RESEARCH AND REVIEWS IN SUSTAINABILITY

The Potential of Small-Scale Solar Organic Rankine Cycle Systems for Decentralised Power Generation in Africa

REVIEW

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ABSTRACT

Access to affordable and reliable electricity remains a significant challenge in Africa, particularly in remote and rural areas where centralised grid expansion is economically unfeasible. Small-scale solar organic Rankine cycle (SORC) systems offer a promising solution for decentralised power generation. The review explores the potential of solar organic Rankine cycle systems as a small-scale power generation solution for Africa with a specific focus on affordable components, including solar collectors, expanders and working fluids. It highlights the importance of cost-effective solutions for SORC. Despite considerable research on SORC systems globally, there is a noticeable lack of studies specifically addressing SORC performance in the climate conditions of Africa. Future research should prioritise optimising system design for this region, focusing on low-cost, robust solutions for variable solar input and limited infrastructure.

Highlights

- Lack of studies focused on SORC implementations in Africa
- Need for climate-optimised and cost-effective SORC systems
- Limited field testing and real-world validation of small-scale SORC systems

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1. INTRODUCTION

Despite global advancements in electrification, approximately 770 million people worldwide still do not have access to electricity, with 562 million in Africa (International Energy Agency, 2021; The World Bank, 2021). Access to electricity remains a critical challenge in many regions where most of the population lacks reliable energy. Notably, over 70% of people without access to electricity in Africa reside in rural areas far from centralised power grids (Hasan et al., 2024). For example, in Nigeria, only 55% of the population has access to the national grid, which covers only 30% of the country's total electricity demand (Ebhota and Tabakov, 2018). Furthermore, Africa's energy demand is projected to double by 2040, driven by rapid population growth and economic development (IRENA, 2019). Therefore, there is an urgent need for substantial investment and innovative energy solutions to bridge the energy access gap (Bhattacharyya, 2012). Population growth outpaced efforts to expand electricity access in Africa in recent years due to the combined effects of COVID-19 and war in Ukraine (IEA, 2024). Between 2010 and 2019, overall electricity access grew by 0.7% per year; however, there was a decline to 0.6% between 2019 and 2021 (International Energy Agency, 2022).

Centralised power generation (CPG) demands a substantial capital investment to extend electricity to remote areas, where infrastructure necessitates a relatively low power supply (Rahbar et al., 2017). Moreover, conventional fossil fuel-based power plants contribute to greenhouse gas emissions. For example, 37 million people in Tanzania still rely on expensive and hazardous lighting sources such as kerosene (Okika et al., 2025). Given the urgency of reducing emissions and promoting renewable energy, there is a growing need to explore alternative, decentralised power solutions (Tchanche et al., 2009). Decentralised power generation units present a promising solution within zero-carbon energy strategies, as they are capable of simultaneously supplying electricity, heating, and cooling from a single integrated unit. These systems, commonly known as trigeneration or Combined Cooling, Heating, and Power (CCHP) systems, offer substantial improvements in overall energy efficiency and contribute significantly to the reduction of carbon emissions at the point of use. In addition to lowering emissions, trigeneration systems enhance access to on-site power generation and can reduce operational costs (Sonar et al., 2014). However, these systems tend to be complex, capital-intensive, and often require the integration of additional renewable sources such as biomass to ensure consistent performance (Sibilio et al., 2017).

Solar energy is a renewable and sustainable recourse that can contribute to decrease of emissions and supports the transition to green energy (Mandal and Reddy, 2025). Africa has 60% of the world's total solar potential yet installed solar PV capacity remains at only 1% (Casati et al., 2023). This underscores the potential of solar energy as a viable solution for electrification in Africa. Even though photovoltaic systems appear to be the most suitable technology for harnessing solar energy, the costs associated with the batteries make the implementation of this technology for rural electrification costly (Constantino et al., 2022). In contrast, solar thermal technologies such as the Solar Organic Rankine Cycle (SORC) offer a promising, battery-free pathway to clean energy access. These systems can support both power generation and thermal applications. Among various renewable energy technologies, the Solar Organic Rankine Cycle system has emerged as a promising solution for off-grid, small-scale electrification (Tchanche et al., 2009).

Expanding access to affordable, clean energy is essential for addressing climate change and expanding electricity access in rural areas. Off-grid renewable energy is promising for overcoming the access gap in rural areas in Africa (International Energy Agency, 2022). While large-scale SORC systems have been successfully commercialised, small-scale SORC is still under development (Baral et al., 2015a).

1.1 NOVELTY AND CONTRIBUTION

While several reviews have examined SORC technologies considering the working fluid, type of solar collectors, numerical modelling ORC system parameters and optimisation (Loni et al., 2021; Matuszewska, 2024), these studies primarily focused on large-scale applications. Wieland et al., (2023) evaluated the recent developments in ORC systems and large-scale implemented ORC projects. Similarly, Ogunmodimu and Okoroigwe, (2018) and Seshie et al., (2018) explored the progress and potential of concreting solar power technologies in Nigeria and Sub-Saharan African region. Baral, (2018) evaluated the feasibility of solar ORC for rural electrification in South Asian countries, considering small and medium-scale systems.

This study focuses on small-scale SORC system for decentralised generation in Africa. This review bridges a gap in the literature by addressing the intersection of climate suitability, affordability, and technological feasibility for rural electrification in this underrepresented region. It emphasizes cost-effective configurations of system components that are technically viable and economically appropriate for rural application in hot climates.

1.2 METHODOLOGY

The present paper is based on selected publications identified through a databases such as ScienceDirect and Scopus using keywords such as "solar", "ORC", "Organic Rankine Cycle", "micro-power", "small-scale", "rural electrification", "off-grid power", "microgrid", "Africa". Additionally, the studies referenced in the initially selected papers were included. Studies published between 2000 and 2024 were considered. Studies that did not involve solar input and focused on medium or large-scale power generation were excluded.

This review explores the potential of solar ORC technology for small-scale and micro-power generation in Africa, analysing its feasibility and challenges in deployment. This review assesses the affordable solutions for solar thermal technology as a practical solution for off-grid power generation in Africa. Section 2 provides an overview of energy access in Africa and highlights the need for decentralised solar thermal systems. Section 3 reviews affordable, small-scale SORC components. Section 4 presents case studies and examines the influence of climatic conditions on the performance of solar ORC. Finally, Section 5 discusses the recommendations for future studies.

2. ENERGY ACCESS IN AFRICA

Access to reliable and affordable electricity remains one of the challenges in Africa. According to *Tracking SDG 7: The Energy Progress Report* (IEA, 2023), Nigeria had the highest number of people without access to electricity in 2021 (86 million), followed by the Democratic Republic of the Congo (76 million) and Ethiopia (55 million). These figures underscore the critical energy access gap in Africa.

Electrification rates remain critically low in many parts of Africa (Figure 1a). For instance, only 38.4% of Tanzania, 7.8% of Chad, 47.5% of Congo, 65% of Cameroon, and 46.9% of Sudan have access to electricity (IEA, 2024). Rural communities are disproportionately affected, where extending national grids can be both logistically challenging and expensive. Providing electricity to a small population in rural areas can be expensive (Constantino et al., 2022). Therefore, least-cost planning is essential for bridging the affordability gap and ensuring reliable and efficient energy access for households in remote areas (International Energy Agency, 2022). Decentralised renewable energy systems offer an effective alternative to grid expansion. To address the challenge of unreliable grid supply and to leverage the region's high solar irradiance potential, Ehtiwesh et al., (2023) conducted a study on decentralised electricity generation for a hospital in Libya using a solar Rankine cycle system integrated with thermal energy storage. Their system successfully managed power output in accordance with the hospital's demand profile.

Small-scale SORC systems can be applied in rural areas where extending the electricity grid is impractical due to challenging geographic terrain (Baral et al., 2015a). They offer a sustainable alternative to diesel generators and traditional biomass, providing power for lighting, appliances, and water pumping. Small-scale solar ORC power systems (0.5–10 kW) are suitable for homes, schools, and rural health centres, providing localised power generation (Baral et al., 2015b). Figure 1b provides a solar resource map of Africa, highlighting the suitability of the area for solar-based technologies in this region.

Although the upfront cost of implementing ORC systems can be high, they provide several advantages that make them attractive for rural electrification. Solar ORC systems are relatively easy to install in off-grid areas, and their components can last a long time due to the low mechanical stress, resulting in reduced maintenance demands over time (Baral et al., 2015b).

Minimising the investment, operation, and maintenance costs is essential for the viability of small-scale solar ORC systems. The next section will explore deeper into the core components of ORC technology, highlighting cost-effective options.

3. OVERVIEW OF SMALL-SCALE ORC COMPONENTS

The ORC is a promising technology for reducing CO_2 emissions by converting waste energy into usable power (Freeman et al., 2015). ORC offers advantages such as compact size, low cost, simple design, and minimal environmental impact, particularly when integrated with renewable energy sources (Rahbar et al., 2017).

ORC technology is well-suited for small-scale power generation, efficiently utilising thermal sources below 300°C to deliver power outputs ranging from a few kilowatts to several megawatts (Derbal-Mokrane et al., 2021). ORC consists of the main components such as a pump, a turbine or expander and a condenser. Figure 2 presents the simple ORC configuration. ORC systems operate using low to medium-temperature heat sources such as waste heat, geothermal, solar and biomass.

Small-scale solar ORC can be relatively costly compared to larger systems. However, reducing component costs would lower investment expenses, making SORC a sustainable solution for energy access in remote areas (Baral et al., 2015a). For example, a study by Bruno et al., (2008) revealed that optimised SORC systems with parabolic trough collectors are more cost-effective than PV panels while offering similar efficiency.

Among the components of SORC systems, solar collectors and expanders have the most significant impact on the initial capital cost (Baral et al., 2015a). The scroll expander accounts for 54% of the total cost, while the working fluid pump contributes 10% (Baral et al., 2015b). These figures highlight the importance of careful component selection and cost optimisation in improving the economic feasibility of small-scale deployments.

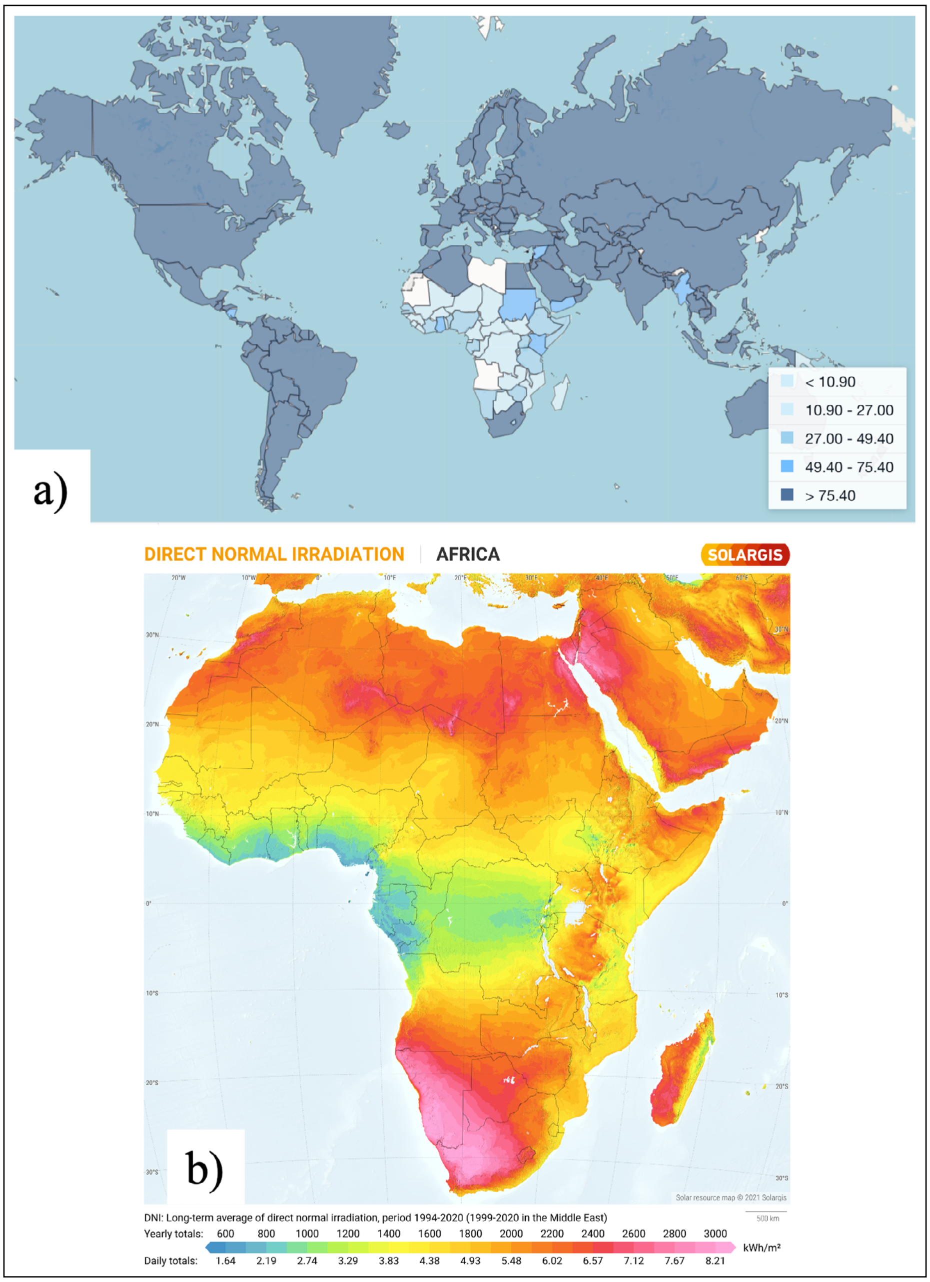

Figure 1 a) Access to electricity (% of population) in 2022 (IEA, 2023), **b)** Direct normal irradiation in Africa (Solargis, 2021).

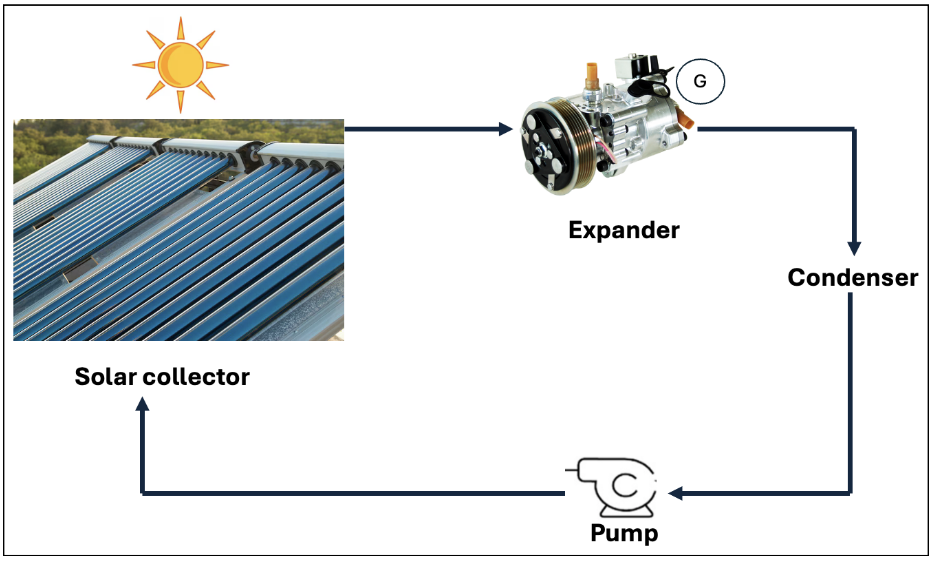

Figure 2 SORC schematic diagram.

SOLAR COLLECTORS

In solar-ORC systems, solar collectors convert solar energy into thermal energy (Loni et al., 2021). The temperature of the thermal energy source for the ORC is crucial, as it directly influences the thermal efficiency of the system. Therefore, the type of solar collectors used significantly contributes to the achievable temperature levels. The main types of solar collectors can be categorised based on temperature ranges (Figure 3): low temperature collectors, such as flat plate collectors (FPC), operate up to approximately 100°C, while low and medium temperature collectors, including evacuated tube collectors (ETC), compound parabolic collectors (CPC), and parabolic trough collectors (PTC), function effectively within the 100–300°C range (Delcea and Bitir-Istrate, 2021).

Solar-driven systems, when designed properly, can achieve strong performance levels. Solar collectors can be classified into stationary and tracking collectors. Stationary collectors remain in a fixed position and do not track the movement of the sun. The most common type of stationary collector, FPC, is widely used for low-grade heat applications due to its affordability. In contrast, PTC are more suitable for high-temperature applications, as they offer superior efficiency at elevated temperatures by tracking the sun (Kalogirou, 2004; J. L. Wang et al., 2010). As fixed position collectors, ETC have been used as collector in ORC applications as it can be used in low and medium-temperature applications of up to 200°C. Although the achievable temperatures of these non-concentrating collectors are lower compared to sun-tracking systems, they can utilise diffuse radiation in addition to direct radiation. This makes them particularly advantageous in regions predominantly dependent on diffuse radiation, such as the UK (Freeman et al., 2017, 2015). ETC-based systems have increased the ORC operating temperature to over 100°C, making them a viable solution for solar power generation systems. Additionally, recently developed evacuated flat plate collectors (EFCs) have also been utilised in ORC applications. EFCs benefit from an evacuated environment, which reduces heat loss, while their flat plate absorber maximises solar utilisation. In ORC applications, EFCs have also demonstrated promising performance, further enhancing solar thermal efficiency for power generation (Calise et al., 2015; Freeman et al., 2017; Kutlu et al., 2018).

EFCs have also been utilised as converted PV/T collectors, where thin amorphous PV cells are placed within the evacuated environment. This configuration allows for simultaneous high-temperature heat collection and direct electricity generation through the PV cells, enhancing the overall solar energy utilisation of the system (Li et al., 2018; Yu et al., 2024). Additionally, evacuated flat plate PV/T collectors have been employed in ORC applications (Ahmad Qureshi et al., 2021; Kutlu et al., 2020).

Among the available solar technologies, parabolic trough collectors are generally preferred due to their ability to deliver high-temperature thermal energy required for efficient ORC operation (Dabwan et al., 2018; Sibilio et al., 2017). In contrast, stationary (non-tracking) solar collectors yield lower operating temperatures, which result in reduced thermal efficiency. Consequently, such systems demand either a larger collector area or must be deployed in regions with consistently high solar irradiance to maintain year-round functionality.

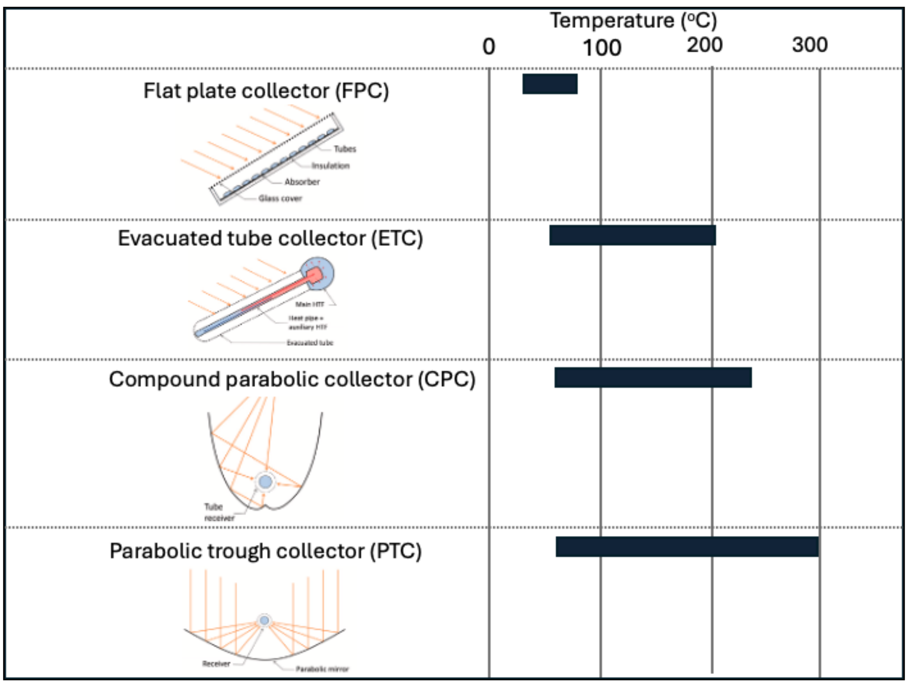

Figure 3 Sollar collector types (Delcea and Bitir-Istrate, 2021; Dickes et al., 2025).

The performance and cost-effectiveness of SORC systems are strongly influenced by the type and size of the solar collector used. Ramos et al., (2018) compared two different solar collectors and revealed that the most efficient solar-ORC setup using FPCs produced a nominal net power output of 460 W with R245fa as the working fluid. In contrast, ETC system generated over 1.7 kW using R1233zd despite both systems utilising the same collector area of 60 m². However, this higher performance came with a significantly greater cost, as the total investment for the ETC system was almost double that of the FPC system. These findings underscore the importance of evaluating both performance and cost when selecting collector types. Ancona et al., (2022) carried out a parametric analysis considering FPC with different sizes (21.5 m², 32 m², and 64.5 m²) in combination with varying size storage tank capacities. The study found that a collector area of 32 m² showed the highest system performance, while larger and smaller collector sizes resulted in reduced efficiency and off-design operation of the system. These findings highlight the importance of carefully matching solar collector size with thermal demand and overall system operating conditions.

Furthermore, the required solar collector area must be optimised for output power, collector type and climate conditions. (Delgado-Torres and García-Rodríguez, 2010) found that a compound parabolic collector (CPC) requires 25–26 m², while a flat plate collector (FPC) needs 22–23 m² to generate 1 kW of power. Fatigati et al., (2022) experimentally tested a small-scale solar ORC system integrated with a 15 m² flat plate collector, demonstrating electrical power outputs ranging from 100 W to 500 W. Baral et al., (2015a) demonstrated the effect of seasonal solar variation on collector sizing. To achieve a solar source temperature of 120°C, 37 m² of collector area was needed in December, compared to only 25 m² in April, highlighting the significant impact of seasonal irradiance on system design. Kutlu et al., (2019b, 2019a) in their study using weather data from Istanbul, Turkey, demonstrated that while sufficient power can be generated on sunny days, system performance drops significantly in winter, rendering the unit unable to meet energy demands consistently. However, African climatic conditions with abundant solar radiation and higher ambient temperatures are more conducive to year-round solar-driven power generation, supporting the viability of these systems in the region. Overall, these studies emphasise the need to optimise solar collector areas according to climate conditions, power output requirements, and cost efficiency.

It should be noted that the success of any technology for domestic small-scale applications relies not just on its efficiency but also on its affordability and reliability. Therefore, it is essential to appropriately integrate ORC components with the solar thermal collector, ensuring that the system achieves the maximum mechanical or electrical energy output at the lowest feasible cost (Freeman et al., 2015). Therefore, selecting the appropriate collector type involves balancing the overall energy yield against the heat source quality, with the deciding factors being the maximum achievable ORC power and the relative cost.

EXPANDER TECHNOLOGY

Expansion machines are a critical component of the ORC system that significantly influences cycle efficiency. Expansion machines (Figure 4) can be categorised into two main types: velocity-based (turbine) and volumetric (scroll expanders, screw expanders, vane expanders, piston expanders) (Song et al., 2015). The selection of the expansion machine depends on factors such as the working fluid, operation conditions and net power output (Rahbar et al., 2017).

Volumetric expanders are generally preferred for small-scale applications due to their high reliability, availability, and lower cost than turbines (Mendoza et al., 2014; Song et al., 2015). Turbines are ideal for large-scale ORC systems due to their high output power and rotation speed, while screw expanders suit medium-scale systems, and scroll and vane expanders, with lower rotation speeds and capacity limitations, are best for small and micro-scale ORC systems (Zhao et al., 2019). Imran et al., (2016) compared different types of expanders, including vane, screw, scroll and piston, for the ORC system. Their findings indicated that screw and

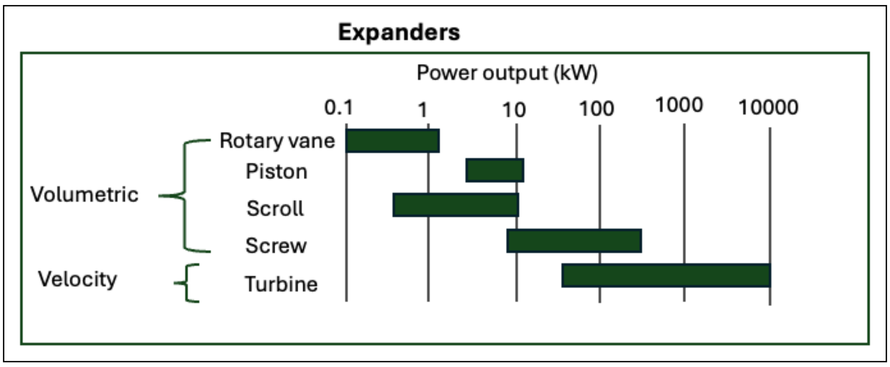

Figure 4 Expander types (Alshammari et al., 2018; Quoilin et al., 2012).

scroll expanders demonstrated superior performance, while vane and piston expanders required further design optimisations. Their study highlighted that scroll expanders are well suited for small-scale power ranges of 1–25 kW due to their simple design. In contrast, screw expanders are found to be less economically viable for applications below 25 kW, primarily due to their higher cost.

For small-scale ORC systems, the expander represents a significant portion of the overall cost (Galloni et al., 2015). Scroll expanders provide a balance between performance and accessibility and are widely used in studies because they can be easily obtained from refrigeration compressors (Zhao et al., 2019). Converted scroll compressors, which are widely available and cost-effective, offer a viable solution for small-scale ORC applications (Campana et al., 2019).

Many studies have investigated scroll expanders modified from existing compressors (Rahbar et al., 2017), including automotive air conditioning (Saitoh et al., 2007; Woodland et al., 2012) and refrigeration compressors (Galloni et al., 2015). Figure 5 shows different types of scroll compressors. Saitoh et al., (2007) demonstrated the feasibility of using a scroll expander, modified from automotive air conditioning systems, in an ORC system combined with a solar collector for a small-scale power generation system. A study by De Lucia et al., (2024) also confirmed the feasibility of employing a commercial scroll compressor as an expander in small-scale solar ORC systems.

The modification of scroll compressors into expanders involves removing the check valve, which was originally installed in the scroll device to stop the discharged high-pressure working fluid from flowing back to the device and prevent the reverse rotation of the scrolls in compressor mode. However, in the expander mode, the check valve stops the fluid from flowing into the scrolls, which should be removed before operation. Figure 6 shows the scroll before modifications and after the removal of the check valve.

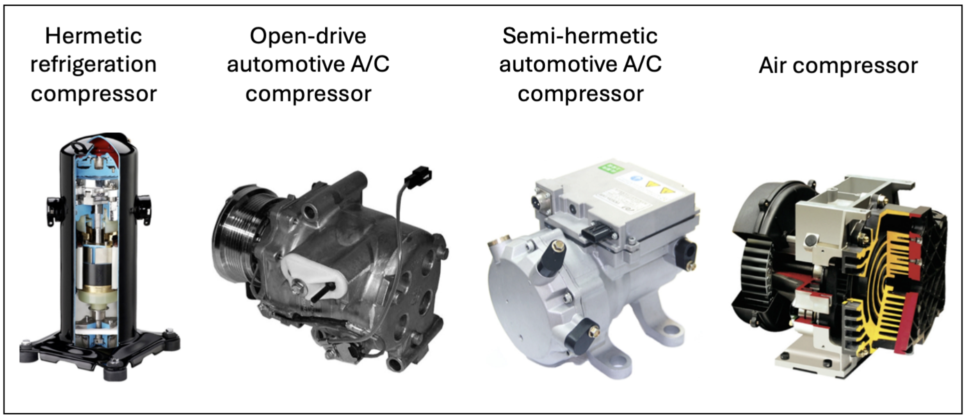

Figure 5 Scroll compressor types for expander modifications (Song et al., 2015).

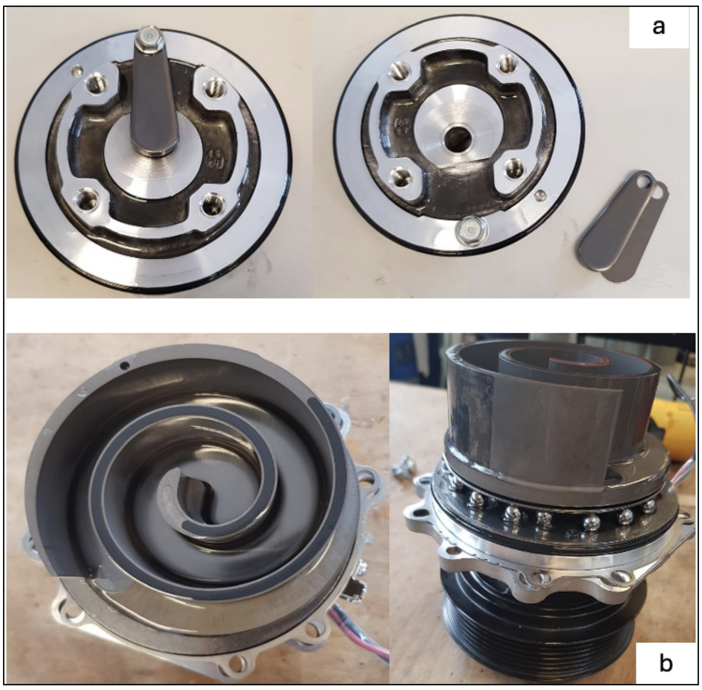

Figure 6 a) Before and after the removal of the check valve, **b)** Orbiting scroll and bearings.

Woodland et al., (2012) analysed the performance of a small-scale ORC system employing an automotive scroll compressor converted into a scroll expander. The results highlighted that off-the-shelf scroll compressors could perform efficiently as adapted expanders in ORC systems, with optimal performance achieved when the expander's built-in volume ratio aligns with system operating conditions. Galloni et al., (2015) investigated small-scale (1- 3 kW) ORC utilising a scroll expander (Air Squared model E15H22N4.25L) for low-grade heat recovery. The proposed system achieved a thermal efficiency of 9.3%, providing a power output of around 1 kW. Manolakos et al. (2007) experimentally evaluated a modified Sanden TRS 105 model compressor, achieving a maximum efficiency of approximately 65% and a power output of around 2.05 kW.

Moreover, some optimisation can be done to improve the performance. De Lucia et al., (2024) highlighted that improvements need to be implemented to achieve maximum isentropic efficiency of converted scroll expanders. Georges et al., (2013) assessed a two-expander configuration using hermetic scroll expanders modified from refrigeration compressors. The findings indicated that the two-expander setup resulted in a 38% increase in thermal efficiency, with each expander attaining an isentropic efficiency of 0.69.

The summary of the performance of the scroll expanders modified from the scroll compressors in studies is presented in Table 1. These studies underscore the potential of utilising converted scroll compressors as scroll expanders in small-scale ORC systems.

WORKING FLUIDS

The selection of the working fluid plays a critical role in the performance and feasibility of ORC systems. The choice of working fluid is highly dependent on the heat source characteristics, operating temperature, pressure conditions, and the specific application (Derbal-Mokrane et al., 2021).

An optimal working fluid must exhibit optimum thermodynamic properties at low-to-medium temperatures, ensuring high thermal efficiency while maintaining economic viability, environmental sustainability, and operational safety, significantly narrowing the list of working fluids (Han et al., 2020).

R245fa is the most employed working fluid in solar-based ORC systems, followed by pentane (R601) (Canada et al., 2024; Derbal-Mokrane et al., 2021). Additionally, for low to medium-temperature applications, working fluids such as Freon 123 (R123) (Baral and Kim, 2015), Isopentane (R601a) (Delgado-Torres and García-Rodríguez, 2010) and NeoPentane (R601) (Wang et al., 2020) can be used. Also, butane (R600) and isobutane (R600a) are recommended as a working fluid, however, for temperature ranges between 70 °C and 120 °C (Lu et al., 2012; Tchanche et al., 2009).

Georges et al., (2013) assessed six working fluids for a small-scale solar ORC system, including R123, R245fa, SES36, Pentane, HFE7000, and Ethanol. In their study, R245fa was selected for further investigation due to its high efficiency and lower system cost, primarily resulting from the smaller expander size requirements compared to other working fluids. Similarly, Quoilin et al., (2011) highlighted trade-offs between overall efficiency and equipment sizing when using different working fluids; for example, while Solkatherm demonstrated superior efficiency, R245fa offered advantages in terms of compact equipment design and cost efficiency. A study by Roumpedakis et al., (2020) investigated several working fluids for the SORC system; the results indicated that R245fa had the highest thermal efficiency, around 7% at 110°C, followed by R152a and R236ea at higher and lower temperatures, respectively.

STUDY	EXPANDER TYPE	WORKING FLUIDS	OVERALL EFFICIENCY (%)	ISENTROPIC EFFICIENCY (%)	ROTATIONAL SPEED (RMP)	ENERGY PRODUCED (kW)
Manolakos et al., (2007)	Scroll expander (Sander TRS 105)	HFC-134a	4	10–65	2000	2.05
Peterson et al., (2008)	Scroll expander	R123	7.2	45–50	600–1400	0.187 – 0.256
Saitoh et al., (2007)	Scroll expander	R113	7 (based on solar radiation)	65	1800 (optimal)	0.450
Galloni et al., (2015)	Scroll expander (Air Squared model E15H22N4.25L)	R245fa	9.3	84.9	3000	1.17
Campana et al., (2019)	Scroll expander (SANDEN TRS090)	R245fa	3	45	200–1500 (optimal 1000–1200)	0.450
Collings et al., (2019)	Scroll expander (E15H022A-SH)	R245fa	8.64 (regenerative); 5.37 (non-regenerative)	74.5 (regenerative); 68.3 (non-regenerative)	–	0.650

Table 1 Scroll expanders converted from scroll compressors used in studies.

R245fa and R134a are among the most commonly used working fluids in small-scale ORC systems; however, these fluids have relatively high Global Warming Potential (GWP) (Heberle et al., 2016; Landelle et al., 2017). Researchers have explored various low-GWP working fluids alternatives, to optimise system performance and reduce environmental impact. However, several studies have shown that low-GWP working fluids exhibited lower performance compared to conventional fluids commonly used in ORC systems (Ancona et al., 2022). Eyerer et al., (2019) investigated low-GWP alternatives by experimentally comparing the performance of R1233zd(E) and R1224yd(Z) against R245fa in a small-scale ORC setup. Their findings showed that R245fa achieved the highest power output, reaching 326 W, which was 9% and 12% higher than R1233zd(E) and R1224yd(Z), respectively.

The cost-efficiency of the system is essential for off-grid power applications in rural areas. Lower cost working fluids such as R152a, R1234ze(E), and R134a lead to shorter payback periods. However, R245fa, despite not being the cheapest option, offers a balance between thermodynamic and economic efficiency (Roumpedakis et al., 2020).

4. REVIEW OF SMALL-SCALE SORC CASE STUDIES

Numerous studies have numerically and experimentally investigated small-scale solar ORC technology implementation across various locations and climate conditions (Table 2). The following case studies highlight the influence of climate, solar collector configurations and working fluids on system performance.

While small-scale SORC systems are primarily explored for off-grid power generation, they also show promise for hydrogen production and desalination applications. Derbal-Mokrane et al., (2021) conducted a numerical assessment of a small-scale ORC system integrated with a PTC solar plant for electrolytic hydrogen production in Algeria. The study demonstrated that the ORC system had an electrical production capacity ranging from 2.24 kW to 8.74 kW. Among the fluids analysed, benzene yielded the highest power output, followed by Toluene, isopentane, and n-pentane, emphasising the importance of thermodynamic properties in optimising power generation efficiency. Several studies showed the potential of the SORC system for reverse osmosis (RO) desalination in remote areas (Manolakos et al., 2009; Tchanche et al., 2010). Tchanche et al., (2010) demonstrated the feasibility of SORC-powered desalination for remote or off-grid areas, emphasising the importance of working fluid selection, heat exchanger effectiveness, and exergy optimisation.

Most studies have focused on applying SORC systems for decentralised power generation in rural and remote areas. Orosz et al., (2013) explored the potential of SORC systems for decentralised energy generation in rural health facilities across Africa. The analysis revealed that SORC systems can be a cost-effective alternative to diesel generators. Quoilin et al., (2011) numerically evaluated a low-cost SORC system designed for remote power generation in rural Lesotho. The system utilised PTC and employed a modified HVAC scroll compressor as the expander, targeting a net electrical output of 3 kW. Their findings demonstrated that climatic conditions such as ambient temperature, wind speed, and solar irradiance directly affect the solar collector's efficiency and the ORC cycle's performance. While lower ambient temperatures can reduce the condensing temperature and enhance cycle efficiency, they also increase heat losses from the collector.

Additionally, Piñerez et al., (2021) performed a numerical evaluation of a small-scale solar ORC system for off-grid power generation in Colombia using historical solar radiation data. The study assessed the impact of different working fluids and found that integrating a solar collector with a storage tank ensures thermal stability during non-radiation hours. The SORC system in the Rancho Grande city location showed the best system performance, with Toluene as the most efficient working fluid, achieving 14.6% energy efficiency and a peak power output of 5.50 kW in October. These results underscore the significant influence of seasonal solar radiation and ambient temperature variations on ORC performance, reinforcing the necessity of climate-specific system optimisation. The study by Kutlu et al., (2025) indicated that solar heat input has the greatest influence in system efficiency.

The weather and environmental conditions significantly influence the SORC system efficiency. Baral et al., (2015a) numerically and experimentally investigated a small-scale SORC system for off-grid electrification in rural areas, considering the weather conditions of Busan, South Korea. The findings showed that power output varied between 0.4 kW to 1.38 kW throughout the year, with maximum production in April and the lowest in December, correlating with solar irradiance variations. Roumpedakis et al., (2020) conducted an optimisation study of small-scale, low-temperature solar-driven ORC systems by evaluating various working fluids, solar collector types, and cities across the South-East Mediterranean region. Their findings revealed that the relationship between solar field size and optimisation parameters is complex and highly dependent on local climate conditions. The highest exergy efficiency (6.2%) was achieved with R245fa and evacuated tube collectors in Istanbul**,** indicating that collector type and working fluid must be optimised

STUDY	CLIMATE/ LOCATION	ENERGY PRODUCED	SOLAR	WORKING FLUID	EXPANDER TYPE	APPLICATION
Derbal-Mokrane et al., (2021)	Algeria/Mediterranean climate	2.24 kW to 8.74 kW	PTC	enzene	Turbine	Hydrogen production
Piñerez et al., (2021)	Colombia/Tropical climate	Up to 5.50 kW	ETC	Toluene	Turbine	Off-grid power generation
Quoilin et al., (2011)	Lesotho/Temperate climate	3 kW	PTC	R245fa	Scroll	Off-grid power generation
Manolakos et al., (2009)	Greece/Mediterranean climate	2.83 (cloudy day), 5.98 kW (sunny day)	ETC	HFC-134a	Scroll	RO desalination
Roumpedakis et al., (2020)	South-East Mediterranean region (Athens, Thessaloniki, Istanbul, Larnaca)/ Mediterranean climate	<5 kW	FPC, ETC, PTC	R245fa (several tested)	Scroll	Off-grid power generation
Ramos et al., (2018)	Southern European area/ Mediterranean climate	1.72 kW	FPC, ETC	R245fa, R1233zd	Turbine	Domestic solar thermal systems
Mavrou et al., (2015)	Greece/Mediterranean climate	1 kW	FPC	Binary mixture	Turbine	Power generation
Baral et al., (2015a)	Busan, South Korea/Humid subtropical climate	0.4–1.38 kW during the year	ETC	R245fa	Scroll	Off-grid power generation
Tchanche et al., (2009)	Bamako, Garoua, Bangkok/ Tropical savanna climate	2 kW	Not specified	R134a (several tested)	Micro-turbine	Not specified
Calise et al., (2015)	Mediterranean climate	6 kW	ETC	n-pentane	Turbine	residential users (DHW)
Tchanche et al., (2010)	Greece/Mediterranean climate	Up to 2 kW	ETC	R134a, R245fa, R600	Not specified	RO desalination
Facão et al., (2008)	Spain, Tunisia, Egypt/ Mediterranean, hot semi-arid, hot desert climates	5 kW	FPC, CPC, PTC	Several tested	Turbine	Residential use
Wang et al., (2010)	China/Temperate climate	1.73 kW	ETC, FPC	R245fa	Rolling-Piston Expander	Off-grid power, RO desalination
Gilani et al., (2022)	Cyprus/Mediterranean climate	3.92 kW	ETC	Isobutene	Turbine	Air conditioning for office building
Taccani et al., (2016)	Italy/Mediterranean climate	670 W	PTC	R245fa	Scroll	Power generation
Fatigati et al., (2022)	Italy/Mediterranean climate	100 – 500 W	FPC	R245fa	Scroll	DHW

Table 2 Case study summaries.

for regional climate conditions to achieve the best performance. Similarly, Calise et al., (2015) investigated solar-driven ORC systems in Mediterranean climates, and results showed that solar collector efficiency varies significantly, reaching 50% in summer but dropping to 20% in winter. Xiao et al., (2024) tested a 4 kW ORC system and found that output power decreases with an increase in temperature from -10°C to 30°C by 13.5%.

Not only temperature and solar radiation but also wind can influence the performance of the SORC system. Marion et al., (2014) showed the energy produced during a sunny day can be decreased due to the high winds, indicating that wind plays a significant role in reducing the effective thermal power of the solar collector.

While numerical models provide valuable insights, experimental studies and field testing are essential to validate ORC performance under actual operating conditions. However, only a few studies have conducted experimental testing. Wang et al., (2010) evaluated experimentally a SORC system using R245fa as the working fluid, integrating ETC and FPC in Tianjin, China, which demonstrated an average power output of 1.73 kW. Taccani et al., (2016) tested an ORC system integrated with a PTC having a surface area of 100 m^2. The results showed that the system achieved a peak electrical output of 670 W under a solar irradiance of 590 W/m^2 and a collector outlet temperature of 100.4 °C. Manolakos et al., (2009) tested a 5 kW solar ORC system installed in Athens; the system achieved an expander efficiency of 14.7% on cloudy days and 28.5% on sunny days. However, these values were significantly lower than those observed in laboratory tests, which reached approximately 75% efficiency. This discrepancy highlights the impact of real-world operational challenges, such as variable weather conditions, system heat losses, and component degradation**,** on SORC efficiency. More experimental validation studies are necessary to improve system reliability, thermal storage integration, and long-term economic feasibility.

5. FUTURE RESEARCH AND RECOMMENDATIONS

While significant progress has been made in improving the efficiency of SORC systems, affordability remains a major challenge for their widespread adoption, particularly in rural areas of developing countries. The economic viability of SORC systems is strongly influenced by factors such as geographical location, local climate conditions, and the availability of solar radiation. Africa, with its abundant solar resources, presents a promising opportunity for the deployment of small-scale SORC systems. These systems have the potential to reduce dependence on conventional energy sources and provide a reliable energy solution for remote and off-grid communities. Therefore, the development of cost-effective, small-scale SORC solutions is essential to improve energy access and support sustainable development across Africa.

The review assessed the affordable components for SORC; the main cost investments come from solar collectors and expanders. The review showed that expander cost can be decreased using a converted scroll expander from the compressor. The performance of a solar ORC system is strongly influenced by solar irradiance, which varies with location, time of day, and collector type, requiring an optimal collector size to maximise power output while minimising costs (Baral et al., 2015b). Solar collectors' surface area and type must be optimally designed to match the local solar resource conditions and the required output power, thereby reducing capital costs.

The successful deployment of ORC technology in rural areas of developing countries depends on its thermal efficiency, affordability and reliability. To advance affordable renewable energy solutions, governments in developing countries should prioritise investments in research and development (R&D) programs (Okika et al., 2025). Mass production of ORC units could significantly cut costs, making them highly feasible for electrifying small, isolated communities (Baral et al., 2015b).

A review of case studies indicated that mostly parabolic trough and evacuated tube collectors with converted scroll expanders and turbine expanders were tested for small-scale SORC systems across different locations. Climate conditions, including temperature and wind exposure, greatly influence the systems' performance. However, there is a lack of studies for Africa despite its high solar potential and growing energy demand. Most existing case studies are based in Europe or other regions with different irradiance profiles. Moreover, most available studies on SORC systems remain at the simulation or laboratory scale. There is a gap in field-tested data on long-term performance, especially under fluctuating real-world conditions in rural and off-grid settings. The field studies showed that lab-scale studies can overestimate the actual performance (Manolakos et al., 2009). Field testing is essential to evaluate the reliability and performance of small-scale solar ORC systems for Africa.

Collaborative efforts among researchers, governments, and industry stakeholders are essential to advance this field. Such partnerships can accelerate the development of cost-effective, climate-adapted SORC systems and support their successful implementation at a small scale in rural regions.

6. CONCLUSION

SORC systems present a promising solution for decentralised energy generation in remote and rural areas, particularly in Africa, where energy poverty remains a critical challenge. This review highlights that while significant technological progress has been made in component development, the widespread deployment of SORC systems is still limited by cost, technical complexity, and a lack of region-specific design optimisation. The real-world system performance is highly dependent on site-specific weather conditions, component selection and economic factors. The reviewed studies underscore that achieving cost-effective and efficient performance of SORC systems requires the careful selection of components to maximise energy output while minimise the cost. Modified scroll expanders and low-cost working fluids such as R152a and R1234ze(E) have shown potential to reduce payback periods, while working fluids such as R245fs offer an effective compromise between performance and affordability. Future research should prioritise the optimisation of solar collector sizing in accordance with local climatic conditions while also addressing the cost-performance trade-off in key components such as expanders.

Bridging the gap between laboratory research and real-world implementation is crucial. Field-tested systems generally underperform compared to simulation models, highlighting the importance of climate-adaptation and real-world testing. There is a lack of studies specifically focused on SORC for African climate conditions despite the region's high solar potential and urgent energy access needs. Future studies should focus on the development and testing of small-scale affordable SORC systems tailored for Africa.

ABBREVIATIONS

CPC	Compound Parabolic Collectors
CPG	Centralised Power Generation
DHW	Domestic Hot Water
ETC	Evacuated Tube Collectors
EFCs	Evacuated Flat Plate Collectors
FPC	Flat Plate Collectors
GWP	Global Warming Potential
HVAC	Heating, Ventilation, and Air Conditioning
ORC	Organic Rankine Cycle
PTC	Parabolic Trough Collectors
PV	Photovoltaic
R&D	Research and Development
RO	Reverse Osmosis
SDG	Sustainable Development Goals
SORC	Solar Organic Rankine Cycle

EDITORIAL INDEPENDENCE STATEMENT

To ensure editorial independence, the manuscript was handled by an editor who is not an author of this paper. This measure was taken to maintain transparency and avoid any potential conflict of interest.

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COMPETING INTERESTS

The authors have no competing interests to declare.

AUTHOR CONTRIBUTIONS

Meruyert Sovetova: Data curation, Formal analysis, Methodology, Visualisation, Writing – original draft, Writing – review and editing; **Cagri Kutlu**: Formal analysis, Writing – original draft, Writing – review and editing, Conceptualisation, Visualisation; **Yuehong Su**: Writing – review and editing, Conceptualisation, **Saffa Riffat**: Writing – review and editing, Conceptualisation.

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