Bringing reversible ORC-heat pump systems into the market: A perspective on the current obstacles and future application potential

Christopher Schifflechner[1*], Marco Astolfi[2], Sotirios Karellas[3], Tryfonas Roumpedakis[3], Marcus Budt[4], Maximilian Weitzer[5], George Kosmadakis[6], Vincent Lemort[7]

[1] *Chair of Energy Systems, Technical University of Munich, Germany*
[2] *Dipartimento di Energia, Politecnico di Milano, Italy*
[3] *Laboratory of Thermal Processes, National Technical University of Athens, Greece*
[4] *Fraunhofer Institute for Environmental, Safety, and Energy Technology UMSICHT, Germany*
[5] *Chair of Energy Process Engineering, Friedrich-Alexander-Universität Erlangen-Nürnberg, Germany*
[6] *INRASTES, National Centre for Scientific Research "Demokritos", Greece*
[7] *Thermodynamics Laboratory, University of Liège, Belgium*
* Corresponding Author: c.schifflechner@tum.de

ABSTRACT

Reversible Organic Rankine Cycle systems, capable of alternating between power generation and (high-temperature) heat pump operation, have demonstrated strong technical feasibility across several lab-scale prototypes. This work assesses why, despite rising scientific interest, commercial deployment remains limited. Expert interviews and a targeted survey among relevant stakeholders reveal a generally positive perception of the technology and technical potential for market entry within the next 2–5 years. Industrial waste heat recovery, geothermal energy, and Carnot batteries show the highest market potential, while building and mobile applications are regarded with more scepticism. A SWOT analysis summarizes the key strengths (e.g. flexibility, cost reduction potential) and main barriers, including component efficiency and system complexity. Particular attention is given to reversible rotating machines, where further R&D is needed. The findings aim to guide future research and commercialization strategies and stimulate an informed discussion within the ORC and heat pump community.

1. INTRODUCTION

Within the last ten years, reversible Organic Rankine Cycles (rev. ORCs) have gained increasing attention since they can be a promising solution for the flexible heat and power supply across various application fields. At the *International Seminar on ORC Power Systems* in 2013, the contribution by Quoilin *et al.* (2013) was one of the first to present the concept of this technology to our community. At the same time, researchers at the University of Bochum were also working on reversible systems for building applications (Schimpf *et al.*, 2011; Schimpf and Span, 2014), while even before that, some industry patents dealt already with the concept (Olivier, 2008; Hansen, 2011). The activities of the authors were a starting point, focusing on the application of rev. ORC systems in buildings and resulted in one of the main publications in this field (Dumont *et al.*, 2015). Over the next editions of the ORC conference series, rev. ORCs have been addressed by very few papers, but this changed during the last two editions. In Seville in 2023, six papers were presented addressing various application fields and increasing experimental activities.

Rev. ORCs have the capability to also operate as a (high-temperature) heat pump (HTHP). Since there is no clear definition of reversible systems in literature regarding plant layout and functionality, the term "reversible heat pump" is sometimes also used for regular heat pumps capable of heating and cooling. However, this work refers to plants capable of ORC and heat pump operation, following the wording in the ORC and HTHP communities. Most of the rev. ORC concepts foresee the use of many key components (especially the heat exchanger(s) and/or rotating machine) and the working fluid in both operational modes. However, there is a high number of potential cycle configurations. Therefore, in this work, the definition of a rev. ORC system is that the circuits of the heat pump and ORC system are not isolated from each other. While the ORC technology has been commercialized for several decades (Wieland *et al.*, 2023), and also more and more commercial heat pumps are installed on both building and large-scale levels (Jesper *et al.*, 2021), rev. ORCs have not entered the market yet.

Nevertheless, there has been an increasing interest in rev. ORCs for several years and multiple research groups and research projects are actively working on the topic. One current focus lies on further experimental demonstration at the lab scale and general advancements in the technology. Thus, the number of publications on various application fields is increasing, whereby the main scope is mainly on the thermodynamic process itself and less on the market potential and economic viability of the process and its potential entry into the market. This means that there is a research gap with regard to the general market potential of the technology, the reasons why the technology is not on the market yet, and the need for further technical and non-technical developments. This work aims to start an in-depth discussion within our research community on those highly relevant matters to gain a better understanding of targeted and streamlined future activities and development.

2. POTENTIAL APPLICATION FIELDS

The following section provides a brief overview of the main application fields relevant to rev. ORC systems. This section is not intended to be a comprehensive literature review, mainly also due to space limitations, but rather aims to contextualize the selected application fields.

2.1 Industrial waste heat recovery (WHR)

Industrial processes release tremendous quantities of waste heat at low or medium temperatures, which is currently still not further utilized (Astolfi *et al.*, 2025). A strongly increasing number of commercial ORC systems are installed to utilize this heat for power generation (Wieland *et al.*, 2023). At the same time, the integration of HTHP systems in industrial processes has also been gaining significant attention over the last few years. Such HTHP systems can use waste heat streams on a low- and medium-temperature level and upgrade it to a higher temperature level (Jovet *et al.*, 2022). Accordingly, it is no surprise that various publications, such as Ravindran *et al.* (2024), deal with the investigation of rev. ORC systems for industrial applications and it might be promising for several industries, such as pulp & paper, food & beverage, cement or steel. Their experimental work with a reversible scroll expander demonstrated a COP of 4.8 for a temperature lift of 41 K and an overall ORC cycle efficiency of 3 %. However, while most studies focus on the rev. ORC technology itself, the potential application in a specific industrial setting often remains rather vague. One promising approach could be in the case of heat engines or industrial waste heat recovery for district heating networks in general. In such a scenario, the ORC mode could be used for power generation during periods with low heating demands and the heat pump to upgrade heat during times with high heating demands. In addition, the application in industrial settings is often also discussed in combination with energy storage by Carnot batteries (cf. Section 2.5).

2.2 Geothermal energy

While high-temperature deep geothermal sources can be utilized for direct power generation by steam turbines and low-temperature resources are commonly used for direct-heat supply of a district heating network, the ORC technology is widely used for power generation from low- and medium-temperature sources, often also in combined heat and power projects (CHP) (Wieland *et al.*, 2023; Van Erdeweghe *et al.*, 2017). In a geothermal CHP plant, a rev. ORC can switch operating modes depending on the actual heating demand of the district heating network. If the heat demand of the district heating network is higher than the conventional geothermal capacity, a large-scale heat pump can be used to cool down the geothermal further and upgrade the temperature level to the required supply temperature of the heating network (Jeßberger *et al.*, 2024). Thus, the integration of a heat pump can avoid the need for fossil-fueled peak load boilers. At the same time, the capacity factor of such heat pumps can be rather low, since the annual operational time might be rather low. Thus, the ORC mode of the reversible system is used for generating electricity when the geothermal heat supply exceeds immediate heating needs, and supplying additional heat in heat pump mode during peak heating demand periods. This capability allows more effective year-round utilization of the geothermal resource. Excess geothermal heat in summer can be converted to electricity, while in winter the cycle can enhance the heat supply to a district heating network, reducing reliance on auxiliary fossil-fueled boilers. Depending on the brine temperature and demand profile, the reversible concept can improve the economics of the surface plant compared to a stand-alone HTHP or ORC system (Kaufmann *et al.*, 2026). The experimental work by Kaufmann *et al.* (2025) with a reversible twin-screw machine demonstrated that the reversible system is working promisingly in both operational modes. The HTHP is capable of thermal loads up to 110 kW at heat sink outlet temperatures of up to 120°C, making it well suited for conventional district heating networks. For conducted temperature lifts between 25 and 57 K, COPs between 6.4 and 3.0 were observed. During the ORC operation, net electric thermal efficiencies of 5-6 % were achieved for various heat source mass flow rates and temperatures between 110 and 130°C. Furthermore, it could also be a promising technology for increasing the flexibility of geothermal ORC systems, e.g. with surface or subsurface thermal storage systems (Aljubran and Horne, 2025).

2.3 Mobile applications

Rev. ORC systems have been proposed for mobile applications ranging from on-road vehicles to vessels. The transportation sector offers opportunities for ORC systems because engines produce substantial waste heat, and vehicles often have on-board demands for heat or cooling (Lang *et al.*, 2013). A rev. ORC can operate as an ORC to recover energy from engine exhaust, coolant, or in the future, from fuel cell or battery systems, into supplementary propulsion power or electricity, thereby improving overall system efficiency. Conversely, when there is a need for heating, the system can run in heat pump mode to provide thermal energy. Furthermore, for application in the car and truck industry, one special aspect is the potential use of the ORC system also as an air conditioning unit (Di Cairano *et al.*, 2020). In addition, ORC systems have been considered for vessels with several demonstrations and commercial applications already implemented. The exploited waste heat sources are the engine jacket cooling water and the exhaust gases. On the other hand, HTHPs for ships are not that common, since steam production is typically handled by the exhaust gas economizer, by recovering a part of the thermal content of the flue gases. Therefore, HTHP operation might be applicable for a small share of the vessel's operational time and mostly when it is at the port. A reversible ORC system is well suited for marine applications since the two previous functions correspond to different operational modes (Kosmadakis and Neofytou, 2022).

2.4 Building applications

The application of rev. ORC in high-efficiency or even net-zero buildings can be seen as the origin of the scientific discourse on the technology (Schimpf *et al.*, 2011; Quoilin *et al.*, 2013). The first detailed characterization of a potential application scenario was provided by Dumont *et al.* (2015). The authors studied a net-zero building with solar thermal collectors and a ground-source heat exchanger, combined with a rev. ORC as the backbone for the building's energy system. The system can operate in three operational modes: ORC operation, producing electricity when a large amount of heat is provided by the collectors; a direct heating mode by using the heat from the collectors; and the heat pump mode for space heating during cold weather conditions. Several further building concepts, including a rev. ORC, have been studied over time. E.g., by also including PV systems into the building's energy concept (Pezo *et al.*, 2024) or incorporating it in a polygeneration system, which also provides cold, as investigated in the recently finished SolBio-Rev project (Charalampidis *et al.*, 2025).

2.5 Carnot batteries

Carnot batteries utilize power-to-heat and heat-to-power processes with the primary purpose of electrical energy storage (Dumont *et al.*, 2020). They are particularly suitable for grid-scale applications with a storage duration of at least several hours, extending to several days or weeks. Novotny *et al.*

(2022) reviewed commercial Carnot battery developments, yet no listed project has progressed beyond concept, demonstration, or pilot stages. However, various research and demonstration projects are currently taking place covering a broad range of technological concepts and temperature levels. Next to high-temperature systems, such as closed Brayton cycles, the ORC technology is intensely studied for low- and medium-temperature systems, e.g. by the RESTORE (Astolfi *et al.*, 2024) and CHESTER project (Tassenoy *et al.*, 2024). However, next to Carnot battery systems consisting of a separated ORC and HTHP, rev. ORC systems are especially promising due to their cost-effective scalability, reliance on widely available components, and dual-use capability. Additionally, they enable efficient integration of low-temperature heat sources, achieving round-trip efficiencies above 50 % (Frate *et al.*, 2020). The technical application of a rev. ORC in the context of Carnot batteries is investigated by Weitzer *et al.* (2025) in a detailed experimental study. 150 stationary operating points were investigated in heat pump and ORC mode. If potential additional heat storage losses are neglected, the experimental results demonstrated a power-to-power (round-trip) efficiency of up to 41.8 % for the Carnot battery

3. METHODOLOGY

As outlined before, research activities on rev. ORCs have significantly intensified in recent years, with multiple studies exploring their application potential across various sectors. However, aspects related to the economic viability, potential business models, and specific pathways for commercial implementation remain largely unaddressed. This raises the central question of why scientific attention is growing while commercial deployment remains yet limited. To address this gap, this work is based on three main branches: (i) including researchers with long-standing expertise in rev. ORC systems and different application fields, (ii) expert interviews conducted across different stakeholder groups and (iii) a freely accessible online survey targeting professionals from both the heat pump and ORC communities.

The authors of this paper are confident that this approach will provide valuable new insights. At the same time, the reader must be aware that the work is not providing a statistically representative or quantitatively robust dataset as typically expected in social or economic sciences. Rather, it aims to gather informed perspectives and collective expert judgment and should be a starting point for an open ongoing discussion within our community. Finally, also the selection of the involved authors, interviewed experts, and people reached for the online survey can cause a one-sided focus, as most individuals involved might have similar views, and we may not even have reached people who are particularly sceptical about the rev. ORC technology. By involving a wide variety of research groups with different focal points within Europe, which is also reflected in the partly differing views on some aspects within the team of authors, we hope to minimise this possible conceptual bias, but since it cannot be ruled out, it should be kept in mind when further analysing and discussing the results.

4. RESULTS

24 experts from various stakeholder groups have participated in the survey. The survey remains open, and additional responses may be incorporated in future updates of this work. Nevertheless, the results already offer valuable insights into the general perception and potential applications.

4.1 General results

Fig. 1 illustrates the general perception of reversible ORC systems based on a 1-to-10 scoring scale, with most responses clustered in the medium-to-high range. This reflects a positive evaluation of the technology's relevance and potential. The figure further shows that the majority of respondents expect market entry within the next 2–5 years, indicating both optimism and a near-term outlook for commercialization. With regard to timescales for development, several participants stated that the commercialisation of small and medium-scale systems could be realised within a very few years by ORC or heat pump manufacturers. Fig. 2 breaks down the perceived application potential across five distinct fields. Industrial waste heat recovery and geothermal systems stand out with the highest average scores and strong support in the "very high" and "high" categories. In contrast, mobile and building applications show a wider spread of opinions, while Carnot battery systems are seen as promising, albeit with some variability. These differences highlight the importance of tailoring development efforts based on specific application needs as well as market potential. The different sectors are discussed in more detail in Section 4.2.

For space reasons, the key results about the general application potential, but also barriers, are summarized in a SWOT analysis (cf. Fig. 3). Next to the clear strengths and opportunities of the technology, e.g. successful proof of concept, lower CAPEX, high flexibility, robust investment, several clear weaknesses are identified, which can be distinguished into technical and non-technical ones: The technical aspects refer mainly to relatively low efficiencies of the reversible rotating machine (cf. Section 5), often in combination with some remaining challenges of the lubrication oil management and also the complex system integration, which prevents standardisation and requires a lot of individual engineering. The non-technological aspects include the unclear exact business case for a commercial project in many settings. In addition, the integration of the rev. ORC technology is a major hurdle in terms of communication with non-technical decision-makers.

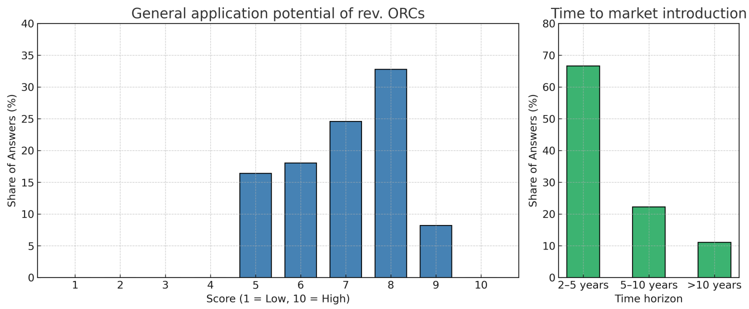

Figure 1: Normalized distribution of the survey answers on the general application potential of rev. ORCs and the potential time horizon for the market introduction.

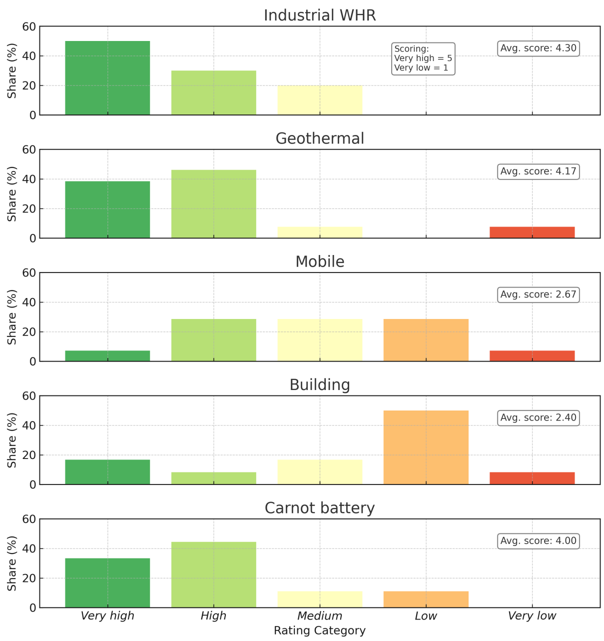

Figure 2: Normalized distribution of the survey answers for five potential rev. ORC fields. Average scores are shown per category, based on scoring from 1 (very low) to 5 (very high).

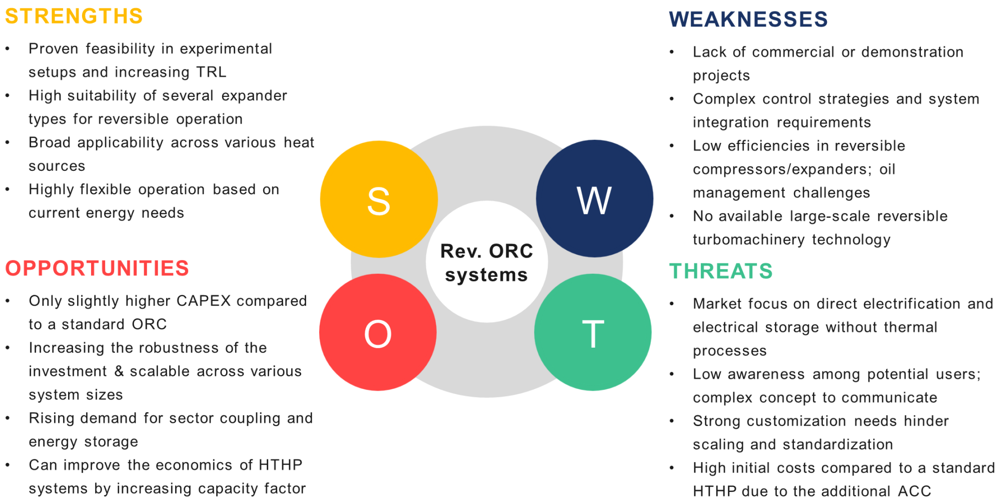

Figure 3: SWOT analysis of the rev. ORC technology.

4.2 Results for the different application fields

This section provides a brief discussion of the results from the survey and the expert interviews on the individual applications, mainly in the form of a standardised ‘factsheet’ for space reasons.

4.2.1 Industrial waste heat recovery

The general evaluation exhibits a high general application potential in the context of WHR. However, the answers also showed some concerns regarding the implementation without thermal energy storage because demand profiles and temperature levels might not always be that suitable for the reversible system. While opinions on rev. ORCs in the steel and cement industry are more sceptical due to the high-temperature levels (making it challenging for the HTHP mode to upgrade heat to a useful level), especially paper & pulp and the food & beverage industry is seen as promising application fields.

Industrial waste heat	**Main potential:**	**Main barriers:**

General assessment:
●●●●◐ 4.3 out of 5
Anticipated plant capacities:
few hundred kW_{el} up to several MW_{el}
	• Robust investment capable of reacting on varying waste heat and heat demand profiles
	• Could be implemented in a Carnot battery concept
	• Various interesting application fields, such as:
	  • Pulp & Paper
	  • Food & Beverage
	  • Cement
	  • Steel
		• The detailed characteristics of many potentially industries might be not suitable
		• Unclearness about detailed real-time demand and waste heat profiles
		• High complexity of the detailed system integration
		• Unclear business case

Figure 4: Key summary for industrial waste heat applications.

4.2.2 Geothermal

The general view on rev. ORC systems in the geothermal context is highly positive, especially by stakeholders from the sector focusing on geothermal CHP projects, since they value the potential all-year use of the surface equipment and having a robust investment against the background of a growing district heating network. One prerequisite is the availability of a sufficiently high brine temperature (e.g. 100°C) to enable meaningful power generation in ORC mode. Furthermore, while conventional geothermal ORC systems are already limited to certain favourable regions, the application potential of rev. ORCs is potentially limited to particular regions, since not only sufficiently high brine temperatures but also larger district heating networks might be required, which is not the case in rural areas. Nevertheless, there is a strong ongoing activity in this application field since both the use case and business case are clearly elaborated. The European FlexGeo project is currently planning the installation of a 200 kWel rev. ORC system at TRL 7 level at a real district heating network.

Geothermal energy	**Main potential:**	**Main barriers:**
General assessment: 4.2 out of 5 **Anticipated plant capacities:** few hundred kW_{el} up to several MW_{el}	• High suitability for a geothermal CHP project due to the year-round utilization of the above-ground plant technology • Robustness for geothermal investments against the background of expanding district heating networks • Additional revenue streams by increased flexibility potential	• Requires a geothermal source with a certain required temperature (e.g. 100-120°C) • Many geothermal sites are in rural regions without a significant large district heating network close by • Potentially limited ORC efficiency in case of low geothermal source temperatures and high ambient temperatures during summer

Figure 5: Key summary for geothermal applications.

4.2.3 Mobile applications

While the overall evaluation of the application potential in mobile systems is partly skeptical, the answers need to be distinguished between on-road and maritime applications. While for both car and truck applications, the market potential is seen currently as rather low, the application on vessels might be of higher interest. Especially against the background of the growing maritime ORC sector, rev. ORCs might be a promising future market. However, next to the promising theoretical application potential, the main challenge might be the practical on-board integration, which requires significant design efforts.

Mobile applications	**Main potential:**	**Main barriers:**
General assessment: 2.7 out of 5 **Anticipated plant capacities:** few kW_{el} up to several hundred kW_{el}	• For cars and trucks rather low at the moment, but the potential technological benefit remains high • Future technologies, such as fuel cells, might also provide sufficient waste heat • Vessels are the most prominent short- and mid-term market potential in the mobility sector	• R&D focus by the automotive industry on other fields; waste heat potential of fuel cell and battery technologies currently often not considered • High on-board complexity on vessels, making the integration more challenging • Strong variations of the use profiles

Figure 6: Key summary for mobile applications.

4.2.4 Building applications

While the theoretical market potential of rev. ORC systems in buildings is tremendous, the current actual market potential is assessed as low. The rev. ORC technology could be a promising aspect in the decarbonization of the building sector, but mainly due to the increasing focus on PV and battery systems, the integration of advanced thermal solutions is economically challenging. Therefore, fewer buildings might have suitable heat sources (e.g. from thermal collectors) available. Finally, also the missing knowledge combined with the conservatism of stakeholders planning buildings' energy systems do not favour more advanced solutions with a higher integration complexity.

Building applications	**Main potential:**	**Main barriers:**
General assessment: 2.4 out of 5 **Anticipated plant capacities:** few kW_{el}	• Large potential of applications, given the cold, heat and power needs of buildings and the path towards low-carbon technologies • Synergies with emerging technologies (e.g low-temperature district heating networks, multi-period thermal storage, electricity grid management (Demand Response))	• Cheap PV and battery systems as the main competing technology • Conservatism of engineering offices dealing with HVAC design It is not easy to convince these offices to install less common technologies • Missing available heat source (thermal collectors) in most new building concepts

Figure 7: Key summary for building applications.

4.2.5 Carnot batteries

The increasing demand for cost-efficient energy storage makes Carnot batteries an attractive solution. For low- and medium-temperature systems, the rev. ORC technology can significantly decrease investment costs. Nevertheless, the minimization of potential performance losses due to the reversible systems compared with two stand-alone ORC and HTHP systems needs to be tackled. At the same time, cheap battery storage systems on the one side and high-temperature Carnot battery technologies on the other side might limit the general market for ORC-based Carnot batteries.

Carnot battery	**Main potential:**	**Main barriers:**
General assessment: 4.0 out of 5 **Anticipated plant capacities:** few hundred kW_{el} up to several MW_{el}	• Significantly lower CAPEX than two standalone ORC/HTHP systems • Strongly increasing demand for energy storage solutions • Integration of low- and medium-temperature (waste) heat sources as heat source for the HTHP mode	• Potential lower performance than two standalone ORC/HTHP systems • Unclear ownership structure and business case • High complexity and more difficult to communicate • Potential focus on high-temperature technologies, such as closed Brayton cycles

Figure 8: Key summary for Carnot batteries.

4.3 Spotlight on the reversible rotating machine technology

To significantly reduce investment costs, a key focus lies on integrating compression and expansion processes within a single machine. Depending on the detailed concept of the reversible system, "reversibility" can refer to either using heat exchangers in both operational modes and/or the rotating machine. Considering a potential reversible rotating machine requires a compromise between ideally designed compressor and expander characteristics, while the efficiency of the overall HP-ORC system is largely dependent on the isentropic efficiency of these processes. The previous sections have demonstrated that the capacities of rev. ORC systems will vary strongly across the different potential application fields. Current R&D activities primarily concentrate on displacement machines (e.g. screw, piston, scroll), which have been demonstrated successfully in several test rigs (Dumont *et al.*, 2015; Kaufmann *et al.*, 2025), while especially the oil management and further improvements of the machines' efficiency remains an important development field.

Nevertheless, turbomachines offer the potential for higher efficiencies and lower maintenance costs, particularly advantageous at higher volume flows, while displacement machines perform better at very low flows. Thus, especially for large-scale rev. ORC systems, the installation of two separate machines (one compressor, one turbine) could be a favourable approach, since such systems allow optimised turbomachines for both modes, while saving significant CAPEX due to shared heat exchangers. Nevertheless, there is also a certain interest regarding reversible turbomachines, which are technically feasible for compressible media and have been prototyped. R&D activities regarding reversible turbomachines have been carried out on axial turbomachines for reversible Brayton processes (Pozzi, 2023) as well as on radial turbomachines in the application area of compressed air energy storages (Hadam and Budt, 2023). The insights gained from these studies are generally transferable to reversible HP/ORC systems. Specific challenges for reversible turbomachines for compressible media include the need for flow guidance and blade geometries that function efficiently in both operating modes. In compressor operation, different pressure and density profiles prevail across the stages compared to turbine operation; this alters the optimal inlet angles of the blades. With a fixed geometry, at least one operating mode will invariably work under suboptimal inlet conditions. Furthermore, reversible turbomachines must operate stably within two distinct operational ranges, which may restrict operational capabilities (e.g. part load range) due to varying design parameters (e.g. throughput, pressure ratio). This also affects the mechanical loads (e.g. axial forces or vibrations) in the two operating modes, and rotation directions differ, complicating the design of bearings and seals. Thus, development needs include utilizing modern optimization techniques, such as automated CFD/FEM simulation of geometry variations, to find superior geometries.

Nevertheless, profile design remains a central challenge – possible solutions include adjustable guide vanes. Furthermore, R&D on novel designs, such as combining axial and radial stages or using additive manufacturing for complex blade profiles and development and testing of prototypes with a focus on experimental research on aerodynamics and new geometries might be a promising approach.

5. CONCLUSION AND OUTLOOK

This work has provided a comprehensive assessment of rev. ORC applications by combining a technical overview with qualitative insights from industry and research stakeholders. While the technological feasibility of rev. ORC systems has been repeatedly demonstrated, commercial deployment is still missing. The survey results confirm a generally positive perception of the technology and demonstrate that, from a technical perspective, a market entry for at least small- and medium-scale systems would be feasible in the next years. Among the assessed application fields, industrial waste heat recovery, Carnot batteries, and geothermal systems stand out for their technical fit and economic promise. In contrast, building and on-road mobile applications face practical limitations and unfavourable general market trends, such as the focus on PV and battery systems for buildings. Key challenges remain, particularly regarding the efficiency and reliability of reversible rotating machinery, the management of optimal working fluid charge when switching from one mode to the other, the complexity of system integration, and the lack of standardized business cases. The SWOT analysis highlights that while rev. ORC systems offer high flexibility and a robust investment decision, these benefits must be better communicated and translated into clear commercial offerings. Additionally, clearer demonstration projects could build confidence among users and investors. Ultimately, fostering collaboration between academic research, technology developers, and end-users will be vital to realizing the full potential of rev. ORC systems.

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