universitaria Superiore IUSS Pavia, Piazza Vittoria 15, Pavia, 27100, Italy*

<sup>3</sup> *Politecnico di Milano, Dipartimento di energia, Via Lambruschini 4a, 20156 Milano, Italy*

\*Corresponding Author: [mattia.baiguini@iusspavia.it](mailto:mattia.baiguini@iusspavia.it)

## ABSTRACT

The waste heat released by high-temperature processes can be exploited by power cycle designed for full electric or combined heat and power applications, with the potential to cover even the cooling demand in a trigenerative perspective. The use of CO<sub>2</sub>-based mixtures as working fluids for power cycles can be a promising solution for power production. These systems present a rejected heat in a temperature range (50–180 °C) that allows, depending on the needs, an effective coupling with a district heating and cooling network. This work investigates the potential of trigenerative system adopting CO<sub>2</sub>-based power cycles which exploit the residual thermal power of the exhaust gases of a small-scale gas turbine. First, the performances of lithium bromide absorption chiller are investigated for various heat source levels, adopting different configuration. Then, various designs of CO<sub>2</sub>-based power cycles are simulated focusing on the coupling with both the district heating and the chiller. A sensitivity analysis on the cycle minimum temperature is presented, evidencing that CO<sub>2</sub> mixtures can achieve remarkable net electric efficiency values even at high cycle minimum temperatures, marking a significant difference with respect to CO<sub>2</sub> cycles. Considering the yearly demand of district heating and cooling, keeping the electric output at design value, the economic profitability of the investment is characterized presenting the LCOE of the retrofitted solution, considered comparable with actual selling prices.

282

## 1 INTRODUCTION

The demand and production of thermal power for space heating and cooling applications rose significantly in the last decades: the International Energy Agency (IEA) reports that from 1990 to 2016 the space cooling demand has tripled, and it is mainly provided by air conditioning systems, consuming 2000 TWh of electricity per years worldwide (IEA, 2018). On the other hand, the agency highlights that fossil fuels account for the 64% of the primary energy used for space heating, with natural gas covering 42% of the share (at around 760 billion Nm<sup>3</sup> in 2021) (IEA, 2022). In this scenario polygeneration plants are crucial not only to achieve high overall efficiency, but also to save primary energy and provide flexible operations. Organic Rankine Cycles (ORC) are nowadays the most used technology for waste heat recovery from high temperature industrial process and from small gas turbine (below 500°C). (Macchi & Astolfi, 2017). In recent years, pure CO<sub>2</sub> (carbon dioxide) and CO<sub>2</sub> mixtures power cycles have been proposed as an alternative technology to ORC (and steam cycle in large size applications) thanks to the higher fluid thermal stability and the compactness of turbomachinery. These systems have been recently investigated in several European H2020 funded projects like SCARABEUS, DESOLINATION, CO<sub>2</sub>OLHEAT, SCO<sub>2</sub>FLEX and SOLARSCO<sub>2</sub>OL. A previous work (Morosini et al., 2023) underlined the advantages of coupling CO<sub>2</sub>-based power cycles with a high (180°C) and a low temperature (100°C) thermal user, in a cogenerative perspective. These results indicate a potentially

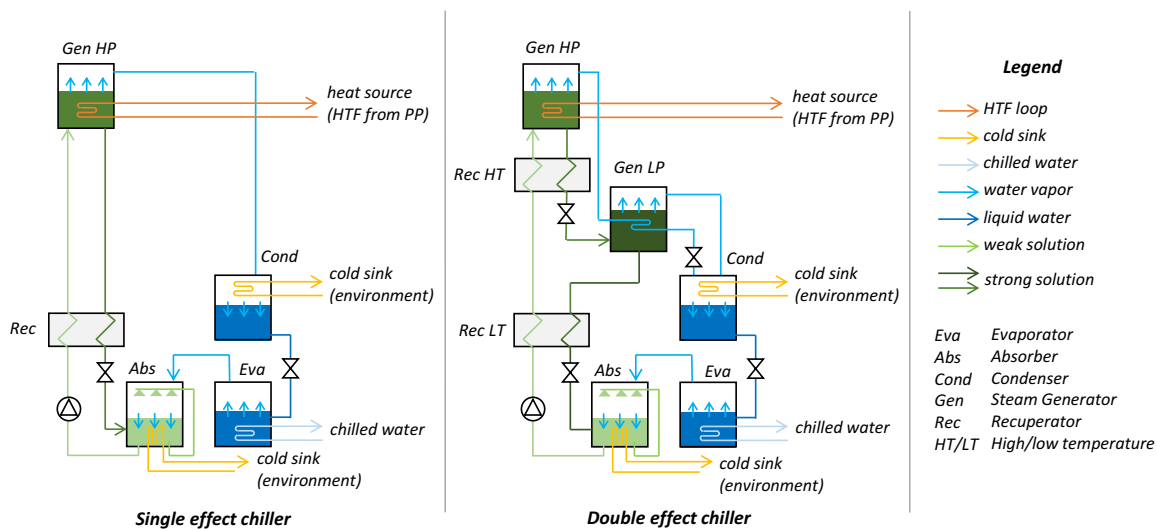


exploitable source to produce chilled water too, thus adopting both district heating and cooling networks.

The concept of trigeneration and polygeneration, using a pure CO<sub>2</sub> based power block, is well known in the literature (Bellos et al., 2022). These systems typically consider electricity, hot and cold water and hydrogen as useful outputs providing an economic analysis on the specific case study. This work aims at investigating the trigeneration potential of pure and mixture CO<sub>2</sub>-based power cycles for heat recovery applications. For this purpose, the absorption chiller (AC) is modelled to estimate the coefficient of performance (COP) of the component at various conditions. Then, different configurations of CO<sub>2</sub>-based power cycles are investigated, aiming at an effective coupling with both the DHC networks. In particular, the revamping of a plant operating with small-scale gas turbines is explored. The heat rejected from the CO<sub>2</sub> power block together with the heat recovered from low temperature exhaust gases is used to produce pressurized hot water for the district heating (DH) during winter season and chilled water for the district cooling (DC) during summer season. Finally a techno – economic analysis is carried-out comparing the original and proposed system layouts in order to minimize the differential electricity production cost. Aspen Plus® V12 (*Aspen Plus* n.d.) is selected as modeling software for all the analyses.

## 2 ABSORPTION CHILLER

An absorption chiller produces cold thermal power (typically chilled water) exploiting a low-medium temperature heat source, adopting a thermodynamic cycle with a mixture of a refrigerant and an adsorbent (Somers et al., 2011). In this work both single effect AC (SEAC) and double effect AC (DEAC) are investigated using H<sub>2</sub>O-LiBr (lithium bromide) mixture as working fluid.



**Figure 1:** Absorption chiller layout: single effect (left) and double effect (right).

Typically, SEAC works at lower pressures (up to 10 kPa) in the vapor generator and exploits heat source temperatures lower than 100°C, leading to COP values of around 0.7. Meanwhile, DEAC and multi effect AC work at higher pressure levels (up to 100 kPa), heat source temperature up to 160°C–180°C, generally resulting in COP above 1 (Somers et al., 2011). In a SEAC (Figure 2 left), the pumped mixture is pre-heated in a recuperator and then heated by the hot source in the generator, up to a partial evaporation, depending on temperature and pressure. The LiBr-rich flow (strong solution) is conveyed to the recuperator, depressurized and fed to the absorber. The generated vapour is first condensed using ambient air as cold sink and expanded down to the evaporation pressure. The pressure levels are set by saturation conditions at the temperature  $T_{cond}$  and  $T_{eva}$ . In the evaporator, cold thermal power is produced typically by cooling down chilled water. The refrigerant enters the adsorber where is mixed with the strong solution, cooled down and send to the pump. In the DEAC solution (Figure 2, right), a layout with two generators in series at different pressure levels is adopted since this layout allowed the

employment of only one pump is adopted (Farshi et al., 2012). As shown in Figure 2 the strong solution exits from the high-pressure generator and it is expanded to an intermediate pressure, corresponding to condensation pressure. Then the evaporated water and strong solution flow into the components previously presented. The advantage of the double effect is to separate more water from the solution, thus increasing the cooling capacity and COP. The H<sub>2</sub>O-LiBr mixture is modelled with the ELECNRTL pre-defined package in ASPEN Plus, as suggested in literature (Somers et al., 2011). The boundary conditions and assumptions, which are consisted with other works (Somers et al., 2011) (Farshi et al., 2012), for the simulation of the AC are reported in Table 1.

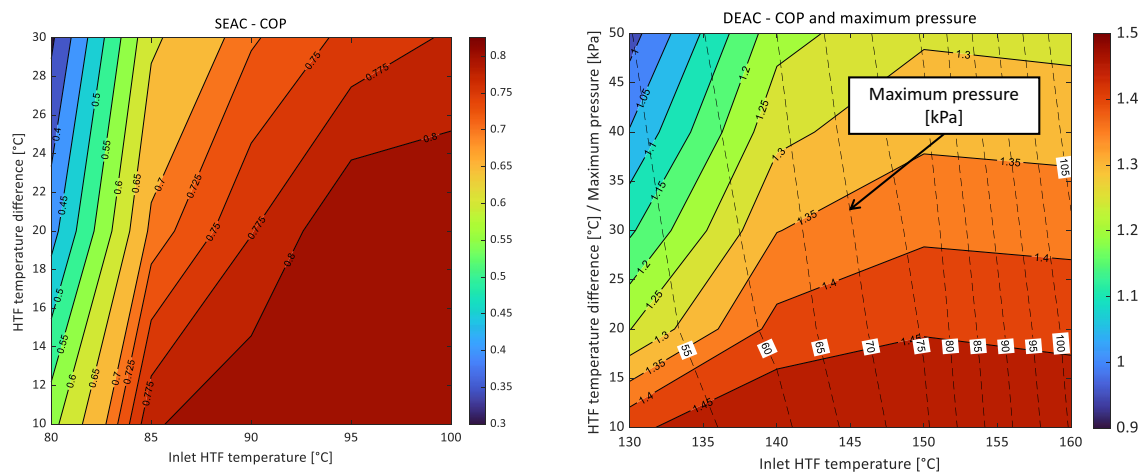
**Table 1:** Simulation boundary conditions and assumptions for the absorption chiller

Chiller Parameter	
Condensation conditions, $T_{cond}/P_{cond}$	40 °C / 7.38 kPa
Evaporation conditions, $T_{eva}/P_{eva}$	3 °C / 0.75 kPa
LiBr concentration (massic)	55%
Minimum approach temperature difference in the generators	5 °C
Pitch point temperature difference in the generators	5 °C
Temperature approach for DC-AC	3 °C

The thermal power is provided by pressurized water that works as heat transfer fluid (HTF). The analysis consists in identify the COP, defined in Eq. (1) as the ratio between the cooling capacity  $\dot{Q}_{CC}$  and the thermal input  $\dot{Q}_{HTF}$ , for various conditions of the HTF, neglecting the electric consumption of the pump (Osta-Omar & Micallef, 2016).

$$COP = \frac{\dot{Q}_{CC}}{\dot{Q}_{HTF}} \quad (1)$$

An optimization analysis is carried out on the maximum pressure of the double effect cycle to find the best value of COP for each HTF maximum temperature ( $T_{HTF,in}$ ) and HTF temperature difference ( $\Delta T_{HTF}$ ), compatible with system constraints. In fact, according to the Dühring chart, crystallization phenomena occurs when the mass concentration of LiBr is above 65% (Salehi et al., 2019). For this reason, the maximum pressure level must be compatible with this threshold to prevent pipes and components clogging. The resulting trends of the COP for both configurations are reported in Figure 2.



**Figure 2:** Absorption chiller COP: single effect (left) and double effect (right)

For both categories of AC, higher COP are computed at high  $T_{HTF,in}$  and low  $\Delta T_{HTF}$  (close to isothermal hot source), with a flat response over a certain value of  $T_{HTF,in}$ , equal to 95°C and 150°C for the SEAC and DEAC, respectively. As in the SEAC the pressure level is fixed by the condensation condition, increasing the  $T_{HTF,in}$  corresponds to a higher vapor fraction leading to a higher cooling capacity. Situations in which the  $\Delta T_{HTF}$  is low also correspond to conditions in which the internal regeneration of the AC is greatest. Therefore, at high  $T_{HTF,in}$  the COP is favoured by greater steam production and,



at the same time, by less  $\dot{Q}_{HTF}$  introduction at low  $\Delta T_{HTF}$ . In the DEAC, every case is optimised maximising the COP and varying the maximum pressure, so this effect is not evident and it is possible to achieve a COP in the range between 1.25 and 1.45 even with relatively low  $T_{HTF,in}$  and large  $\Delta T_{HTF}$ . In the DEAC the optimum high pressure varies from 50 kPa to 105 kPa and for each case, the limit is set due the reaching of the crystallization constraint.

### 3 CASE STUDY

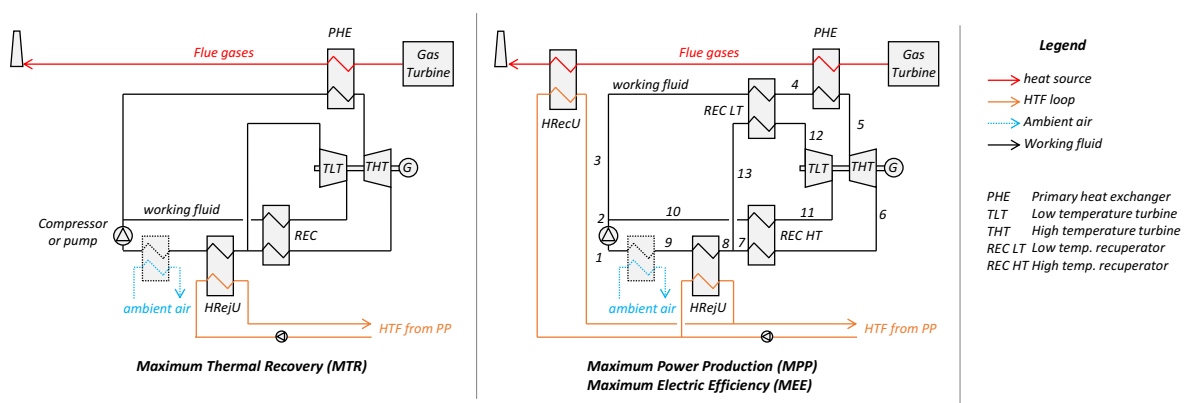
An existing trigeneration power plant, located in the city of Milan (A2A, 2023), is selected as case study. In Table 2 the components and the power balance of the system are listed. The electric power is produced by two Taurus 60S-7801 5MWe gas turbines by Solar Turbine (Taurus 60, n.d) each one powered by natural gas with an input thermal power of 17 MW. The expander outlet temperature is 510°C and the flue gas mass flow rate is 43.22 kg/s. In this study, the heat recovery units and the compressors chiller are replaced by a trigenerative CO<sub>2</sub> based power cycle for additional electricity production.

**Table 2:** Trigeneration power plant components

Components	Power
Gas turbines	10 MWe
Heat recovery steam generator	16 MWth
Compressor chillers	7.5 MWth

#### 3.1 CO<sub>2</sub> power cycles

For the power cycles analysis, the stack temperature is set to 120°C leading to an available thermal power ( $\dot{Q}_{fg}$ ) of 18.33 MW from both turbines at full load. The flue gas directly releases heat to the working fluid with a minimum temperature approach of 30°C in the primary heat exchanger (PHE) thus avoiding the use of a high temperature HTF loop. The cascade cycle is selected for this application as suggested by a previous work (Morosini et al., 2023) and it is here proposed in two different architectures (Figure 3) differing in one recuperator with the aim to consider three different design criteria: maximization of thermal recovery (MTR) namely ensure a complete exploitation of the heat source from the power plant, maximization of the power production (MPP) and maximization electric efficiency (MEE). Each cycle is investigated with both pure CO<sub>2</sub> in supercritical cycle and mixture of CO<sub>2</sub> and dopant in transcritical cycle.



**Figure 3:** Cascade Cycle. MTR configuration (left), MPP/MEE (right)

MTR cycle adopts only one recuperator to exploit the heat available from high temperature turbine exhaust for heating the fluid expanded by the low temperature turbine. As result the heat introduction process starts right after the compressor (pure CO<sub>2</sub> cycle) or the pump (CO<sub>2</sub> mixtures), allowing for a complete cooling of the heat source in the power cycle heat introduction process and leading to a heat

source recovery factor ( $\chi = \dot{Q}_{PHE}/\dot{Q}_{fg}$ ) equal to 1. The heat rejected by the cycle is recovered in the HRejU unit by heating up a HTF loop (Figure 3). On the contrary MPP and MEE cycles adopt an additional recuperator that allows to preheat the high temperature working fluid loop fluid before the heat introduction by cooling down the hot working fluid released by the low temperature turbine. In this case, the internal heat recovery is improved allowing to increase the cycle thermodynamic efficiency at the expense of the heat source recovery factor. As a result, the heat source is not totally exploited and thus after the power plant utilization it can still release heat to the HTF loop in the HrecU unit (Figure 3). A sensitivity analysis is carried out on the minimum cycle temperature ( $T_{min,cy}$ ) between 50°C and 70°C considering ambient air as cold sink when the plant is not working in cogenerative mode or when a fraction of the rejected thermal power cannot be used for HTF heating. For each design criteria (MTR, MPP, MEE), for each minimum temperature and for both pure CO<sub>2</sub> and blended CO<sub>2</sub>, the power plant (for a total number of 30 cases) is optimized with the aim to maximize the electric power for MTR (while guaranteeing  $\chi = 1$ ) and MPP architectures and to maximize electric efficiency for MEE one. The following design parameters are varied to identify the optimal design: i) minimum pressure which impacts on the dopant molar fraction for working fluid blends, ii) split fraction after the pump and iii) maximum cycle temperature. Table 3 reports the assumed values for the analysis: turbomachinery efficiencies refer to small-scale applications, while a maximum pressure (250 bar) is necessary in order to do not penalize the performance (Alfani et al., 2021) (Morosini et al., 2023).

**Table 3:** Power block parameters

<b>Cycle Parameter</b>	
Cycle maximum pressure	250 bar
PHE minimum temperature approach	30 °C
Recuperators pinch point (MITA)	10 °C
Pressure drops (PHE/HRecU and HRejU)	3/1 bar
Pressure drops recuperator (HP/LP)	1/2 bar
Isentropic efficiency (expander/compression)	85/80 %
Generator/Motor efficiency, $\eta_{g/m}$	97/97 %

286

Table 4 provides the properties for the chosen working fluids. Hexafluorobenzene (C<sub>6</sub>F<sub>6</sub>) is the selected dopant because its high thermal stability (up to 600°C) and the mixture is modelled with the Peng Robinson EoS (Di Marcoberardino et al., 2022). Differently, CO<sub>2</sub> is modelled with the Span and Wagner EoS (Span & Wagner, 1996).

**Table 4:** Pure fluids and mixture properties

<b>Fluids</b>	<b>Molar weight</b> [kg/kmol]	<b>T<sub>cr</sub></b> [°C]	<b>P<sub>cr</sub></b> [bar]	<b>Binary interaction parameter</b> [-]
CO <sub>2</sub>	44.01	31.06	73.83	$k_{ij} = 0.16297 - 0.0003951 \cdot T [K]$
C <sub>6</sub> F <sub>6</sub>	186.06	243.58	32.73	

### 3.2 District heating and cooling system

The water for DH is supplied at 95°C and has a return temperature of 60°C (Mise, 2020) and the provided temperature range for the chilled water is from 6°C to 12°C (AIRU - Annual Report, 2022). An intermediate loop (IL) of heat transfer fluid is implemented to avoid direct heat transfer between the power plant working fluid and both the district heating water or the absorption chiller mixture, as proposed in Figure 3. The temperature limits of the IL must be compatible with the source and utilization range; therefore, the selected IL range is defined once the temperature range of working fluid and gases are computed. A minimum temperature approach of 10°C is always considered in each heat exchanger.

### 3.3 Key Performance Indicators

The performance of the power plant is evaluated through the electrical efficiency  $\eta_{el}$  and the differential levelized cost of electricity (LCOE). The first is defined in Eq. (2).

$$\eta_{el} = \frac{\sum \dot{W}_{TURB} \cdot \eta_{g/m} - \dot{W}_{pump/comp}/\eta_{g/m}}{\dot{Q}_{PHE}} = \frac{\dot{W}_{el}}{\dot{Q}_{PHE}} \quad (2)$$

From the economical point of view, the goal is finding the layout and the design parameters that minimize the differential LCOE related to the installation of the CO<sub>2</sub> based power plant with respect to a reference case where the electric power is produced only with the gas turbines and the hot and cold thermal power are produced from a total exploitation of the exhaust gases sensible content ( $\dot{Q}_{fg}$ ), and the second, representing the solution proposed in this work. Therefore, the yearly differential cost considers the annualized investment cost of the power block (*Capex*), the operating costs (*O&M*) and the profit loss related to the reduced fraction of hot and cold thermal power with respect to the reference scenario because of electrical power production. LCOE is expressed as follow:

$$LCOE = \frac{Capex \cdot CRF + O\&M + \Delta E_{hot} \cdot LCOH + \Delta E_{cold} \cdot LCOC}{8760 \cdot u_{el} \cdot \dot{W}_{el}} \quad (3)$$

The *Capex*, corresponding to the sum of the equipment and Balance of Plant (BoP) costs, is calculated according to Weiland et al (Weiland et al., 2019), and the correlation of Wright et al (Wright et al., 2016) only for the gas-CO<sub>2</sub> PHE. The specific *O&M* is 30 \$/kW and the BoP cost are the 30% of the total equipment cost (Marchionni et al., 2018). *LCOH* is the Levelized Cost Of Heating and it is equal to 80 \$/MWh (Næss-Schmidt et al., 2021), while the Levelized Cost Of Cooling (LCOC) is calculated by using the correlations and assumptions proposed by Correa et al (Correa-Jullian et al., 2019): assuming a COP of 1.3, LCOC is equal to 40 \$/MWh. The utilization factor *u* is 91% (corresponding to 8000h/year) while heat for DH is required for 41% of the running hours (15 weeks/year) and heat for the absorption chiller 24% of the running hours (9 weeks/year). The capital recovery factor (CRF) is 7.8%.  $\Delta E_{hot}$  and  $\Delta E_{cold}$  are the reduction of thermal energy and cooling energy with respect to the reference case.

287

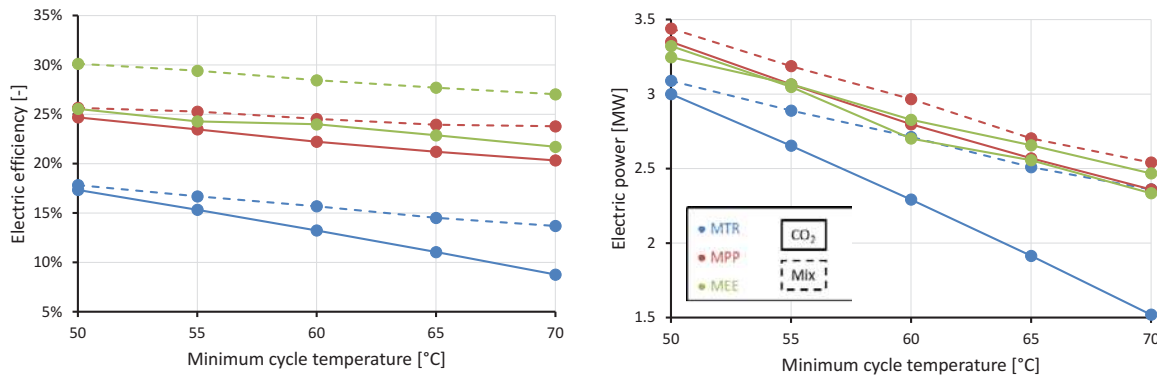
## 4 RESULTS AND DISCUSSION

### 4.1 Considerations on Cycle optimization

For the MTR and MPP conditions (pure CO<sub>2</sub>), optimal cycle minimum pressure is rather constant while reducing the cycle maximum temperature has two opposing effects: from one hand it allows to increase the heat input to the cycle by reducing the recuperator outlet temperature, while, on the other hand, it implies a reduction of cycle efficiency. However, the two effects are nearly balanced and the power output varies by less than 1.5% in the cycle maximum temperature optimal range between 440°C and 480°C. For MEE the highest cycle efficiency corresponds to a turbine inlet temperature of 480°C (compatible with the minimum temperature approach in PHE). Results reported in this paper refer only to the optimal cases and nominal conditions.

## 4.2 Power Cycle Performance

Figure 4 depicts the trend of electric efficiency and power output for all the cycle combination varying the cycle minimum temperature.



**Figure 4:** Electric efficiency (left) and electric generation (right)

Increasing the  $T_{min,cy}$  implies a penalization of the cycle performance due to the increase of fluid specific volume (for pure CO<sub>2</sub> cycles) and reduction of the pressure ratio (blended CO<sub>2</sub>) but the effect is more marked for the pure CO<sub>2</sub> cases since transcritical cycles always benefit by a fluid pressurization in liquid state that is less affected by change in the working fluid volumetric behavior. Among the different cycles configuration, the MTR cycle with CO<sub>2</sub> is the most penalized one since the need of ensuring a complete heat source cooling in the PHE which results in a limitation of the cycle pressure ratio and leads to cycle minimum pressures higher than the optimal one: all these effects are exacerbated when the cycle minimum temperature increases. While the use of pure CO<sub>2</sub> always leads to the lowest efficiency and power production it is interesting to note that the MTR cycle with CO<sub>2</sub> mixture for high cycle minimum temperature can get a power output close to the other cycles because the lower efficiency is compensated by and higher recovery factor with respect to both MPP and MEE configurations. The complete cascade cycle featuring also the second recuperator in both MPP and MEE cases outperform the MTR thanks to a more effective regeneration. In the MEE case, the TIT (Turbine Inlet Temperature) is set to the maximum value of 480°C, compatible with the constraint on the minimum pinch temperature at the PHE, justifying the highest electric efficiency. At the same TIT, the mixture has higher thermodynamic efficiency (around +3%) thanks to more balanced heat capacities within the recuperators. However pure CO<sub>2</sub> takes advantage of the lower PHE inlet temperature due to an unbalanced recuperator, experiencing higher electrical output. This effect is true only at low cycle minimum temperature, while at high temperatures an evident efficiency drops of pure CO<sub>2</sub> compared to the mixture can be noticed due to the increase of the compressibility factor. As regards the MPP strategy, which represents the trade-off between the heat source cooling grade and the cycle efficiency, the mixture outperforms pure CO<sub>2</sub> even if the optimal TIT is around 10°C lower to provide a more effective heat source cooling, without involving a substantial cycle efficiency penalization. In fact, pure CO<sub>2</sub> suffers both the distance from the critical point and the unbalanced recuperators, while the mixture keeps the benefits of liquid compression and balanced heat capacities by varying the composition.

## 4.3 Hot and cold power nominal availabilities

Thermal power is released by the system to the IL through the HRecU and HRejU units that completes the flue gas cooling down to stack temperature and collects the useful heat released by the cycle respectively. The amount of heat collected by each unit depends on the specific cycle layout, the optimization strategy, and minimum cycle temperature, as shown in Figure 5 for 50°C and 70°C cycle minimum temperature cases. Moreover Figure 6 summarizes the resulting annual produced energy. In the MTR configuration, the entire thermal duty of the sensible heat source is provided to the cycle through the PHE and exploited with a relatively-low cycle efficiency compared to the other layouts considered (Figure 3), but the amount of rejected thermal power from the HRejU unit is considerable as represented in Figure 5. The good temperature level (above 180°C of the rejected heat) provided by the MTR configuration allows the exploitation of the total duty for DH and DC purposes, depending on

the seasonal need. Above 100°C the HRejU is used in a DEAC, while the fraction below 100°C in a SEAC, with COP evaluated according to the maps in Figure 2.

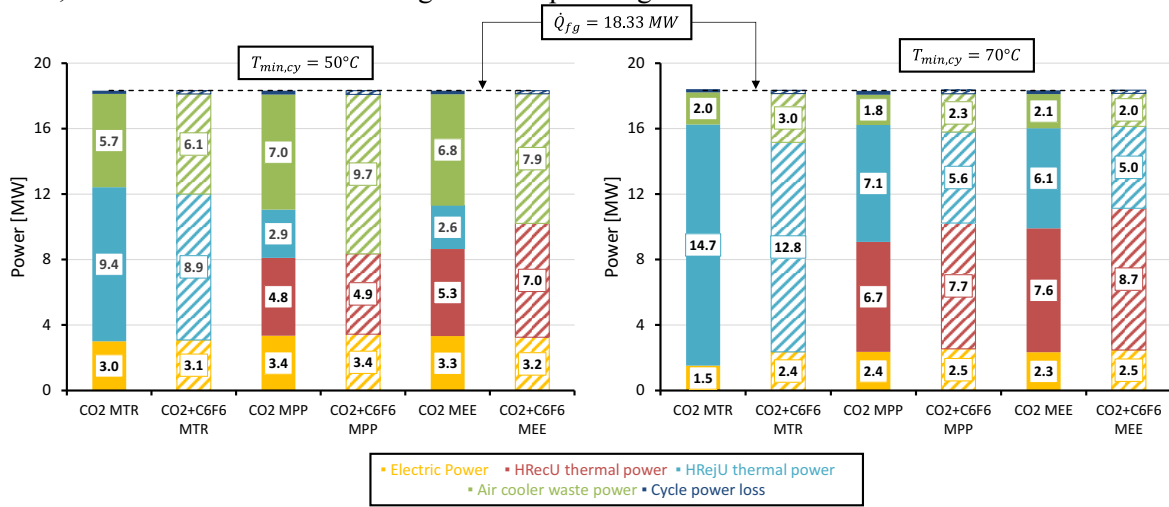


Figure 5: Power balance for  $T_{min,cy} = 50^\circ C$  (left) and  $T_{min,cy} = 70^\circ C$  (right) in winter season.

On the other hand, the MEE and MPP configurations present a good fraction of thermal power available also from the HRecU at high temperatures (above 220°C), that can be entirely used for DH and DC through a DEAC. As regards the HRejU unit of these configurations, the thermal duty available for DH purposes strongly depends on the cycle minimum temperature since the required temperature range for the intermediate HTF is 70-100°C. Due to this limitation, an air cooler is always necessary to dissipate the residual thermal power. Instead, in summer season, the terminal temperatures of the HTF loop can be adjusted to exploit the entire rejected duty in a SEAC, with an associated COP depending on the specific temperature range and the air cooler is not required. As highlighted in Figure 6, the best annual energy production is reached with the mixture in MEE strategy at 70°C minimum temperature, mainly due to better thermodynamic efficiency compared to CO<sub>2</sub> and higher valuable heat at the HrecU for DC and DH.

289

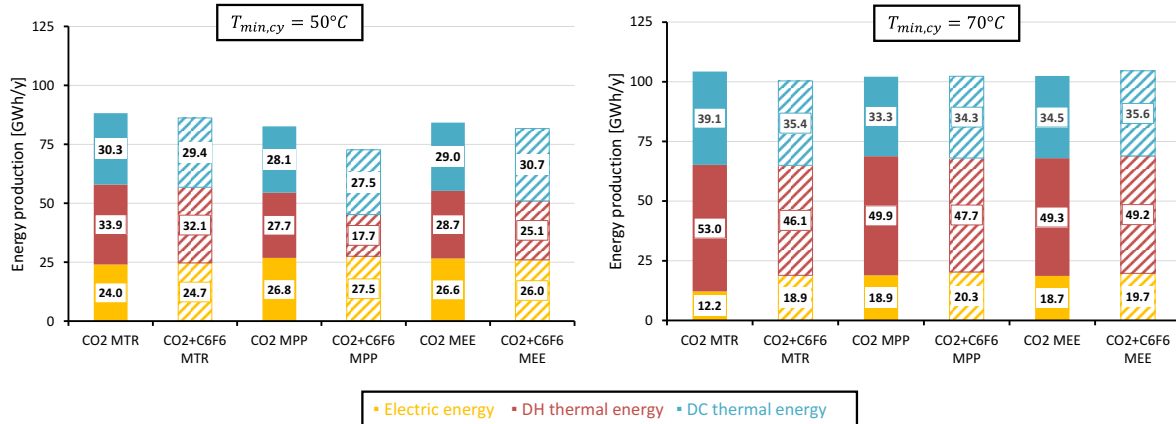


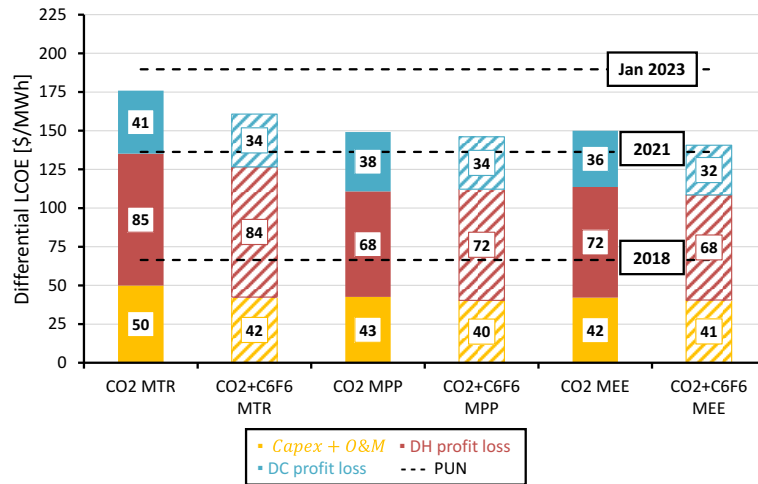
Figure 6: Annual energy production for  $T_{min,cy} = 50^\circ C$  (left) and  $T_{min,cy} = 70^\circ C$  (right).

#### 4.4 Differential LCOE

Previous results suggests that the cycles operating with a minimum cycle temperature of 70°C are reasonably the most promising ones since they allow to heat rejection to the environment during both summer and winter season, thus only this case is considered in this preliminary economic analysis. Figure 7 shows the resulting differential LCOE of the different cases, as expressed in Eq. (3), highlighting the *Capex* and *O&M* costs and the costs relating to the missed selling of heat and cold. Considering the annual energy balance depicted in Figure 6 (right), the higher electricity output



produced by the mixture based cycles, with respect to the cycle operating with pure fluid, lead to a reduction of the LCOE. On the other hand, the CO<sub>2</sub> MTR case of is characterized by the minimum  $\Delta E_{hot}$  and  $\Delta E_{cold}$  because of the highest annual thermal production. Nevertheless, the annual electric production mainly affects the differential LCOE. Considering only electricity as output, all the analyzed cases are economically viable compared to different Italian electric gross prices (PUN – Prezzo Unico Nazionale) (GME, 2023), however the cases that has a lower electric energy generation are the most penalized.



**Figure 7:** Differential LCOE for  $T_{min,cy} = 70^{\circ}C$  cases compared to the Italian PUN.

MPP configuration has the lowest specific power cycle cost ranging from 3736 \$/kW for the mixture to 4723 \$/kW for CO<sub>2</sub> since the larger power production is not obtained with a substantial increase of equipment cost with respect to the MEE case. MTR case is on the contrary the most penalized one since it does not maximize power production and uses large heat exchangers to provide complete heat source cooling leading to a cost of 176 \$/MWh. Also accounting for profit losses due to the missed selling of heating and cooling due to power production the LCOE strongly increases leading to final values that are up to three times higher than the LCOE due to only *Capex* and *O&M* costs. MEE case with mixture has the lowest differential LCOE with values around 140 \$/MWh. The studied trigeneration plant is economically feasible for PUN related to the recent years where the geopolitical circumstances lead to a very variable natural gas price and the relative PUN. On the contrary, adopting lower PUN prices related to a more stable global situation the installation of a cogenerative power plant would require incentives or the application of carbon tax to fossil fuel use to be economically competitive as generally true for any cogenerative power system.

## 5 CONCLUSIONS

In this paper, a theoretical revamp of a trigeneration plant is presented. By first analyzing the H<sub>2</sub>O-LiBr absorber, it is possible to quantify the COP at different heat source condition. Then, simulations were carried out on a heat recuperative plant with different designs using CO<sub>2</sub> and a CO<sub>2</sub> mixture as working fluids. The maximum thermal recovery configuration in the PHE has higher thermal energy production comparing MPP and MEE, however on the economic aspect, the MTR presents a high differential LCOE due to the lowest electric energy production. The MPP strategy ensures high electric production and it proves to be the ideal approach when only energy production is considered as useful outcomes. However, for trigenerative scopes, the MEE configuration presents a good compromise between outputs and investment cost. The mixture of CO<sub>2</sub> and C<sub>6</sub>F<sub>6</sub> is preferable with respect to pure CO<sub>2</sub>.

## NOMENCLATURE

### Acronyms

AC	Absorption Chiller
BoP	Balance of Plant
Capex	Capital Expenditure
COP	Coefficient Of Performance
CRF	Capital Recovery Factor
DC	District Cooling
DEAC	Double Effect Absorption Chiller
DH	District Heating
ELECNRTL	Electrolyte-NRTL
HRecU	Heat Recovery Unit
HRejU	Heat Rejection Unit
HTF	Heat Transfer Fluid
IL	Intermediate Loop
IEA	International Energy Agency
MITA	Minimum Internal Temperature
Approach	
MPP	Maximum Power Production
MEE	Maximum Electric Efficiency
MTR	Maximum Thermal Recovery
O&M	Operation & Maintenance
PHE	Primary Heat Exchanger
PUN	Prezzo Unico Nazionale
SEAC	Single Effect Absorption Chiller
TIT	Turbine Inlet Temperature

### Roman and Greek letter

$P$	Pressure	bar/kPa
$\dot{Q}$	Thermal power	MW
$T$	Temperature	°C
$\dot{W}$	Mechanical Power	MW
$\Delta T$	Temperature difference	°C
$\eta$	Efficiency	(-)
$\chi$	Recovery factor	(-)

### Chemical formula

$CO_2$	Carbon Dioxide
$C_6F_6$	Hexafluorobenzene
$H_2O$	Water
$LiBr$	Lithium Bromide

### Subscript

comp	compressor
cond	condensation
cy	cycle
el	electric
eva	evaporation
fg	flue gases
g	generator
m	motor
min	minimum
pump	pump
turb	turbine



## APPENDIX A

**Table 5:** Streams thermodynamic properties for the best economic case for pure fluid and mixture. For the mixture case the dopant fraction is 19%.

Stream	CO <sub>2</sub> + C <sub>6</sub> F <sub>6</sub> MEE Case				CO <sub>2</sub> MPP Case			
	Flow [kg/s]	T [°C]	P [bar]	Vapor Frac. [-]	Flow [kg/s]	T [°C]	P [bar]	Vapor Frac. [-]
1	66.1	70	93.5	0	72.7	70	118	1
2	66.1	93.9	254	0	72.7	129.8	254	1
3	35.7	93.9	254	0	38.5	129.8	254	1
4	35.7	278.5	253	1	38.5	236.8	253	1
5	35.7	480	250	1	38.5	470	250	1
6	35.7	412.8	97.9	1	38.5	390.3	122	1
7	35.7	118.6	96.9	0.71	38.5	139.8	120	1
8	66.1	114.3	95.9	0.67	72.7	139.8	120	1
9	66.1	80	94.9	0.28	72.7	80	119	1
10	30.4	93.2	254	0	34.2	129.8	254	1
11	30.4	400.8	253	1	34.2	379.3	253	1
12	30.4	334.4	96.9	1	34.2	303.3	122	1
13	30.4	109.6	95.5	0.64	34.2	139.8	120	1

## REFERENCE

- International Energy Agency, I. (n.d.). *The Future of Cooling Opportunities for energy-efficient air conditioning Together Secure Sustainable*. Retrieved March 7, 2023, from [www.iea.org/t&c/AIRU-the-Italian-District-Heating-Association-promotes-and-spreads-the-application-and-innovation-of-energy-installations-in-district-heating-systems](http://www.iea.org/t&c/AIRU-the-Italian-District-Heating-Association-promotes-and-spreads-the-application-and-innovation-of-energy-installations-in-district-heating-systems). (n.d.). [www.ecoline.it](http://www.ecoline.it)
- Alfani, D., Binotti, M., Macchi, E., Silva, P., & Astolfi, M. (2021). sCO<sub>2</sub> power plants for waste heat recovery: design optimization and part-load operation strategies. *Applied Thermal Engineering*, 195, 117013. <https://doi.org/10.1016/J.APPLTHERMALENG.2021.117013>
- Aspen Plus | Leading Process Simulation Software | AspenTech. (n.d.). Retrieved April 11, 2023, from <https://www.aspentech.com/en/products/engineering/aspens-plus>
- Bellos, E., Said, Z., Lykas, P., & Tzivanidis, C. (2022). A review of polygeneration systems with CO<sub>2</sub> working fluid. *Thermal Science and Engineering Progress*, 34, 101435. <https://doi.org/https://doi.org/10.1016/j.tsep.2022.101435>
- Correa-Jullian, C., Crespo, A., Cortés, F., & Ibarra, M. (2019). *Simulation of a Solar Fired Absorption System for a Case Study in the Dairy Industry*. 1–10. <https://doi.org/10.18086/EUROSUN2018.04.16>
- Di Marcoberardino, G., Morosini, E., Di Bona, D., Chiesa, P., Invernizzi, C., Iora, P., & Manzolini, G. (2022). Experimental characterisation of CO<sub>2</sub> + C<sub>6</sub>F<sub>6</sub> mixture: thermal stability and vapour liquid equilibrium test for its application in transcritical power cycle. *Applied Thermal Engineering*, 118520. <https://doi.org/10.1016/j.applthermaleng.2022.118520>
- Farshi, L. G., Seyed Mahmoudi, S. M., Rosen, M. A., & Yari, M. (2012). *Use of low grade heat sources in combined ejector-double effect absorption refrigeration systems*. <https://doi.org/10.1177/0957650912446902>
- IEA. (2022). *Heating*. <https://www.iea.org/reports/heating>
- Macchi, E., & Astolfi, M. (2017). *Organic Rankine Cycle (ORC) Power Systems - 1st Edition* (1st Editio). <https://doi.org/https://doi.org/10.1016/C2014-0-04239-6>
- Marchionni, M., Bianchi, G., & Tassou, S. A. (2018). Techno-economic assessment of Joule-Brayton cycle architectures for heat to power conversion from high-grade heat sources using CO<sub>2</sub> in the supercritical state. *Energy*, 148, 1140–1152. <https://doi.org/10.1016/J.ENERGY.2018.02.005>
- MISE. (2020). *Progetto modifica della Centrale di teleriscaldamento di Milano Bicocca, localizzata nel Comune di Milano - Info - Valutazioni e Autorizzazioni Ambientali - VAS - VIA - AIA*. <https://va.mite.gov.it/it-IT/Oggetti/Info/7576>
- Morosini, E., Doninelli, M., Alfani, D., Astolfi, M., Di Marcoberardino, G., & Manzolini, G. (2023). Analysis of the potential of CO<sub>2</sub> based mixtures to improve the efficiency of cogenerative waste heat recovery power plants. *5th European SCO<sub>2</sub> Conference for Energy Systems: March 14-16, 2023, Prague, Czech*

- Republic*, 169–178. <https://doi.org/10.17185/DUEPUBBLICO/77287>
- Næss-Schmidt, S., Jensen, H. N., & Jasper, L. (2021). *District heating tariffs in Europe. Comparison of tariffs and regulation in Europe*. April, 1–36. <https://open.overheid.nl/repository/ronl-ec66e0006b7e0acc22629091d63b448a4af5b0c3/1/pdf/heating-tariffs-in-europe.pdf>
- Osta-Omar, S. M., & Micallef, C. (2016). Mathematical Model of a Lithium-Bromide/Water Absorption Refrigeration System Equipped with an Adiabatic Absorber. *Computation 2016, Vol. 4, Page 44, 4(4)*, 44. <https://doi.org/10.3390/COMPUTATION4040044>
- Salehi, S., Yari, M., Mahmoudi, S. M. S., & Farshi, L. G. (2019). Investigation of crystallization risk in different types of absorption LiBr/H<sub>2</sub>O heat transformers. *Thermal Science and Engineering Progress, 10*, 48–58. <https://doi.org/10.1016/J.TSEP.2019.01.013>
- Somers, C., Mortazavi, A., Hwang, Y., Radermacher, R., Rodgers, P., & Al-Hashimi, S. (2011). Modeling water/lithium bromide absorption chillers in ASPEN Plus. *Applied Energy, 88(11)*, 4197–4205. <https://doi.org/10.1016/J.APENERGY.2011.05.018>
- Span, R., & Wagner, W. (1996). A new equation of state for carbon dioxide covering the fluid region from the triple-point temperature to 1100 K at pressures up to 800 MPa. *Journal of Physical and Chemical Reference Data, 25(6)*, 1509–1596. <https://doi.org/10.1063/1.555991>
- Weiland, N. T., Lance, B. W., & Pidaparti, S. R. (2019). SCO<sub>2</sub> power cycle component cost correlations from DOE data spanning multiple scales and applications. *Proceedings of the ASME Turbo Expo, 9*. <https://doi.org/10.1115/GT2019-90493>
- Wright, S., ... C. D.-F. I. S., & 2016, undefined. (2016). Thermo-economic analysis of four sCO<sub>2</sub> waste heat recovery power systems. *Sco2symposium.Com*. <http://sco2symposium.com/papers2016/SystemModeling/059paper.pdf>

### ACKNOWLEDGEMENT

This publication was produced while attending the PhD programme in *PhD in Sustainable Development And Climate Change* at the University School for Advanced Studies IUSS Pavia, Cycle XXXVIII, with the support of a scholarship financed by the Ministerial Decree no. 351 of 9th April 2022, based on the NRRP - funded by the European Union - NextGenerationEU. (web site [phd-sdc.it](http://phd-sdc.it)).

This study was carried out within the *NEST - Network 4 Energy Sustainable Transition* (D.D. 1243 02/08/2022, PE00000021) and received funding under the National Recovery and Resilience Plan (NRRP), Mission 4 Component 2 Investment 1.3, funded from the European Union - NextGenerationEU. This manuscript reflects only the authors' views and opinions, neither the European Union nor the European Commission can be considered responsible for them.



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.