

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**

 **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

pocketORC: A BROWSER-BASED CALCULATOR FOR TEACHING ORGANIC RANKINE CYCLE POWER SYSTEMS

Martin T White

*Thermo-Fluid Mechanics Research Centre, School of Engineering and Informatics,
University of Sussex, Falmer, Brighton, UK*

Corresponding Author: martin.white@sussex.ac.uk

ABSTRACT

This paper presents a steady-state design model for an organic Rankine cycle (ORC) power plant that is completely web-browser based and does not rely on any external libraries (e.g., for the computation of thermodynamic properties). This means the tool can be easily accessed by students via any electronic device with a web browser and used as a teaching aid to teach basic principles relating to ORC power systems. Therefore, ORC power cycles can be introduced interactively without requiring any programming knowledge or the distribution and installation of source files. This allows ORC power systems to be introduced earlier in the curriculum, and to a wider variety of students, than might otherwise be possible. The current version of the model combines the Peng-Robinson equation of state with a thermodynamic model of a recuperated ORC system and discretised heat exchanger sizing models. The model is written in the Python programming language and the PyScript framework is used to call Python code directly from HTML. The user can vary cycle variables such as the condensation temperature, pressure ratio, degree of superheat, recuperator effectiveness and heat-source temperature drop via the graphical-user interface which returns key indicators of cycle performance such as thermal efficiency and power output amongst others. The tool enables single-point calculation and parametric studies of a single variable and includes introductory self-paced lessons. This allows students to develop an understanding of the influence of different cycle variables on cycle performance. This paper provides an overview of the tool and its capabilities, alongside discussing its potential role as a teaching aid to support the introduction of ORC power systems into the curriculum.

53

1 INTRODUCTION

Over recent decades there has been a growing interest in the organic Rankine cycle (ORC) as a suitable power cycle for the conversion of low-temperature heat into power. Specifically, the ability of the cycle to convert low temperature heat from renewable sources, such as solar thermal and geothermal, alongside industrial waste heat, into power means the cycle could be an integral part of future clean energy infrastructure. Alongside this, there is a growing acknowledgement about the importance of heat pumps in the electrification and decarbonisation of heat production, and ORC systems and heat pumps share several similarities in terms of the underlying scientific fundamentals.

As such, there is a clear need for engineers and energy professionals who develop an understanding of these technologies during their education who then have the skills necessary to work with these technologies in their professional careers. Unfortunately, the complex thermodynamic nature of organic fluids means it can be difficult to fully address the underlying physics within traditional teaching activities. For example, a traditional Brayton cycle can be easily modelled using a simple system of equations that can be formulated based on the ideal gas law. This means a relatively simple system of equations can be easily solved by students, and trends in performance parameters, such as efficiency, with key cycle variables can be readily established. In comparison, for an ORC system, or indeed a

steam Rankine cycle, the more complex thermodynamic behavior means such activities can only be carried out if tabular thermodynamic properties are provided, and a rather tedious analysis procedure adopted. This may typically mean that when carrying out hand calculations in class only single-point calculations can be done, whilst trends can be shown to students but not easily replicated.

The challenge of introducing these cycles operating with more complex thermodynamic fluids into the curriculum can be aided with the use of computational modelling tools. This could include using standard software such as Excel with a suitable add-in or using more specialist open-source or commercial software. Within the ORC community there have been a number of open-source tools that have been developed for ORC power cycles in mind, which includes, amongst others, CoolProp (Bell et al., 2014) for predicting fluid properties, ThermoCycle (Quoilin et al., 2014) and ThermoPower (Casella & Leva, 2003) for dynamic modelling in Modelica, the ORC modeling kit (Dickes et al., 2016) for steady state simulation, and NiceProp (Giuffrè & Pini, 2022) for characterising the non-ideal gas dynamics of organic fluids. However, many of these tools are perhaps aimed more at other researchers, alongside post-graduate students that may be completing MSc or PhD research projects in the area. They also require downloading and installing source code, and therefore a degree of fluency in programming. As such, these tools may not be that suitable for undergraduate students, or indeed post-graduate students who may have an interest in renewable and sustainable energy technologies and are enrolled onto taught courses related to energy policy, economics or business management. These students stand to benefit by learning about ORC systems, but may lack familiarity or confidence in computational modelling or programming. Of course, example models could be setup in commercial modelling software, such as Simulink or Aspen as examples, but this requires a certain level of literacy with those tools, alongside timetabled computer labs where students have access to licensed software.

This paper introduces a new steady-state modelling tool for ORC power systems, named pocketORC, that operates straight from the web browser and relies purely on data entry via a web form. This means topics related to the design and simulation of ORC power systems can be introduced in the curriculum, and students can carry out cycle simulations in real time using any electronic device with access to the internet. As such, the effect of the working fluid, and trends in key performance parameters with different cycle variables can be easily assessed in real time. This paper is structured in three parts. Firstly, an overview of the tool is provided in Section 2, which includes details on how the tool has been developed and a summary of its capabilities. This is followed by an overview of the underlying mathematical modelling in Section 3. In the third part of this paper, examples of how this tool could be used to introduce ORC power systems into the curriculum are discussed.

The tool can be accessed via the following link: <https://martintwhite.github.io/pocketORC/>.

2 OVERVIEW AND IMPLEMENTATION

pocketORC is a steady-state simulation tool for ORC systems that is based on in-house Python scripts that have been developed by the author for predicting the thermodynamic properties of organic fluids and for simulating ORC power systems. The inputs required to run the pocketORC tool, alongside the outputs generated via the tool, are integrated within a graphical-user interface written in HTML. To call the Python scripts directly from HTML, the recently developed open-source PyScript framework (Anaconda, 2022) is employed. This enables the Python scripts to be uploaded onto the web server and to be run directly from the browser. As such, no installation of any local files is necessary.

An overview of the capabilities of the model is provided in Figure 1. For several fixed inputs that define the intended heat source and heat sink, alongside component parameters, the user can vary the working fluid and six different cycle variables to vary the performance of the system. The outputs of the model include the power output, mass-flow rate, first- and second-law efficiencies alongside the pinch points and UA requirements of the heat exchangers. These are reported in tabular form, alongside a temperature-entropy diagram of the resulting cycle. The tool can simulate a range of different cycle variants, including simple subcritical cycles, recuperated cycles, transcritical cycles and trilateral or

partially evaporating cycles. Currently, three working fluids can be modelled, namely R1233zd(E), *n*-pentane and hexamethyldisiloxane (MM), although additional fluids can be easily added in the future.

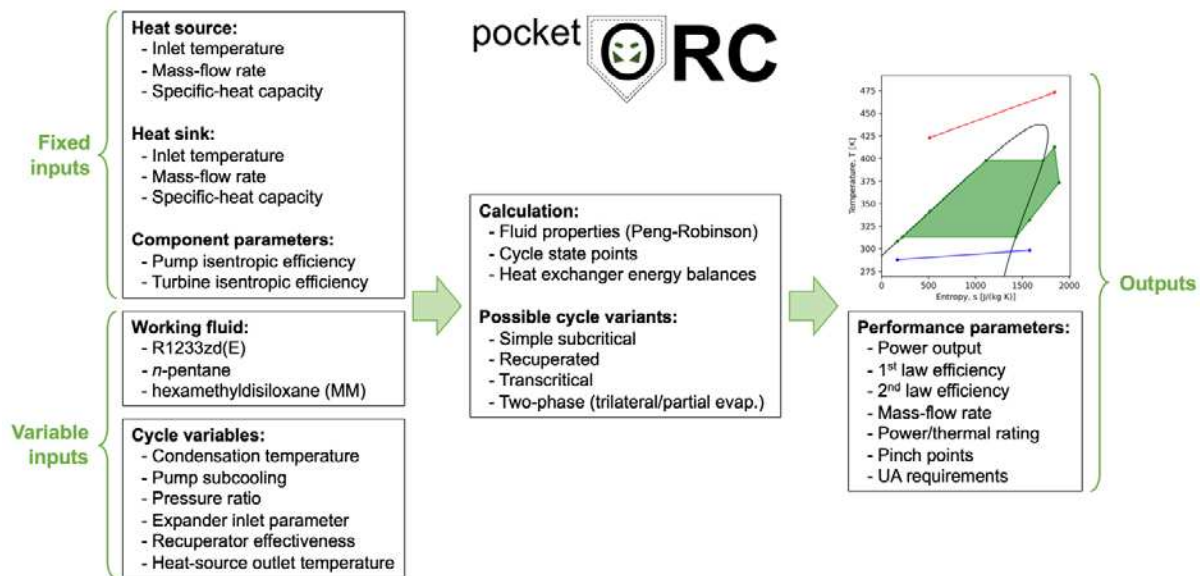


Figure 1. Overview of the modelling capabilities of pocketORC.

3 MATHEMATICAL MODELLING

This section summarises the underlying mathematical modelling that takes place under the hood of pocketORC. To an experienced researcher working with ORC systems, it is anticipated that this theory is very familiar and therefore the precise mathematical details will not be provided here. Instead, a short summary of the approach is provided, alongside supporting justifications. A more detailed description of the underlying calculations will be made available on the website.

3.1 Thermodynamic properties

Thermodynamic properties of the working fluid are calculated using an in-house thermodynamic module based on the Peng-Robinson equation that has been developed by the author in a previous work (White & Sayma, 2018). Although the Peng-Robinson equation of state is not as accurate as state-of-the-art multi-parameter equations of state, such as those implemented within software packages such as CoolProp and REFPROP, the Peng-Robinson equation of state is known to provide reasonable predictions for fluid properties, particularly in the vapour-phase region. In the previous work, a maximum deviation in power output of 5.9% was found between cycle calculations completed using the Peng-Robinson equation of state and using REFPROP (White & Sayma, 2018). This level of accuracy is considered sufficient for a tool whose primary purpose is teaching. More importantly, the in-house module is simple and is uploaded to the web server as a single python script which can be run directly using PyScript. The module includes all the necessary calculations for modelling thermodynamic cycles, including the prediction of saturation properties at fixed temperature or pressure and the prediction of single-phase properties based on temperature-pressure, pressure-enthalpy, and pressure-entropy flash calculations. Working fluids are defined based on six fluid parameters, including the critical temperature, critical pressure, acentric factor, and the coefficients for a second-order polynomial describing the variation in ideal-specific heat capacity with temperature.

3.2 Thermodynamic cycle modelling

The thermodynamic cycle model is largely based on cycle modelling activities previously completed by the author (White & Sayma, 2019, White 2021). The cycle is assumed to operate under a steady-state and no heat losses or pressure drops are considered. The model can be used to simulate different cycle architectures, including recuperated and transcritical cycles, alongside cycles operating with two-

phase expansion. The heat source and heat sink are both modelled as fluid streams with a fixed specific-heat capacity, where the inlet temperature, mass-flow rate and specific-heat capacity of each stream are model inputs. The pump and turbine are modelled with a fixed isentropic efficiency. All heat exchangers are modelled as counter-flow heat exchangers using a discretised approach to determine the fluid temperature profiles. The log-mean temperature difference is then used to determine the total UA value (i.e., product of overall heat transfer coefficient U and heat exchanger surface area A) for each heat-transfer region, namely preheating, evaporation, superheating, precooling, condensation, subcooling and recuperation.

For a fixed heat source and heat sink, alongside fixed isentropic pump and turbine efficiencies, there are six variables that can be used to adjust the performance of the cycle. These are: the condensation temperature; the degree of subcooling at the pump inlet; the pressure ratio; the expander inlet parameter; the recuperator effectiveness; and the heat-source outlet temperature. All of these have standard definitions, except for the expander inlet parameter, x , which is used to enable cycles with single- and two-phase expansion to be modelled using a single parameter (White, 2021). If $x < 1$, then x defines the expander inlet vapour quality, otherwise it determines the expander inlet temperature from:

$$T = T_{ev} + (x - 1)(T_{hi} - T_{ev}) \quad (1)$$

where T is the expander inlet temperature, T_{ev} is the evaporation temperature and T_{hi} is the heat-source inlet temperature. Thus, by allowing x to range between 1 and 2 it is possible to move the expander inlet condition from being saturated vapour ($x = 1$) to an expander inlet temperature that equals the heat-source inlet temperature ($x = 2$).

For a given set inputs, the model returns first- and second-law efficiency, the working-fluid mass-flow rate, the power rating or thermal load of each component, alongside the pinch-point temperature difference and UA value for each heat exchange process.

56

4 USAGE AS A TEACHING TOOL

4.1 Single-point performance calculation and parametric studies

In the first instance, pocketORC can be used as a single point calculator, in which, for a given set of fixed parameters and inputs, the tool calculates the performance of the cycle. The output of this calculation is a table that reports the key performance indicators alongside a temperature-entropy diagram of the cycle with the heat-source and heat-sink temperature profiles superimposed. Thus, based on an understanding of how different cycle variables influence performance, it is possible to carry out a manual iterative process in which the cycle can be optimised for a defined heat source and heat sink. In this capacity, pocketORC is a useful tool for any ORC practitioner looking to get an idea of the achievable performance from an ORC operating within a given application. A typical output from a single-point calculation completed using pocketORC is shown in Figure 2.

The second feature of pocketORC is the ability to carry out single-variable parametric studies. Any one of the six cycle variables can be selected as the parametric variable and a minimum and maximum value can be specified. Using those inputs, pocketORC creates an array of 10 input values ranging from the minimum to the maximum with a constant step and reports the variation in cycle performance parameters in the form of a table. The resulting data can be readily copied and pasted into a spreadsheet or similar program for further post processing if necessary. A typical output from a parametric study completed using pocketORC is shown in Figure 3.

4.2 Introductory lessons into ORC technology

Alongside the single-point and parametric calculators, pocketORC also includes lessons that are available on the website and which students can work through at their own pace. These lessons combine a qualitative explanation of important concepts with interactive plots which are again written in Python and interfaced with the website via PyScript. The aim of these lessons is not to delve into detail

regarding the underlying mathematical calculations, but instead to build up a working model of an ORC power system. Through this, the key cycle variables and fixed parameters considered within the calculator are introduced. It is assumed that before starting these lessons, the student already has some familiarity with important concepts such as thermodynamic state variables (i.e., temperature, pressure, density, enthalpy, entropy) and the general operating principle of a closed-loop power cycle, such as the steam Rankine cycle.

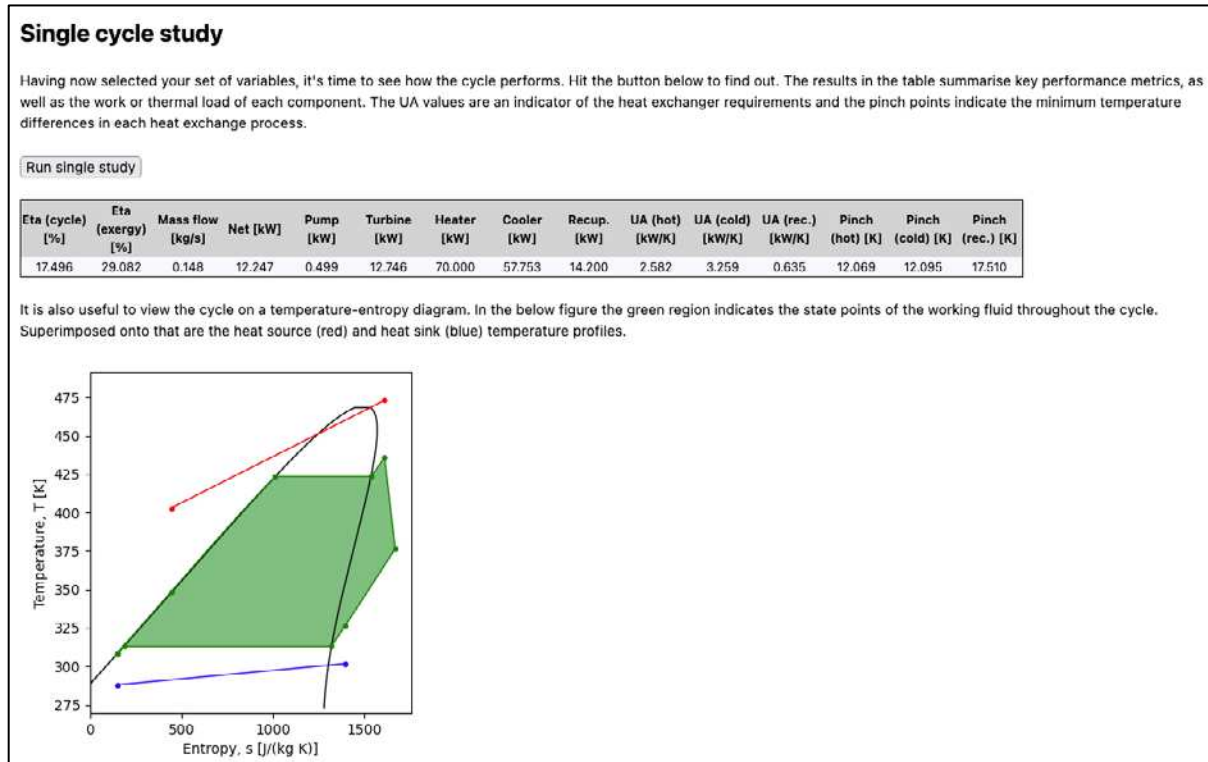


Figure 2. Example output from pocketORC for a single-point performance calculation.

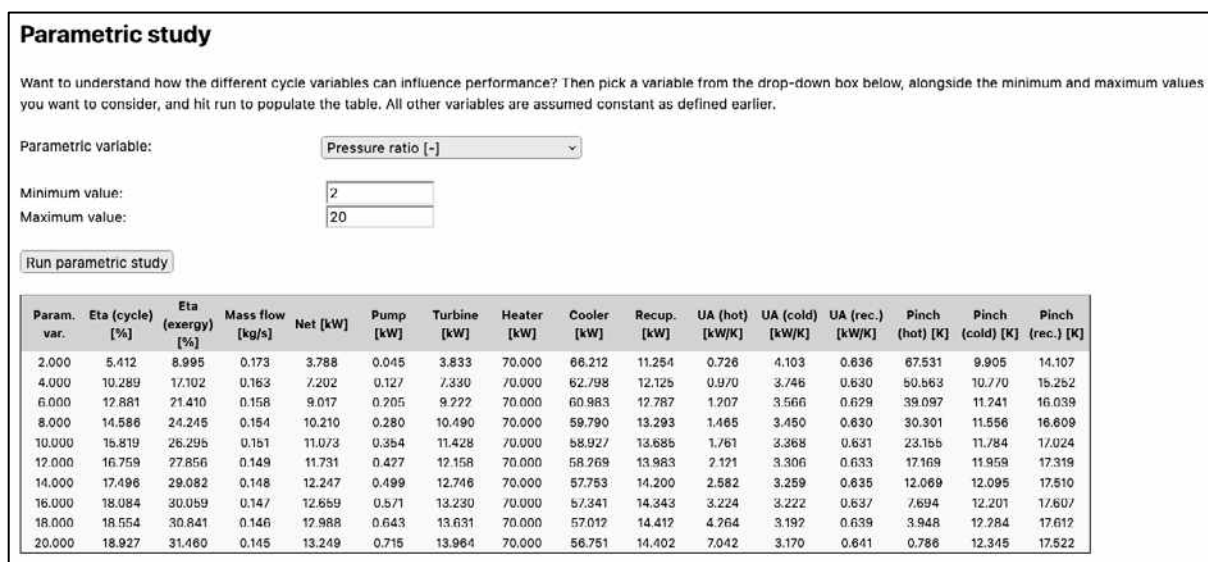


Figure 3. Example output from pocketORC for a parametric study considering pressure ratio.

The lesson structure for pocketORC is provided in Table 1, which summarises the topic of each lesson and the parameters introduced. Examples of the interactive plots generated within the first three lessons are provided in Figure 4. For example, the content of Lesson 1 focusses on introducing the first two variables which control the evaporation and condensation processes, namely the condensation

temperature and pressure ratio, and the corresponding interactive plot enables the user to see these in the temperature-entropy plane (Fig. 4(a)). This is extended to the variables controlling the pump and expander inlet conditions in Lesson 2, as shown in Fig. 4(b). At this point an ideal cycle with isentropic compression and expansion processes can be defined and the cycle efficiency can be evaluated, which is the first topic of Lesson 3 (Fig. 4(c)). This is extended to real cycles, before recuperation, heat exchanger energy balances and alternative cycles are introduced in Lessons 4, 5 and 6 respectively.

Table 1: Summary of the lesson structure for pocketORC.

#	Title	Topics covered	Parameters introduced
1	Saturated properties	- Saturation properties - Evaporation and condensation	- Condensation temperature - Pressure ratio
2	Single-phase properties	- Subcooled and superheated properties - Pump and expander inlet conditions	- Degree of pump subcooling - Degree of expander superheating
3	Ideal and real cycles	- Ideal cycle - Real cycle	- Cycle efficiency - Pump isentropic efficiency - Expander isentropic efficiency
4	Recuperation	Recuperated cycles	Recuperator effectiveness
5	Heat exchangers	- Heat source modelling - Heat sink modelling	- Heat source inlet temperature, outlet temperature, mass-flow rate - Heat sink inlet temperature, outlet temperature, mass-flow rate - Net power output
6	Alternative cycles	- Transcritical cycles - Two-phase expansion	Expander inlet parameter

58

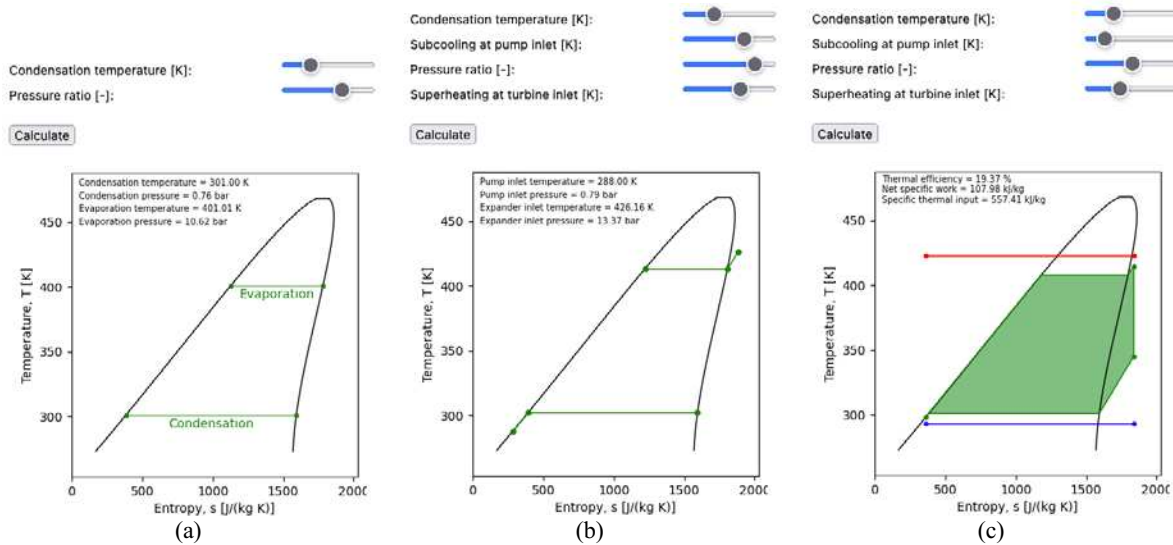


Figure 4. Example interactive plots created within Lessons 1, 2 and 3 of pocketORC.

4.3 Wider integration within the curriculum

It is intended that the available lessons, and the pocketORC calculator itself, provide a useful set of tools to introduce ORC power systems into the curriculum. Whilst these can be used as a self-paced introduction into ORC systems, several additional teaching activities can also be envisioned.

In the first instance, the tool can be used to set students an open design exercise, which could involve designing an ORC system for a particular application. In this scenario, a specific application could be introduced (i.e., geothermal, solar-thermal, waste-heat recovery) and defined in terms of an available heat source and heat sink. The students are then tasked with designing an optimal system for that application. This could be left open-ended with students free to establish optimal values for all six variables for a given working fluid, or the scope could be narrowed by fixing the heat source outlet temperature, considering simple cycles without recuperation, and providing recommendations for the degree of subcooling. Thus, simple parametric studies concerning the remaining three cycle variables can be completed by the students.

More widely, an ORC system comprises of several engineering components which themselves are introduced within the curriculum. More specifically, ORC systems are reliant on pump and turbines, alongside heat exchangers, which are components introduced within taught modules on turbomachinery and heat transfer respectively. Thus, pocketORC can be used as an aid to introduce the design of these components for ORC power cycles. In this capacity, pocketORC can be used by students to define the boundary conditions that are used in the subsequent design of these components. For example, at the time of writing the author is planning on introducing a project relating to the design of an air-cooled condenser for ORC power plants within a master's level module focused on heat transfer applications. Another possibility would be to ask the students to take the system-level analysis beyond the calculations completed within the tool. This could include evaluating a particular ORC system design from a techno-economic perspective, which would involve translating the outputs from pocketORC, such as the component power ratings or heat exchanger UA values, into estimated costs based on published cost correlations. In this capacity, ORC technology can be introduced to students from a broader energy background who may be interested in these economic factors.

59

Finally, it is worth noting the similarities in the analysis of an ORC and that of a heat pump system. Thus, the infrastructure used to build pocketORC could be easily extended to introduce a similar calculator for heat pump systems. This extension is currently planned for later in the year. This could open the possibility of introducing heat pump systems in a similar fashion to ORC systems, which could ultimately allow students to compare different technical options for a given heat source. For example, for a given waste heat stream students could be asked to evaluate and compare the performance of an ORC or heat pump system and then select the most viable option.

5 CONCLUSIONS

The wider implementation of ORC power systems requires energy professionals that have the necessary technical skills to design, simulate and evaluate the feasibility of the technology in different application areas. Principally, this knowledge should be developed within the taught curriculum of engineering and related courses. However, the high degree of scientific literacy, and potentially computing literacy, required to design and simulate ORC power cycles can hinder the extent to which the topic can be introduced in taught courses. With this in mind, this paper has introduced a new web-browser based calculator for ORC power systems that is suitable for a wider student audience. It is intended that the calculator, alongside the supporting self-paced lessons, can aid with the introduction of ORC technology at an earlier stage within the curriculum and provide a useful tool for ORC practitioners alike. Alongside providing an overview of the tool and its implementation, this paper has summarised its capabilities and put forward a vision of how it could be used as an additional teaching aid. This includes supporting open design exercises, designing power cycle components, and potentially helping to benchmark the technology against other technologies from a techno-economic perspective.

NOMENCLATURE

A	heat exchanger area	(m ²)
T	expander inlet temperature	(K)
T_{ev}	evaporation temperature	(K)
T_{hi}	heat-source inlet temperature	(K)
U	overall heat transfer coefficient	(W/m ² K)
x	expander inlet parameter	(-)

REFERENCES

- Anaconda Inc., 2022, PyScript. Online: <https://docs.pyscript.net/latest/index.html> [Last accessed: 29/03/2023]
- Bell, I.H., Wronski, J., Quoilin, S., Lemort, V., 2014, Pure and pseudo-pure fluid thermophysical property evaluation and the open-source thermophysical property library CoolProp, *Ind. Eng. Chem. Res.*, 53, 6, 2498—2508.
- Casella, F., Leva, A., 2003, Modelica open library for power plant simulation: design and experimental validation, *Proceedings of the 2003 Modelica Conference*, 3-4th November, Linköping, Sweden, pp. 41-50.
- Dickes, R., Ziviani, D., de Paepe, M., van den Broek, M., Quoilin, S., Lemort, V., 2016, ORCmKit: an open-source library for organic Rankine cycle modelling and analysis, *Proceedings of ECOS 2016 – The 29th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems*, 19-23th June, Portorož, Slovenia.
- Giuffrè, A., Pini, M., 2022, NiceProp: An interactive Python-based education tool for non-ideal compressible fluid dynamics, *SoftwareX*, 17, 100897.
- Quoilin, S., Desideri, A., Wronski, J., Bell, I., Lemort, V., 2014, ThermoCycle: A Modelica library for the simulation of thermodynamic systems, *Proceedings of the 10th International Modelica Conference*, 10-12th March, Lund, Sweden.
- White, M.T., Sayma, A.I., 2018, A generalised assessment of working fluids and radial turbines for non-recuperated subcritical organic Rankine cycles, *Energies*, 11(4), 800.
- White, M.T., Sayma, A.I., 2019, Simultaneous cycle optimization and fluid selection for ORC systems accounting for the effect of the operating conditions on turbine efficiency, *Front. Energy Res.*, 7, 50.
- White, M.T., 2021, Cycle and turbine optimisation for an ORC operating with two-phase expansion, *Appl. Therm. Eng.*, 192, 11682.

ACKNOWLEDGEMENT

The author would like to acknowledge all of those that took the time to test out the pocketORC tool and provide valuable feedback during its creation.

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.