

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)

4th to 6th

SEPTEMBER

SEVILLE 2023

 **eus** EDITORIAL
UNIVERSIDAD DE SEVILLA

Sevilla, 2024

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 7th 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 licencianta 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 licencianta.

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

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 ₂ 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 Giostri, 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 Giostri	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 ₂ 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 ₂ -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 ₂ -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 ₂ -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 Laoonual	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 ₂ -Plume Geothermal (CPG) Systems for CO ₂ component manufacturers: opportunities and development needs Authors: Christopher Schiffelechner, 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 Schiffelechner, 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 Toulankine, 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 ₂ -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 ₂ 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 Ziolkowski, 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 Guede	751
ID142 - Aerodynamic design and numerical analysis of a counter-rotating centrifugal compressor Authors: Cheikh Brahim Abed, Arthur Leroux	761

INVESTIGATING R1234ZE AND R1234YF AS REPLACEMENTS TO R134A IN WASTE HEAT RECOVERY ORC APPLICATIONS

James Bull*, James Buick, Jovana Radulovic

¹ *University Of Portsmouth, Anglesea Rd, Portsmouth PO1 3DJ*

*Corresponding Author: james.bull@port.ac.uk

ABSTRACT

The ever-growing energy demand across the globe puts significant pressure on the power generation sector to find renewable and sustainable alternatives to fossil fuels. Organic Rankine Cycle (ORC) technology can be applied to low-medium temperature heat sources to generate useful work. In this paper, an ORC cycle, powered by a medium temperature exhaust gas at 423.15 K, is modelled. Working fluids R1234ze and R1234yf were compared as replacements to R134a and considered across a variety of operating conditions comparing both the energetic and exergetic performance. Sizing of heat exchangers (evaporator and condenser) has also been undertaken. Following a comprehensive evaluation, R1234ze is recommended as a viable replacement to R134a, specifically regarding the pump and turbine performance.

1 INTRODUCTION

Increasing global energy demand has put significant strain on the energy sector to find alternative sources to the finite fossil fuels in order to reduce global warming and ozone depletion. Researchers have concentrated on two primary strategies to tackle these challenges: enhancing the utilization of renewable and sustainable energy sources and optimizing the efficiency of energy systems to maximize energy utilization from a source.

The five main renewable energy sources can be categorized into the following; hydropower, biomass, solar, wind and geothermal. Hydropower has the greatest benefit within energy storage systems due to large capacity and low cost, however in many cases it requires an initial resource investment to create the storage in the first place (Zhao et al., 2022). Biomass energy plays a significant role in eliminating fossil fuel use, specifically in countries with an abundance of bioresources (Vallios et al., 2009). Solar, wind and geothermal energy are all important renewable energy sources with high potential for energy generation. Li et al. (2015) compared the use of geothermal power plants against the solar and wind generation systems and identified significant advantages for the former. Specifically, geothermal power generation demonstrated greater stability in power output in higher capacity with a lower ecological effect. Bett and Thornton (2016) further supported this when analyzing the impact climate has on the wind and solar power across Britain. The results show that the seasonal variability in potential power generated for solar and wind is up to 70% and 30%, respectively, across the year.

An alternative to renewable and sustainable energy sources is that of waste heat recovery (WHR). Waste heat recovery allows the utilization of otherwise wasted heat energy from industrial processes, power generation, or other sources. By capturing and reusing this heat, energy efficiency is significantly improved. This reduces the overall energy consumption and the reliance on primary energy sources, leading to lower greenhouse gas emissions and a more sustainable use of resources (Zhang & Akiyama, 2009). Waste heat recovery possesses several advantages compared to the renewable energy sources described above. Since WHR is an integrated application to existing processes, it does not require land development or resource extraction. Additionally, WHR also exhibits a high potential utilization factor

compared to solar or wind energies (Jung et al., 2014). Various technologies can be employed to harness WHR, such as the organic Rankine cycle (ORC) (Galanis et al., 2009). The Organic Rankine Cycle (ORC) is one of the most versatile power cycle technologies implemented in a variety of low-medium temperature scenarios. While similar to the conventional Rankine cycle, the ORC utilizes refrigerants or organic substances as working fluids instead of water. This allows for the recovery of energy from low-temperature waste heat sources, facilitated by the lower boiling points of organic working fluids compared to water (Nguyen et al., 2010).

Arguably, the most important aspect of designing an ORC system is the working fluid selection. Over the years many researchers have investigated the working fluid selection against a range of operational conditions and system components (Bao & Zhao, 2013; Campos Rodríguez et al., 2013; Özcan & Ekici, 2021; Zeyghami, 2015). Specifically, one of the most used working fluids in a variety of low-medium grade ORC applications is R134a (Lai et al., 2011; Quoilin et al., 2013; Saleh et al., 2007; Shengjun et al., 2011). Environmentally speaking, although R134a has an Ozone Depletion Potential (ODP) of 0, it is a hydrofluorocarbon (HFC) with a global warming potential GWP of 1430 (Lemmon et al., 2018). This is of significant importance based on the harmful impact high GWPs has on the environment and the subsequent regulations implemented to phase out such working fluids (Schulz & Kourkoulas, 2014). Two working fluids often used to replace R134a are R1234ze and R1234yf, both of which having an ODP of 0 and GWP of 6 and 4, respectively (Lemmon et al., 2018). Yamada, Mohamad, and Kien (2012) highlighted that comparing R134a to a selection of working fluids in a basic ORC, both R1234ze and R1234yf displayed similar performance. Le et al. (2014) optimized a basic and regenerative supercritical ORC and identified R1234ze as the best working fluid for net power against R134a. Moles et al. (2017) directly compared R1234yf and R1234ze against R134a within a basic and regenerative cycle. The main findings presented indicate both fluids offer similar performance to R134a at lower evaporating temperatures. However, as the evaporating temperature increases R1234yf requires a higher pump power and produces a lower net cycle efficiency, whereas, R1234ze requires lower pump power and produces higher pump efficiency.

235

From the literature above it is clear there is a need not only to investigate ORC systems for waste heat recovery, but also to aide the expanse of research dedicated to identifying suitable replacements to R134a. Therefore, this paper aims to add to the existing working fluid evaluations of R134a replacements by comparing the performance against R1234ze and R1234yf. The working fluids are evaluated through modelling an ORC system heated by exhaust gas at 423.15 K. The comparison will include a heat exchanger sizing for the evaporator and condenser. An energetic and exergetic analysis of the ORC system will be considered to establish both the thermodynamic performance and assess the areas of energy waste between the working fluids.

2 METHODOLOGY

2.1 Organic Rankine Cycle

The ORC configuration and T-S diagram for the system setup is shown in Figure 1. The assumptions made for the cycle include no system heat losses and no pressure drop within the pipework. In order to complete the energetic and exergetic analysis, REFPROP was used to determine the required properties of the working fluids considered (Lemmon et al., 2018). The heating fluid was set as exhaust air and the cooling fluid was set as water. Table 1 demonstrates the assumed variables for the energetic and exergetic analysis.

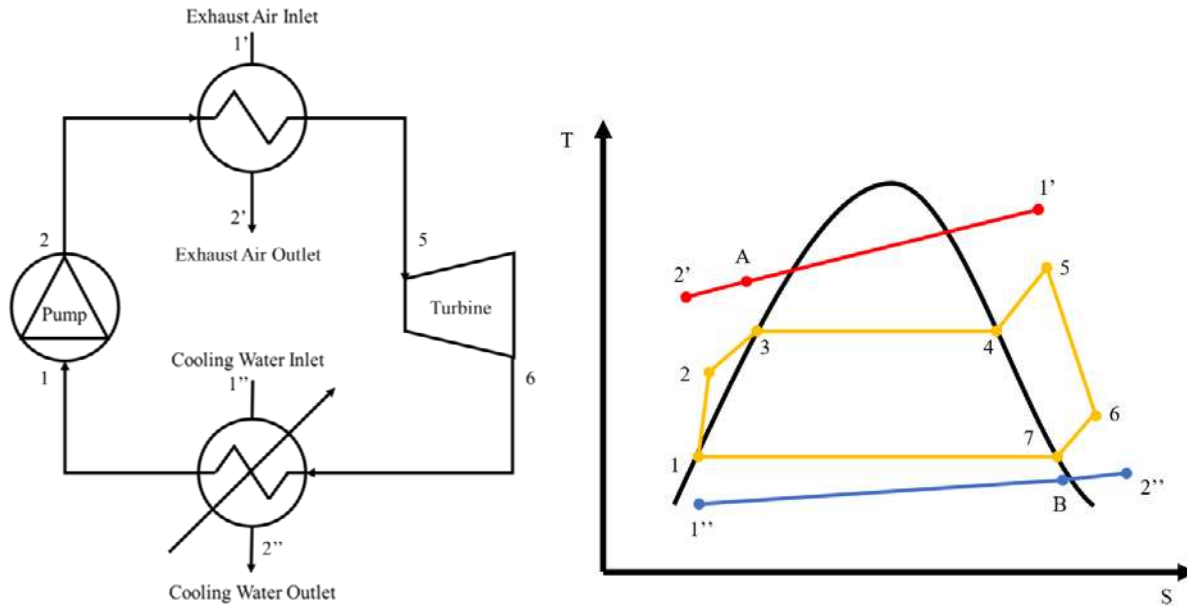


Figure 1: Organic Rankine Cycle configuration and T-S diagram

Table 1: Assumed parameters for the energetic and exergetic analysis

Variable	Value	Variable	Value
Ambient temperature	298.15 K	Condenser Pinch Point	10 K
Heating Fluid inlet Temperature	423.15 K	Pump inlet Temperature	293.15 K
Cooling Fluid inlet Temperature	278.15 K	η_{Pump}	80%
Approach Temperature	20 K	$\eta_{Turbine}$	70%
Evaporator Pinch Point	20 K		

236

The maximum temperature of the ORC was determined from the heating fluid inlet temperature minus the approach temperature. The maximum pressure of each working fluid was set as the saturated liquid pressure at 363.15 K. The energetic and exergetic analysis was completed using equations (1)-(10) (Cengel et al., 2011; Dincer & Rosen, 2012).

$$\eta_{Pump} = \frac{h_2 - h_1}{h_{2is} - h_1} \quad (1)$$

$$\eta_{Turbine} = \frac{h_5 - h_6}{h_5 - h_{6is}} \quad (2)$$

$$W_{Net} = W_{Turbine} - W_{Pump} = (h_5 - h_6) - (h_2 - h_1) \quad (3)$$

$$Q_{in} = h_5 - h_2 \quad (4)$$

$$\eta_{Cycle} = \frac{W_{Net}}{Q_{in}} \quad (5)$$

The exergy efficiency was evaluated using equation (6).

$$\eta_{ex} = \frac{W_{Net}}{Q_{in} \left(1 - \frac{T_0}{T_5}\right)} \quad (6)$$

And the exergy destruction for each component of the cycle was calculated using equations (7)-(10).

$$Ex_{D,E} = \dot{m}_{wf}((h_5 - T_0 s_5) - (h_2 - T_0 s_2)) + \dot{m}_{wf}(h_5 - h_2) \left(1 - \frac{T_0}{T_5}\right) \quad (7)$$

$$Ex_{D,T} = \dot{m}_{wf}((h_5 - T_0 s_5) - (h_6 - T_0 s_6)) + \dot{m}_{wf}(h_5 - h_6) \quad (8)$$

$$Ex_{D,C} = \dot{m}_{wf}((h_6 - T_0 s_6) - (h_1 - T_0 s_1)) \quad (9)$$

$$Ex_{D,P} = \dot{m}_{wf}((h_2 - T_0 s_2) - (h_1 - T_0 s_1)) + \dot{m}_{wf}(h_2 - h_1) \quad (10)$$

2.2 Heat Exchanger

There are three primary types of heat exchangers frequently used: fin and tube, plate, and shell and tube configurations. To maintain consistency in modeling the evaporator and condenser for all fluids, a shell and tube configuration is chosen. This configuration is preferred due to its versatility in accommodating various temperature ranges and fluid states between the hot and cold sides. The configuration for the shell and tube heat exchangers is that of TEMA type E, shown in Figure 2.

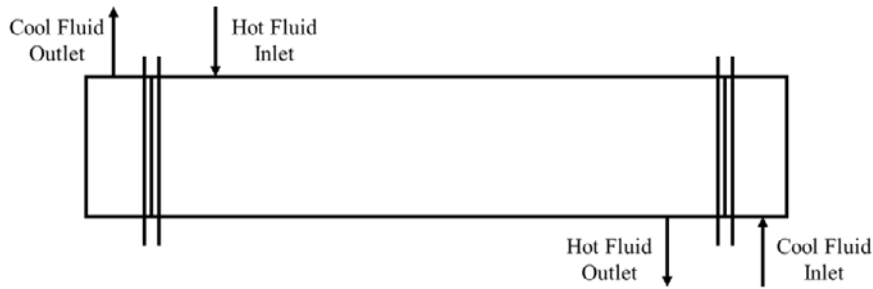


Figure 2: Shell and Tube Heat Exchanger Configuration TEMA Type E

The methodology used is off the work done by Bull et al. (2020) using the shell and tube heat exchanger design methodology from (Kakac et al., 2020; Kern, 1983). To account for the phase change of the working fluid, the evaporator calculations were split into three sections: pre-heater, phase change and super heater. The condenser calculations were split into two sections: phase change and super heater. To split the sections, the appropriate heating and cooling fluid temperatures were calculated from the corresponding working fluid phase change temperatures with the general energy balance equation shown in equation (11).

$$\dot{m}_{wf}(h_{out} - h_{in}) = \dot{m}_{hf/cf} C_{p,hf/cf} (T_{out} - T_{in}) \quad (11)$$

Where the $\dot{m}_{hf/cf}$ and $C_{p,hf/cf}$ is the mass flow rate and the specific heat capacity of the heating/cooling fluid respectively. The mass flow rate for each working fluid was fixed at the required mass flow rate for the ORC to output 10 kW of power. In order to size the heat exchanger, the shell and tubes diameters were set as 0.06 m and 0.01 m, respectively, and 1 shell pass with 2 tubes. In addition, the heat exchanger was modelling with negligible tube thickness and no fouling or baffles. For each section, average values for density, viscosity, specific heat capacity and thermal conductivity were calculated through REFPROP.

2.2.1 Pre-heat and Super heat

To calculate the heat transfer area required the log mean temperature difference was determined by equation (12).

$$\Delta T_{LMCF} = \frac{\Delta T_1 - \Delta T_2}{\ln \left(\frac{\Delta T_1}{\Delta T_2} \right)} \quad (12)$$

With correction factor (F) incorporated for the pre-heater and super-heater sections defined by equation (13) and subsequent corrected LMTD given by equation (14):

$$F = \frac{\sqrt{R^2 + 1}}{(R - 1)} \frac{\ln \left(\frac{1 - P}{1 - PR} \right)}{\ln \left(\frac{\frac{2}{P} - 1 - R + \sqrt{R^2 + 1}}{\frac{2}{P} - 1 - R - \sqrt{R^2 + 1}} \right)} \quad (13)$$

$$\Delta T_{LM} = \Delta T_{LMCF} F \quad (14)$$

The overall heat transfer coefficient was determined by equation (15):

$$U = \frac{1}{\frac{1}{h_{wf}} + \frac{1}{h_{hf/cf}}} \quad (15)$$

Where the heat transfer coefficient for the working fluid side and the thermal fluid side are given by equation (16):

$$h = \frac{Nu k}{D} \quad (16)$$

The values for the Nusselt number were calculated using the Dittus-Boelter correlation shown in equation (17):

$$Nu = 0.023 Re^{0.8} Pr^n \quad (17)$$

The heating exponent, n , is 0.4 and 0.3 for the cold fluid and hot fluid respectively. The required heat transfer area is calculated using equation (18):

$$A = \frac{Q_{ht}}{U \Delta T_{LM}} \quad (18)$$

Where the heat transferred for each section is calculated using equation (19):

$$Q_{ht} = \dot{m}_{wf}(h_{out} - h_{in}) \quad (19)$$

2.2.2 Phase Change

The Shah correlation (Shah, 1979) for two-phase flow was additionally incorporated for the heat transfer coefficient in the phase change section for the evaporator and condenser using equation (20):

$$h_{lv} = h_l \left[(1 - x)^{0.8} + \frac{3.8 x^{0.76} (1 - x)^{0.04}}{p_r^{0.38}} \right] \quad (20)$$

Where the mixture, x , was averaged to 0.5 and the reduced pressure was calculated with the critical fluid pressure using equation (21):

$$p_r = \frac{p_{crit}}{p_2} \quad (21)$$

2.2.2 Pressure Drop

The Pressure drop for the heat exchangers was calculated using equations (22) and (23):

$$\Delta p_t = \frac{2 f_t L \rho u_t^2}{D_t} \quad (22)$$

$$\Delta p_s = \frac{f_s G_s^2 D_s}{2 \rho D_e} \quad (23)$$

Where the respective friction factors are given by equations (24) and (25):

$$f_t = (1.58 \ln(Re_t) - 3.28)^{-2} \quad (24)$$

$$f_s = e^{(0.576-0.19\ln(Re_s))} \quad (25)$$

3 RESULTS

The following results include the respective adjustments to the evaporation and condensation pressure for each fluid based on the pressure drop calculated. The energetic performance characteristics is compared for each fluid and shown within Table 2. A percentage comparison of the energetic performance characteristics is shown in Table 3.

Table 2: Comparison of energetic analysis results

Fluid Name	Mass Flow (kg/s)	Net Power (kW)	Pump Power (kW)	Turbine Power (kW)	Rate of Heat In (kW)	Efficiency (%)	Back Work Ratio
R134a	0.271	8.622	0.654	9.276	71.10	12.127	0.071
R1234ze	0.285	8.503	0.548	9.051	73.49	11.571	0.061
R1234yf	0.320	8.530	0.794	9.324	76.05	11.217	0.085

Table 3: Percentage comparison of energetic analysis results against R134a

Fluid Name	Mass Flow (%)	Net Power (kW)	Pump Power (%)	Turbine Power (%)	Heat In (%)	Back Work Ratio (%)
R1234ze	5.087	-1.381	-16.229	-2.428	3.360	-14.144
R1234yf	18.155	-1.071	21.345	0.510	6.960	20.729

Based on the cycle parameters set within the methodology, R134a required the lowest mass flow rate and achieved the highest cycle efficiency of 0.271 kg/s and 12.127 %, respectively. Interestingly, R1234ze required the lowest pump power of 0.548 kW, and subsequently, generated the lowest turbine output power of 9.051 kW. However, R1234ze required 16.229 % less pump power compared to R134a in order to generate only 2.428 % less turbine power and achieve 1.381 % less net power. This result is further reflected by the back work ratio as R1234ze has the lowest with a value of 0.061, a 14.144 % drop from that of R134a. On the other hand, R1234yf displayed contrasting results, requiring the highest pump power, heat input, turbine power output, and subsequently displaying the highest back work ratio with the lowest cycle efficiency. Based on the energetic analysis conducted, despite favorable performance shown from R134a, R1234ze could be used as a suitable replacement in an ORC of this nature.

Table 4: A comparisons of exergetic analysis results

Fluid Name	Evaporator (kW)	Turbine (kW)	Condenser (kW)	Pump (kW)	Exergy Efficiency
R134a	29.408	21.599	61.545	1.155	46.583
R1234ze	30.290	20.989	64.616	0.967	44.430
R1234yf	31.340	21.616	67.370	1.405	43.069

Table 5: A percentage comparison of exergetic analysis results against R134a

Fluid Name	Evaporator (%)	Turbine (%)	Condenser (%)	Pump (%)
R1234ze	2.999	-2.823	4.989	-16.262
R1234yf	6.570	0.081	9.463	21.639

Table 4 demonstrates a comparison of the exergetic analysis results and Table 5 highlights the percentage comparison against R134a. Overall, R134a displayed the lowest exergy destruction for the evaporation and condenser components of the ORC. Additionally, R134a had the highest exergy efficiency of 46.583 % indicating increased reversibility of the system. Taking into consideration the exergy destruction reported at each component, R1234ze showed lower exergy destruction compared to R134a in both the turbine and pump by 2.823 % and 16.262 %, respectively. However, R1234yf not only demonstrated the lowest exergy efficiency of 43.069 %, it also had the highest exergy destruction across all components of the cycle presented. Similar to the energetic analysis, the exergetic analysis indicates that R1234ze proves to be a favorable replacement to R134a, especially when considering the fluid performance through the pump and turbine sections of the ORC.

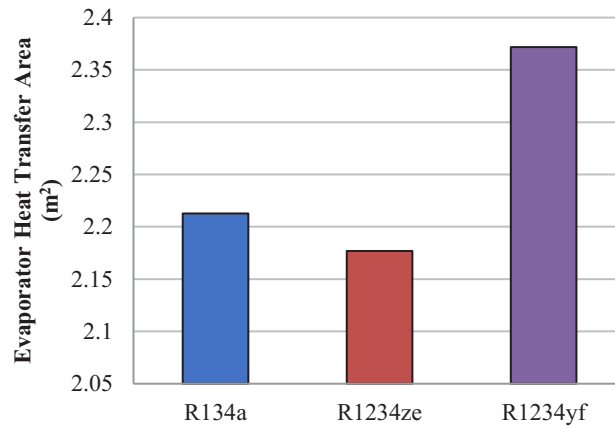


Figure 3: Evaporator heat transfer area required

Figure 3 demonstrates the heat transfer area required through the evaporator section of the ORC. The area required for R134a, R1234ze and R1234yf was calculated as 2.212 m², 2.177 m² and 2.371 m², respectively. Although R134a displayed the lowest mass flow rate and lowest heat in, shown in Table 2, R1234ze demonstrated the lowest area required for the heat exchanger. In contrast, R1234yf demonstrated the highest heat transfer area required. A similar correlation can be noted for the condenser heat exchanger sizing. Figure 4 presents a comparison of the heat transfer area required for the condenser section of the ORC. Overall, R1234yf has the highest area required of 31.768 m². Whereas R1234ze displays the lowest area of 29.347 m².

240

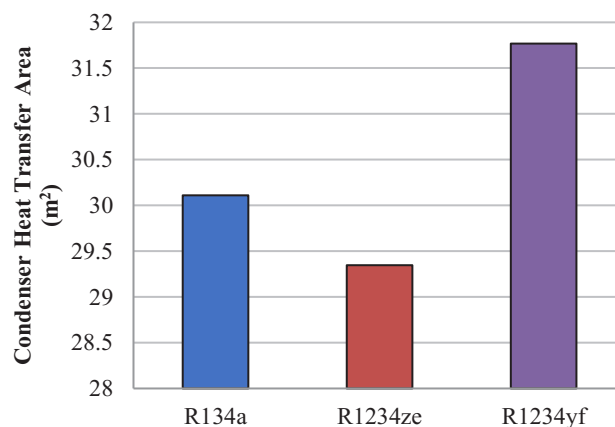


Figure 4: Condenser heat transfer area required

4 CONCLUSIONS

The results present in this study indicate the following conclusions:

- Based on the energetic analysis, although R134a displayed the best overall performance, R1234ze could be used as a suitable alternative.
- During the exergetic analysis, R1234ze proved to be a suitable replacement especially through the pump and turbine sections of the ORC.
- In both the condenser and evaporator heat exchanger sizing, R1234ze demonstrated the lowest area required.
- In all aspects evaluated within this paper, R1234yf would not be recommended as a suitable replacement to R134a.

NOMENCLATURE

T	Temperature
p	Pressure
η	Efficiency
W	Work done
h	Enthalpy
Q	Heat
Ex	Exergy
s	Entropy
$\dot{m}$	Mass Flow Rate
C_p	Specific Heat Capacity
U	Heat Transfer Coefficient
D	Diameter
Nu	Nusselt Number
Re	Reynolds Number
Pr	Prandtl Number
A	Heat Transfer Area
ρ	Density
G	Mass Flux
f	Friction Factor
u	Velocity
L	Heat Exchanger Length
Subscript	
1,2,3,4,5,6,7	Position in ORC
is	isentropic
ex	Exergy
D	Destruction
P	Pump
E	Evaporator
T	Turbine
C	Condenser
0	Ambient Conditions
wf	Working Fluid
hf	Heating Fluid
cf	Cooling Fluid
in	Generalized Reference Inlet
out	Generalized Reference Outlet
LM	Log Mean
ht	Heat Transferred
lv	Liquid-Vapor Phase
crit	Critical Point
r	Ratio

s Shell
t Tube

REFERENCES

- Bao, J., & Zhao, L. (2013). A review of working fluid and expander selections for organic Rankine cycle. *Renewable and Sustainable Energy Reviews*, 24, 325–342.
- Bett, P. E., & Thornton, H. E. (2016). The climatological relationships between wind and solar energy supply in Britain. *Renewable Energy*, 87, 96–110. <https://doi.org/10.1016/j.renene.2015.10.006>
- Bull, J., Buick, J. M., & Radulovic, J. (2020). Heat exchanger sizing for organic rankine cycle. *Energies*, 13(14), 1–10. <https://doi.org/10.3390/en13143615>
- Campos Rodríguez, C. E., Escobar Palacio, J. C., Venturini, O. J., Silva Lora, E. E., Cobas, V. M., Marques Dos Santos, D., Lofrano Dotto, F. R., & Gialluca, V. (2013). Exergetic and economic comparison of ORC and Kalina cycle for low temperature enhanced geothermal system in Brazil. *Applied Thermal Engineering*, 52(1), 109–119. <https://doi.org/10.1016/j.applthermaleng.2012.11.012>
- Cengel, Y. A., Boles, M. A., & Kanoğlu, M. (2011). *Thermodynamics: an engineering approach* (Vol. 5). McGraw-hill New York.
- Dincer, I., & Rosen, M. A. (2012). *Exergy: energy, environment and sustainable development*. Newnes.
- Galanis, N., Cayer, E., Roy, P., Denis, E. S., & Désilets, M. (2009). Electricity generation from low temperature sources. *Journal of Applied Fluid Mechanics*, 2(2), 55–67. <https://doi.org/10.36884/jafm.2.02.11870>
- Jung, H. C., Krumdieck, S., & Vranjes, T. (2014). Feasibility assessment of refinery waste heat-to-power conversion using an organic Rankine cycle. *Energy Conversion and Management*, 77, 396–407. <https://doi.org/10.1016/j.enconman.2013.09.057>
- Kakac, S., Liu, H., & Pramuanjaroenkij, A. (2020). *Heat exchangers: selection, rating, and thermal design*. CRC press.
- Kern, D. (1983). *Process Heat Transfer*. Tosho Printing Co., LTD.
- Lai, N. A., Wendland, M., & Fischer, J. (2011). Working fluids for high-temperature organic Rankine cycles. *Energy*, 36(1), 199–211. <https://doi.org/10.1016/j.energy.2010.10.051>
- Le, V. L., Feidt, M., Kheiri, A., & Pelloux-Prayer, S. (2014). Performance optimization of low-temperature power generation by supercritical ORCs (organic Rankine cycles) using low GWP (global warming potential) working fluids. *Energy*, 67, 513–526. <https://doi.org/10.1016/j.energy.2013.12.027>
- Lemmon, E. W., Bell, and I. H., Huber, M. L., & McLinden, M. O. (2018). *NIST Standard Reference Database 23: Reference Fluid Thermodynamic and Transport Properties-REFPROP, Version 10.0*, National Institute of Standards and Technology. <https://www.nist.gov/srd/refprop>
- Li, K., Bian, H., Liu, C., Zhang, D., & Yang, Y. (2015). Comparison of geothermal with solar and wind power generation systems. *Renewable and Sustainable Energy Reviews*, 42, 1464–1474.
- Moles, F., Navarro-Esbri, J., Peris, B., Mota-Babiloni, A., & Mateu-Royo, C. (2017). R1234yf and R1234ze as alternatives to R134a in Organic Rankine Cycles for low temperature heat sources. *Energy Procedia*, 142, 1192–1198.
- Nguyen, T. Q., Slawwhite, J. D., & Boulama, K. G. (2010). Power generation from residual industrial heat. *Energy Conversion and Management*, 51(11), 2220–2229.
- Özcan, Z., & Ekici, Ö. (2021). A novel working fluid selection and waste heat recovery by an exergoeconomic approach for a geothermally sourced ORC system. *Geothermics*, 95(November 2020). <https://doi.org/10.1016/j.geothermics.2021.102151>
- Quoilin, S., Van Den Broek, M., Declaye, S., Dewallef, P., & Lemort, V. (2013). Techno-economic survey of Organic Rankine Cycle (ORC) systems. *Renewable and Sustainable Energy Reviews*, 22, 168–186. <https://doi.org/10.1016/j.rser.2013.01.028>
- Saleh, B., Koglbauer, G., Wendland, M., & Fischer, J. (2007). Working fluids for low-temperature organic Rankine cycles. *Energy*, 32(7), 1210–1221. <https://doi.org/10.1016/j.energy.2006.07.001>
- Schulz, M., & Kourkoulas, D. (2014). Regulation (EU) No 517/2014 of The European Parliament and of the council of 16 April 2014 on fluorinated greenhouse gases and repealing Regulation (EC)

- No 842/2006. *Off. J. Eur. Union*, 2014(517), L150.
- Shah, M. M. (1979). A general correlation for heat transfer during film condensation inside pipes. *International Journal of Heat and Mass Transfer*, 22(4), 547–556.
- Shengjun, Z., Huaixin, W., & Tao, G. (2011). Performance comparison and parametric optimization of subcritical Organic Rankine Cycle (ORC) and transcritical power cycle system for low-temperature geothermal power generation. *Applied Energy*, 88(8), 2740–2754.
- Vallios, I., Tsoutsos, T., & Papadakis, G. (2009). Design of biomass district heating systems. *Biomass and Bioenergy*, 33(4), 659–678. <https://doi.org/10.1016/j.biombioe.2008.10.009>
- Yamada, N., Mohamad, N., & Kien, T. (2012). Study on thermal efficiency of low- to medium-temperature organic Rankine cycles using HFO–1234yf. *Renewable Energy*, 41, 368–375.
- Zeyghami, M. (2015). Performance analysis and binary working fluid selection of combined flash-binary geothermal cycle. *Energy*, 88, 765–774. <https://doi.org/10.1016/j.energy.2015.05.092>
- Zhang, L., & Akiyama, T. (2009). How to recuperate industrial waste heat beyond time and space. *International Journal of Exergy*, 6(2), 214–227.
- Zhao, J. F., Oh, U. J., Park, J. C., Park, E. S., Im, H. Bin, Lee, K. Y., & Choi, J. S. (2022). A Review of World-wide Advanced Pumped Storage Hydropower Technologies. *IFAC-PapersOnLine*, 55(9), 170–174. <https://doi.org/10.1016/j.ifacol.2022.07.030>

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.