Organic Rankine Cycle Power Systems: From the Concept to Current Technology, Applications, and an Outlook to the Future

Colonna di Paliano, P; Casati, EIM; Trapp, C; Mathijssen, T; Larjola, J; Turunen-Saaresti, TE; Uusitalo, A

DOI
10.1115/1.4029884

Publication date
2015

Document Version
Accepted author manuscript

Published in
Journal of Engineering for Gas Turbines and Power

Organic Rankine Cycle Power Systems: from the Concept to Current Technology, Applications and an Outlook to the Future

Piero Colonna *
Propulsion & Power
Delft University of Technology
Delft, The Netherlands

Emiliano Casati
Propulsion & Power
Delft University of Technology
Delft, The Netherlands

Carsten Trapp
Propulsion & Power
Delft University of Technology
Delft, The Netherlands

Tiemo Mathijssen
Propulsion & Power
Delft University of Technology
Delft, The Netherlands

Jaakko Larjola
Laboratory of Fluid Dynamics
Institute of Energy Technology
Lappeenranta University of Technology
Lappeenranta, Finland

Teemu Turunen-Saaresti
Laboratory of Fluid Dynamics
Institute of Energy Technology
Lappeenranta University of Technology
Lappeenranta, Finland

Antti Uusitalo
Laboratory of Fluid Dynamics
Institute of Energy Technology
Lappeenranta University of Technology
Lappeenranta, Finland

ABSTRACT

The cumulative global capacity of organic Rankine cycle (ORC) power systems for the conversion of renewable and waste thermal energy is undergoing a rapid growth, and is estimated to be approx. $2,000$ $\mathrm{MW_e}$ *considering only installations that went into operation after 1995. The potential for the conversion into electricity of the thermal power coming from liquid-dominated geothermal reservoirs, waste heat from primary engines or industrial processes, biomass combustion, and concentrated solar radiation is arguably enormous. ORC technology is possibly the most flexible in terms of capacity and temperature level, and is currently often the only applicable technology for the conversion of external thermal energy sources. In addition, ORC power systems are suitable for*

*Corresponding author, Email: P.Colonna@TUDelft.nl

the cogeneration of heating and/or cooling, another advantage in the framework of distributed power generation. Related research and development is therefore very lively. These considerations motivated the effort documented in this article, aimed at providing consistent information about the evolution, state, and future of this power conversion technology. Firstly, basic theoretical elements on the thermodynamic cycle, working fluid, and design aspects are illustrated, together with an evaluation of the advantages and disadvantages in comparison to competing technologies. An overview of the long history of the development of ORC power systems follows, in order to place the more recent evolution into perspective. Then, a compendium of the many aspects of the state of the art is illustrated: the solutions currently adopted in commercial plants and the main-stream applications, including information about exemplary installations. A classification and terminology for ORC power plants are proposed. An outlook on the many research and development activities is provided, whereby information on new high-impact applications, such as automotive heat recovery is included. Possible directions of future developments are highlighted, ranging from efforts targeting volume-produced stationary and mobile mini-ORC systems with a power output of few $\mathrm{kW_e}$*, up to large* $\mathrm{MW_e}$ *base-load ORC plants.*

1 Introduction

The concept of an engine based on the Rankine thermodynamic cycle, whereby the fluid is an organic compound instead of water (see figs. 1a–1b) originates from two main observations [1–3]:

- if the selection of the working fluid is an additional degree of freedom for the design of the thermodynamic cycle, the fluid can be chosen such that it is optimal from a thermodynamic and technical point of view. The properties of the fluid, e.g., the vapor-liquid critical point, the saturation line, and the specific heat, directly affect how well the temperature profile of the thermal energy source and sink can be matched by the corresponding cycle heating and cooling processes, see, e.g., figs. 1c–1d. Furthermore, cycle configurations that are not possible if water is the working fluid can be contemplated: the supercritical cycle configuration is possible even if the thermal energy source is at low temperature. As for the advantages with respect to technical aspects, it is notable that: (i) the fluid pressure and density levels within the system can be selected, to a certain extent, independently of the cycle temperatures (for example, relatively low fluid temperature in the evaporator can correspond to high pressure and vice versa), (ii) effective thermal energy regeneration can be realized by means of one single non-extractive de-superheating process.

- For low power output, from few kW up to few MW, the realization of an efficient, reliable, and cost-effective steam expander is challenging: the mass flow is extremely small, the expansion ratio comparatively large, and the specific work over the expansion is also very large, thus the design of a simple axial or radial turbine is problematic and the efficiency bound to be low. Steam volumetric expanders in turn must be complex, as challenging lubrication issues must be dealt with, and the net expansion efficiency is heavily affected by blow-by and friction losses. Water cannot effectively lubricate contact surfaces within the expander, therefore it must be mixed with a lubricant, which decreases thermodynamic efficiency, and can thermally decompose, in case it flows through the evaporator. In addition, for several applications, the freezing temperature of water is too high, and the very low pressure in the condenser can lead to unfeasibly large dimensions of this component. If the working fluid is organic, the much smaller enthalpy decrease of an expanding vapor allows to design an expander, be it a turbine [2,4,5] or a positive displacement machine (e.g., screw, scroll, vane, and piston expanders) [6], featuring a lower rotational speed and higher volumetric flow for given power output. For the majority of the organic Rankine cycle (ORC) working fluids, the expansion process is completely dry, thus blade erosion issues in turbines and inherent expansion inefficiency due to condensation are avoided. Several ORC working fluids are also suitable as a lubricant for rotating machinery, thus further simplifying the system. Finally, for many such fluids the freezing temperature is much lower than that of water and, moreover, freezing does not involve a detrimental volume increase.

The selection of the working fluid affects the thermodynamic performance of the system and, at the same time, the design of all its components. The reader is referred to Ref. [7] for a detailed treatment. For example, if the thermal energy source is relatively small and at rather high temperature (say 2 $\mathrm{MW_{th}}$ and $T_{\mathrm{source}} > 300\,^{\circ}\mathrm{C}$), the selection of a fluid formed by complex molecules (large specific heat) yields to a slightly superheated and regenerated cycle as the corresponding optimal configuration, see also fig. 1 and table 1. The relatively large volume flow due to the small enthalpy drop over the expansion, i.e. Δh_{is}, allows for the design of an efficient and simple turbine, with sufficiently large flow passages. In particular, small Δh_{is} values allow also to limit the number of stages (e.g., 2 or 3 axial or radial-outflow stages), and the resulting rotational speed may be $2-10$ times smaller compared to a steam turbine designed for the same operating conditions. In turn, the very low values of the sound speed of the expanding organic vapor are such that the flow is supersonic for modest pressure ratios. The dominant need of reducing the number of stages leads in most cases to the acceptance of a highly supersonic first stator, which requires special care in the fluid-dynamic design. Depending on the condensing temperature, the volume flow at the outlet of the turbine can be large, thus requiring a comparatively bulky regenerator and condenser. As a consequence, cost issues related to the heat transfer equipment might arise. Additional challenges ensue in case vacuum conditions in the condenser have to be managed. Conversely, the overall low pressure in the system can be beneficial as far as the cost of the evaporator and safety issues are concerned. It is also notable that regeneration positively affects the thermal efficiency of the cycle, but might negatively affect the temperature at which the heat source can be cooled (possibly limited by the temperature of state 3 in fig. 1a), thereby the amount of thermal power that can be converted into mechanical power. Similar reasoning can be applied to other applications, e.g., low- and medium-temperature geothermal energy conversion, leading to different results.

The working fluid is also subjected to a number of other constraints, which can be more or less stringent depending on the application, namely the ideal fluid should be

- non-toxic, non-flammable, non-corrosive, and cost-effective,
- characterized by a low or zero Global Warming Potential (GWP) and Ozone Depletion Potential (ODP),
- thermally stable and compatible with all the containing and sealing materials up to the cycle maximum temperature,

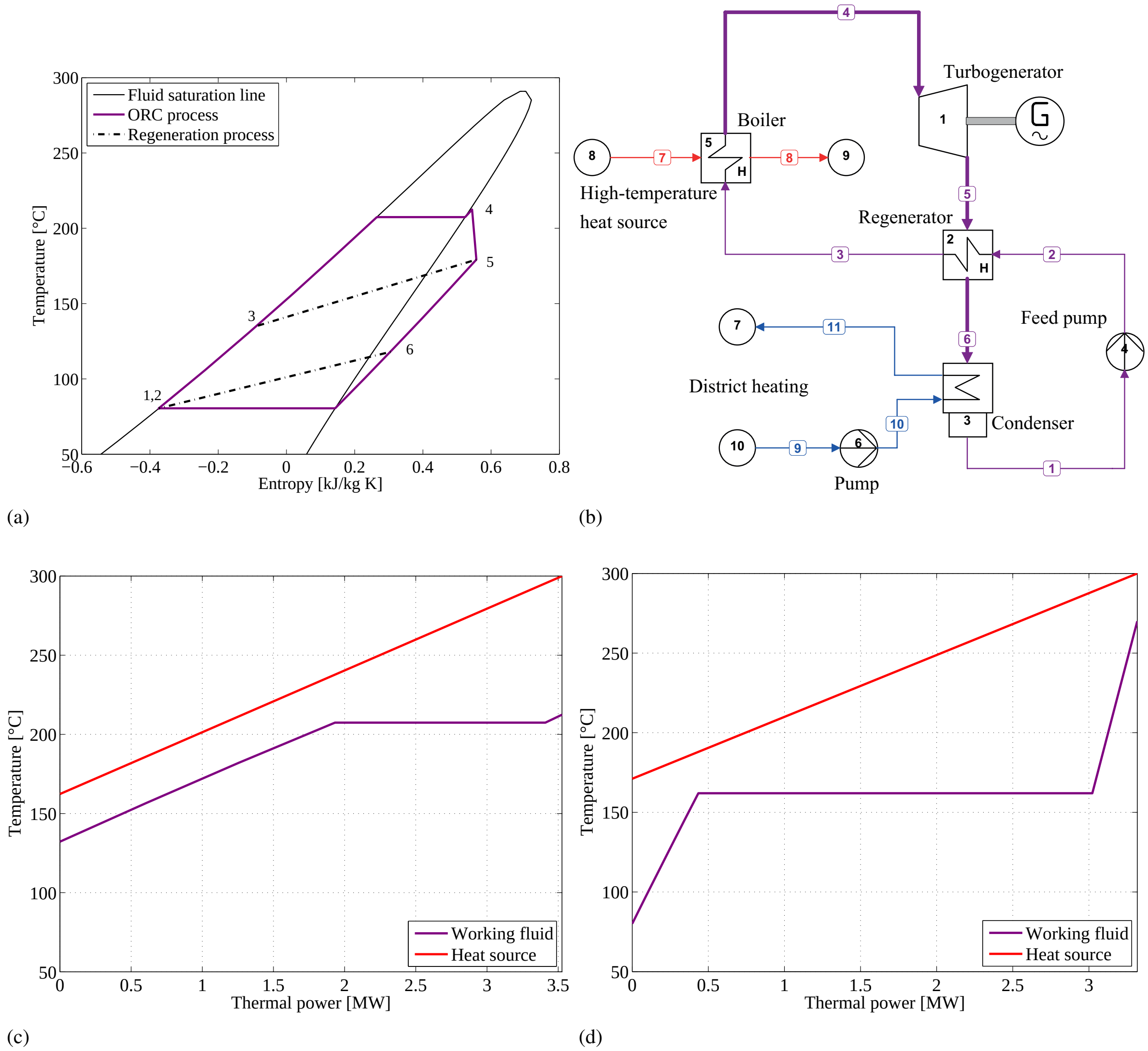


Fig. 1: The processes forming an exemplary superheated/regenerated Organic Rankine cycle power plant in the $T-s$ thermodynamic plane of the working fluid, see also table 5, (a) together with the corresponding process flow diagram (b). (c) $\dot{Q}-T$ diagram of the evaporator of the ORC system, assuming that the energy source is flue gas at 300 °C, compared to the $\dot{Q}-T$ diagram of the boiler of a simple steam power plant (d) having as energy input flue gas in the same conditions. The thermodynamic cycles of the ORC and steam power plants have been optimized for maximum net power output having as optimization variables the evaporation pressure and turbine inlet temperature, subject to a constraint on the same minimum pinch point in the evaporator (a minimum superheating of 5 °C is also imposed). The main cycle parameters are reported in table 1.

- possibly a good lubricant, featuring also good heat transfer properties,
- if used for generator cooling, electrical insulator and compatible with the adopted resin.

These exemplary considerations show that the design of an optimal system is a complex problem, possibly leading to multiple technical solutions, with different equipment selection, each with its advantages and disadvantages. With reference to the example previously illustrated, the selection of a working fluid made of simpler molecules would result in a faster-rotating and smaller turbine, possibly affected by lower efficiency, and requiring a reduction gear or power electronics for the coupling of the electrical generator to the grid. In turn, the adoption of such a fluid could eliminate the need for a regenerator, and

	siloxane MDM	H_2O
$T_{\text{in,source}}$ [°C]	300	300
$\dot{m}_{\text{in,source}}$ [kg s^{-1}]	23.6	23.6
ΔT_{pp} [°C]	30	30
$\eta_{\text{is, turbine}}$ [–]	0.90	0.90
$\eta_{\text{is, pump}}$ [–]	0.65	0.65
$T_{\text{in,T}}$ [°C]	212	270
T_{cond} [°C]	80	80
$p_{\text{in,T}}$ [bar]	3.5	6.5
$p_{\text{out,S}} = p_{\text{cond}}$ [bar]	0.09	0.47
$\dot{m}$ [kg s^{-1}]	11.9	1.3
$\beta = p_{\text{in,T}}/p_{\text{out,S}}$ [–]	37.7	13.7
Δh_{is} [kJ/kg]	56.7	491.3
$\dot{W}_{\text{net}}$ [kW]	573.4	528.2

Table 1: Main data referred to the exemplary optimal ORC system of fig. 1 and to an optimal steam power plant designed for the same thermal source capacity and operating conditions, i.e., condensing temperature T_{cond}, pinch point temperature difference in the evaporator ΔT_{pp}, and isentropic efficiency of the machines η_{is}. The subscripts 'T' and 'S' stand for total and static conditions, $\dot{m}$ is the mass flow rate, Δh_{is} the isentropic specific work across the expansion. An efficiency of 96% is assumed for the electrical generator and pump electric motor. The optimal thermodynamic cycle for the steam power plant is in this case a superheated cycle with no regeneration.

entail a more compact and super-atmospheric condenser.

With reference to high-temperature applications, one remarkable deficit of currently adopted working fluids (hydrocarbons, siloxanes, perfluorocarbons) is their thermal stability in contact with typical containing materials, which sets the peak cycle temperature threshold at around 350 °C, depending on the specific fluid, and on additional technical, operational and cost-related constraints. These are the frequency of fluid charge substitution, the level of fluid purity, the level of plant sealing, and the de-aeration requirements in the low-pressure part of the plant. Ideally, an organic fluid which would not thermally decompose (in contact with stainless steel) at temperatures up to $500 - 600$ °C would substantially increase the conversion efficiency in some applications. So far the highest thermal stability in realistic operating conditions was reported for a mixture of pentafluorobenzene and hexafluorobenzene [8]. The fluid underwent dynamic thermal tests at temperatures up to 468 °C, and no decomposition was observed during the 532 hour test. The fluid is claimed to feature low toxicity in case of acute and subacute exposures, but products of thermal decompositions of perfluorocarbons are chemically aggressive and possibly highly toxic [9].

One of the main and unique advantages of ORC power systems is that the technology is applicable to virtually any *external* thermal energy source,[1] with temperature differences between the thermal source and sink ranging from approximately 30 to 500 °C [10]. ORC systems are therefore technically suitable for the conversion of renewable or renewable-equivalent energy sources such as

[1] External with respect to the power system, as opposed to the internal combustion of reciprocating engines or gas turbines.

- geothermal reservoirs (liquid-dominated or steam-dominated, whereby the steam is too contaminated with acid gases and solid particles to be directly expanded in a turbine),
- solar radiation,
- biomass combustion,
- industrial waste heat recovery,
- urban solid waste, and landfill gas combustion,
- thermal energy recovery from other prime movers (reciprocating engines, gas turbines, fuel cells, etc.),
- ocean thermal gradient.

The graph of fig. 2, a version of which was first presented at the 1st International Seminar on ORC Power Systems in 2011 [11], synthetically shows the current relation between the temperature of the energy source and the power capacity of ORC power systems versus steam power plants. The graph refers either to systems that are commercially available, or to those currently under development and studied. Notably, the state of the art is quickly evolving, therefore fig. 2 has been adapted here in order to account for the fact that the boundary of ORC technology applications is expanding toward the region of conventional steam power plant applications. This chart might need to be updated in few years. If large-capacity

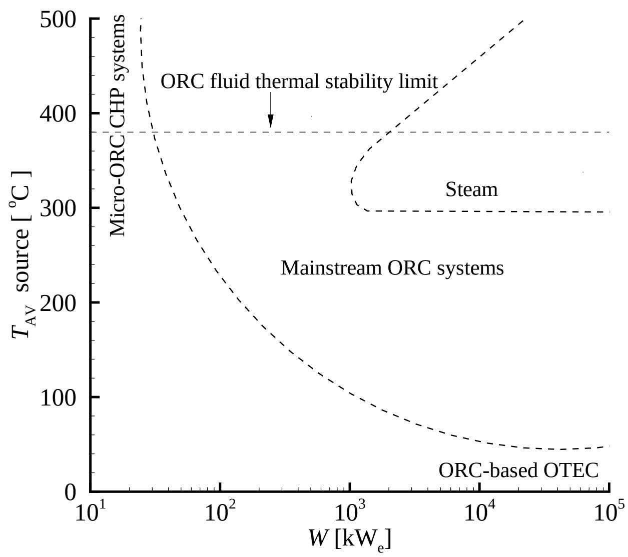


Fig. 2: Current and future fields of application of ORC versus steam power systems in terms of average temperature of the energy source, and power capacity of the system. Boundaries are indicative, and evolving in time. Adapted from Ref. [11].

high-temperature energy conversion systems are excluded from the comparison (primarily therefore steam power plants), competing technologies for the conversion of the mentioned energy sources are in principle the Stirling engine, the closed Brayton cycle (CBC) power plant, and the externally-fired gas turbine (EFGT). For low-temperature energy sources, e.g., geothermal reservoirs or heat recovery, the Kalina cycle power plant [12] is also a potential competitor, though power plants based on this concept are at a lower development stage vs. ORC power systems, and face difficulties due to inherently higher complexity [13].

Conventional Stirling engines can operate efficiently only if the thermal energy source is at high temperature (indicatively $700-1100$ °C), therefore they are developed mainly for highly concentrated solar energy conversion [14,15], biomass and biogas combustion [16], and domestic micro-cogeneration [17] for a power range from 1 kW_e up to approximately several tens of kW_e. The necessarily complex kinematic mechanisms, and the challenging high-temperature sealing requirements for the typically leak-prone working fluids (helium, hydrogen, nitrogen, air) have so far hampered the reliability of the systems being developed. Organic working fluids have been proposed for high-pressure/moderate-temperature Stirling engines [18], but no actual development is known to the authors. High power density, high net conversion efficiency (the world record is possibly 31.25% [19]) and perhaps low cost, if large-series production is envisaged, are positive features of Stirling engine technology.

Developments of medium-capacity CBC power plants are related to systems employing carbon dioxide[2] as working fluid [20], and they have been initially proposed for next-generation nuclear power plants [21]. As previously illustrated, CO_2, being a simple molecule, is arguably unsuitable for the design of low power output expanders. The development of medium-capacity ($10-50$ MW_e) supercritical CO_2 closed Brayton cycle power plants is now actively pursued for next generation concentrated solar power (CSP) plants [22], since high conversion efficiency at moderate peak cycle temperature is attainable (e.g., approx. 50% at 750 °C).

The EFGT concept is proposed for biomass combustion or gasification [23], and for high-temperature solar conversion [24], the main challenge being the high temperature at which the primary heat exchanger must operate. Prototypes so far achieved limited efficiency, and issues of reliability still need to be solved.

Fossil-fuel fired ORC systems compete with fuel cells, micro-gas turbines, Stirling and reciprocating engines for innovative applications, like micro-cogeneration of heat and power (micro-CHP) for apartments and houses [25]. Domestic cogeneration, that is the use of small CHP systems in place of conventional gas or diesel boilers, can be beneficial in terms of fuel utilization in countries with cold or moderate climate.

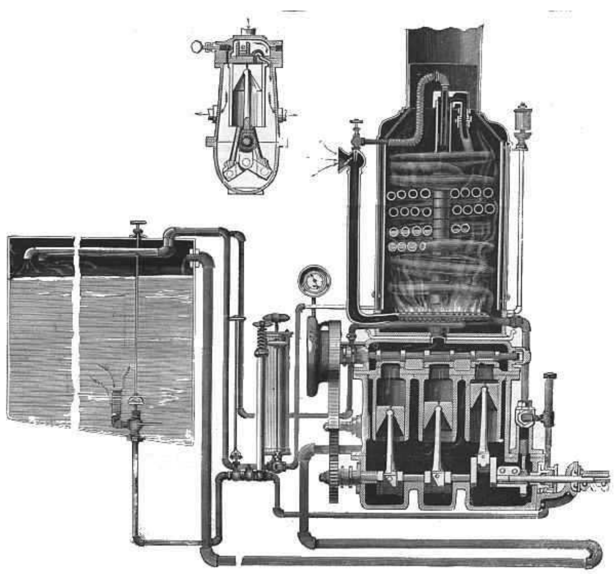
Research and development of ORC technology has been receiving an ever increasing impulse starting from the beginning of this century, together with a rapid increase of the installed power capacity, and the number and diversity of applications. This work is born out of the need for a reasoned synthesis about the evolution of this technology (sec. 2), its state-of-the-art (sec. 3), and an outlook toward the future (sec. 4), providing information on both commercial applications and active research topics.

2 Evolution

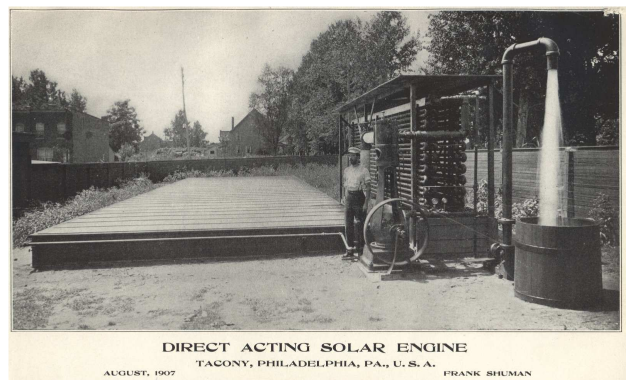
The idea of using a fluid different from water in a Rankine cycle for power conversion is rather old. As early as 1826, T. Howard patented the concept of an engine using ether as the working fluid [26]. Among the low-boiling pressure fluids, several inorganic substances were considered and tested throughout the years, with some success. However, this short review

[2]Carbon dioxide is an organic compound, as it contains carbon, therefore systems based on supercritical CO_2 thermodynamic cycles entailing working fluid condensation, as it is the case in some proposed configurations, qualify as supercritical organic Rankine cycle systems.

is limited to Rankine engines employing organic substances. A patent of F. W. Ofeldt [27] is at the basis of several ORC engines adopting a reciprocating expander fed by a naphtha vaporizer and powering launches, see fig. 3a. Naphtha was used as fuel, working fluid and lubricant, allowing to avoid the cost of the specialized operator needed for steam engines, because of the much lower evaporation pressure in the boiler. The Gas Engine & Power Company of New York claimed in 1890 to have sold five hundred ORC engines based on the Ofeldt design [28]. Simultaneously in Europe (1888), a British inventor



(a)



(b)

Fig. 3: Earliest ORC engines. 3a: engine of the Ofeldt naphta launch, 1897. Fuel is pumped in the bows by air pressure, generated by a hand pump, and passes through a coil boiler. Part of the vapor issuing from the boiler is fed to the burner that heats the boiler itself, and the rest drives a three-cylinder engine. The long U-tube at the bottom is the condenser [29]. 3b: Shuman's solar ORC-based pumping system prototype installed in Philadelphia (PA), 1907. The flat solar collector is also visible. It was called *the hot box*, with double glazing containing the blackened pipes acting as the vapor generator [30].

by the name of A. Yarrow also developed a naphtha-based ORC engine for launches [31]. One of these engines, built by the Swiss company Escher Wyss AG (later to become Sulzer), reached a certain fame as it propelled the *Mignon*, the boat that A. Nobel launched in 1891 [32]. Even if the boiler was operated at a pressure lower than that of steam engines, the early days of ORC engines were affected by several accidents [33].

F. Shuman, in 1907, was probably the first engineer who had the idea of a solar ORC engine: he used a flat solar collector of 110 m^2 to boil ether at temperatures around 120 °C and drive a 2.6 kW engine, see fig. 3b [34]. T. Romagnoli in 1923 used water at 55 °C to boil ethyl chloride and run a 1.5 kW engine [7, 35].

Professor L. D'Amelio (1893-1967), chair of thermal and hydraulic machinery at the University of Naples (Italy), is possibly the father of modern ORC technology. In 1936, his work on a solar power plant for irrigation based on an ORC engine using monochloroethane as working fluid [36] won him a prize of 10,000 Lire.[3] A series of 3 cm-deep vessels full of water would receive solar radiation, thus heating the water up to approximately 60 °C. The water is circulated to a shell

[3]The prize was awarded by the Libyan governatorate of Italy and the National Association of Combustion Control. Such solar ORC plant would have been used to pump water in the arid areas of North Africa.

Table 2: Specifications of the first solar ORC power plant proposed by Prof. L. D'Amelio in 1935 as reported in Ref. [36].

Working fluid	C_2H_5Cl
Surface of solar collectors	270 m^2
Evaporation temperature	40 °C
Evaporation pressure	2.7 bar
Condensation temperature	23 °C
Condensation pressure	1.3 bar
Turbine isentropic efficiency	0.65
Net power output	4 kW
Net conversion efficiency	0.036

and tube evaporator where the working fluid is heated and evaporated in small pipes at approximately 40 °C. The vapor is expanded in an impulse axial turbine, and generates mechanical work. The monochloroethane vapor is condensed at 23 °C, and the liquid is pumped back to the evaporator. The design specifications of the plant are reported in table 2. The estimated thermal conversion efficiency was of approximately 3.6%. The cited monograph outlines for the first time all the main principles of ORC system and turbine design, including the selection of the working fluid among several candidates, depending on the operating temperature/pressure, turbine design, and other relevant fluid features. Criteria for ORC turbine design depending on fluids were further detailed by D'Amelio in Refs. [37, 38]. In 1939, these ideas were implemented in a 2.6 kW prototype for the conversion of low-grade geothermal energy which was commissioned and operated successfully in a laboratory of the University of Naples [39]. The experience gained with the prototype led to the realization of an 11 kW geothermal ORC pilot power plant on the island of Ischia (Italy) in 1940. A second power plant of 250 kW based on the same technology was built in 1943 but was never operated [40]. After the second world war, D'Amelio resumed his studies on the ORC concept, and his work presented at the first conferences on solar energy received considerable attention [41, 42].

The first commercially operated geothermal ORC power plant, a so-called binary power plant, was functional for a short period at Kiabukwa, in the Democratic Republic of Congo, in 1952 [43]. It featured a power capacity of 200 kW_e, utilized geothermal water at 91 °C as heat source, and it supplied power to a mining company. The second oldest geothermal ORC power plant was commissioned at Paratunka in the Kamchatka peninsula in 1967 [43, 44]. It was a pilot plant exploiting geothermal water at 85 °C, rated at 670 kW_e, and using refrigerant R12 as the working fluid [45]. It provided a small village with electricity and greenhouses with heating.

Dr. L. Bronicki met Prof. D'Amelio during his MSc studies in the late 50's in Naples,[4] and started to study the application of the ORC principle to small solar power plants [46]. He made an important contribution by outlining for the first time the relation between the working fluid and the design of the expander in an article published on an international journal [1]. In the 60's, perfluorocarbons were studied by others as working fluids for mini-ORC turbines [47]. Several experimental solar ORC systems have also been reported. In these systems static non-focusing collectors were adopted, thus

[4] June 2013, personal communication.

achieving comparatively low maximum cycle temperature (around 100 °C), and solar-to-electric efficiency (typically $< 5\%$). Furthermore, also during the 60's, few ORC-driven systems for the pumping of water for irrigation or desalination purposes have been documented [34].

In these years, Dr. Bronicki and his group designed, built, and tested several small solar ORC units ($2-10$ kW) with monochlorobenzene as the working fluid. These systems featured inlet fluid temperatures of the order of 150 °C. Some of these plants have been reported as having run for 12 years without repairs [48]. In 1972, they realized a highly unconventional 0.4 kW unit powered by a radioisotope, featuring a much higher turbine inlet temperature (TIT), and thus a cascaded cycle configuration was adopted, employing a different working fluid in the top and bottoming cycle systems [49]. The group then succeeded in deploying the results of these studies in the first commercial application of mini-ORC turbogenerators, i.e., the powering of remote telecommunication stations and of the auxiliaries of gas pumping stations [50]. The most important requirement was reliability in order to allow for a very long operation without service, while conversion efficiency was not so relevant (approx. 5%). The first units of this type (3 kW_e), using monochlorobenzene as the working fluid, were operational in 1961. In the period between 1961 and 1988, thousands of these small ORC turbogenerators were installed. The power capacity ranges from 0.2 to 6 kW_e, the working fluid is commonly dichlorobenzene, or more rarely trichlorobenzene, due to the need of high thermal stability, being the working fluid directly heated by combustion flue gases. These systems pioneered the high-speed hermetic turbogenerator solution: the radial-inflow turbine and the generator are enclosed in a single sealed canister, and are connected to a vertical axis. Journal bearings support the shaft, using the working fluid as a lubricant and coolant, without additives. The generator is a solid-rotor brushless alternator. The three-phase output of the alternator is connected to the rectifier feeding the load. The electrical output terminals reach the outside of the assembly thanks to ceramic feed-throughs. The high boiling point of the working fluid enables returning the condensate by gravity without the need for a feed pump. The stainless steel evaporator is of the once-through type, and the condenser is naturally air-cooled in order to avoid moving parts. The recuperator is tube-in-shell [46, 51]. In more recent years, photovoltaic panels substituted mini-ORC turbogenerators for these applications.

ORC power systems have been adopted also in combination with solar ponds, whereby a temperature gradient is established in a water basin by an artificially induced salinity-gradient. An experimental 5 MW Solar Pond Power Plant (SPPP) was operated from 1983 to 1990 in Beit Ha'aravah, Israel [52]. A 100 kW SPPP operated from 1986 to 2002 at temperatures as low as 65 °C in El Paso, Texas [53].

The first experimental geothermal cascading ORC power plant was called Magmamax, and it was located in East Mesa (California) [54]. Its initial design was very ambitious, as it was based on two interconnected ORC power plants. The topping cycle utilized isobutane as the working fluid, while the bottoming cycle adopted propane. The plant was commissioned in 1979, and was rated at 12.5 MW_e gross power (and 11 MW_e net power). Though it went through a number of operational problems and changes, it paved the way for the following generations of binary geothermal power plants. After two other small experimental geothermal ORC power plants [53], in 1984 the company founded by Dr. Bronicki commissioned its first commercial ORC power plant for the conversion of geothermal energy in Wabuska, Nevada, featuring a capacity of 700 kW_e [53].

As a consequence of the oil crisis of the late 70's, many other geothermal units manufactured by several companies followed, while also the capacity of these plants gradually increased toward the multi-Megawatt range. The working fluids were mainly light hydrocarbons, chlorobenzenes, and chloro-fluoro-carbons (CFC). In this period, few ORC power plants were used also for the conversion of other renewable energy sources, like industrial waste heat, engine exhaust gases, and solar radiation. The largest of these plants was built in Japan at Mitsui Engineering & Shipbuilding, featuring a power output of 15 MW_e [55]. As a result of rising concerns about air pollution, followed by rising fuel prices during the oil crisis, investigations on the use of Rankine engines for automobiles started in the 70's [56,57]. Both steam and organic compounds were considered as working fluids with either a turbine or a piston expander. A 30 kW prototype was successfully tested as bottoming cycle on a long-haul truck [8, 58], but never made it to the commercial market. In the 80's, intense research and development activity occurred also in East Germany, Finland, France, Japan, Israel, Italy, USSR and the US.

Barber et al. were possibly the first to evaluate the potential of ORC technology in North America [59, 60]. In 1975, they presented the first results of a research activity aimed at coupling an array of solar flat-plate collectors, a 1 kW ORC turbogenerator using R113 as the working fluid, and a compression chiller for air conditioning. The evaporation and condensation temperatures were equal to 93 and 35 °C, the efficiency of the ORC module was 7%, and the system overall COP approximately 0.5 [61]. The possibility of reaching maximum cycle temperatures higher than 300 °C by adopting focusing collectors (mainly linear) has been investigated between 1975 and 1977: a prototype was tested at Sandia National Laboratories in New Mexico, in combination with parabolic trough collectors to heat a thermal oil loop powering an ORC turbogenerator of 32 kW_e, and also supplying space heating and cooling with an absorption air conditioner [62]. Also in the US, from 1976 to 1984, the Jet Propulsion Laboratory developed a power system using parabolic dishes coupled with an ORC power module. The cavity receiver was designed to heat toluene at 400 °C and approx. 4.2 MPa. The rotating parts (single-stage impulse turbine, centrifugal pump, and alternator) were mounted on a single shaft rotating at 60,000 rpm. The same working fluid was also used for bearing lubrication [63]. A solar-to-electric conversion efficiency of 18% was measured, with a power output of 16 kW_e, thus lower than the design value, due to test conditions [64]. Other notable developments were related to five 600 kW_e units for industrial heat recovery [65], and to a concept for electricity generation for the international space station [66, 67].

Particularly relevant were the studies carried out in Italy during the 60's and the 70's by Prof. G. Angelino, one of the fathers of modern ORC power systems technology, together with his colleagues at Politecnico di Milano, Prof. M. Gaia and Prof. E. Macchi. Their work was important also because it helped laying the scientific and technical basis for research and development [2]. An example of the application of these investigations is documented in a study presented by Bado and colleagues, a 35 kW_e perfluorocarbon (C_8F_{16}) unit providing a net electric conversion efficiency of 19% at condensing and collectors cooling loop exit temperature equal to 40 and 300 °C [68]. Such unit was subsequently built and tested, and a net efficiency of 17% was recorded at a turbine inlet temperature of approximately 270 °C [69, 70]. In this first prototype, a 4-stage axial turbine running at 6,000 rpm was coupled to a 3,000 rpm generator through a gear. Based on these studies, a company was established in 1980 by M. Gaia, initially involved in the realization of experimental solar and geothermal ORC power plants adopting various working fluids and single or multi-stage axial turbines [2]. Notable is the Borj Cedria 12 kW_e

solar power station in Tunisia, which was commissioned in 1983. The working fluid was tetrachloroethylene, and during field tests a net electrical efficiency of 11% was recorded, with evaporation and condensation temperatures equal to 84 and 20 °C [71]. Studies on the use of siloxanes as working fluids for high-temperature ORC power systems were conducted in collaboration with Angelino and co-workers [67, 72]. The first biomass-fuelled turbogenerator was commissioned in Bière (Switzerland), in 1998 [11]. It was a skid-mounted 300 kW_e genset, using siloxane MDM as the working fluid, and featuring a 2-stage axial turbine. The plant was ordered by the Swiss army in order to provide electricity and cogenerated heat to a barrack.

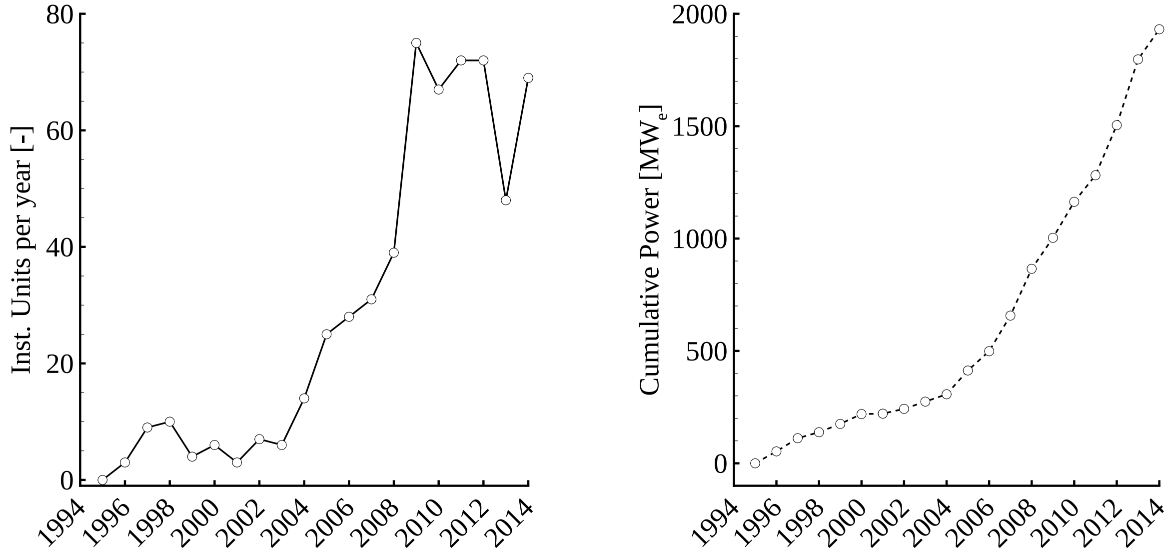
In Finland, Prof. Jaakko Larjola led the development of high-speed hermetic turbogenerators in the hundreds of kW_e range, in which the turbine, generator and pump share the same shaft. One of the first applications of this type of ORC systems was the use of the turbogenerator (25 kW_e) as the charger of the batteries of a deep-see submersible [73]. The hermetic turbogenerator configuration was similar to the early mini-ORC units for remote power applications [74, 75]. The knowledge acquired with these developments was later utilized in commercial units that were marketed starting from the early 2000 by a company in the Netherlands [76].

Information concerning operational ORC power plants referred to the period before 1995 are collected in Ref. [3], containing also data from Ref. [77], which in addition covers earlier years. During the 1980's, however, interest rates were high and fossil fuels relatively cheap: this led to most of the experimental plants being shut down because economics were not attractive. The main data related to the majority of the plants that have been commercially operated after 1995 are shown in table 3. Fig. 4 presents a quantitative assessment of the evolution of installed ORC power plants in the same period, in terms of both cumulated installed power and number of units.

Table 3: Overview of the main characteristics of commercial ORC power plants commissioned after 1995, data from company websites and personal communication. For older data see, e.g., Refs. [3, 77]. Fluids: see also nomenclature in table 4. Out. cogen$-T$: thermal power cogenerated $-$ delivery temperature. Energy source: B = Biomass, G = Geothermal heat, S = Solar radiation, and WH = Waste Heat. Turbine type: ax = axial, rad. in (out) = radial inward (outward) flow. N_{stgs}: number of turbine stages. *na* stands for *not available*.

Manufacturer	Output	Working	Energy	Turbine	Turbine inlet		N	Year
	kW_e	fluid	source	type/N_{stgs}	T_{max}, °C	P_{max}, bar	units	commiss.
Atlas Copco [78]	2,100	R134a	WH	rad. in/1	*na*	*na*	1	2012
	22,500	n-butane	G	rad. in/1	*na*	*na*	2	2013
	3,600	iso-butane	G	rad. in/1	*na*	*na*	1	2014
	22,500	n-butane	G	rad. in/1	*na*	*na*	2	2015
Exergy [79–81]	1,000	FC	B	rad. out/*na*	*na*	*na*	2	2012
	1,000	HC	G,B	rad. out/*na*	*na*	*na*	2	2013
	100 – 1,000	refr.,FC,Sil	WH,B	rad. out/*na*	*na*	*na*	4	2014
	1,200 – 12,000	HC	WH,G	rad. out+axial/*na*	*na*	*na*	7	2015
GE Energy [82]	125	245fa	B,WG	rad. in/1	121	17.2	>100	2009 – 2011
GE Oil & Gas [83–85]	17,000	cyclo-pentane	WH	rad. in/2	250	*na*	1	2012
	17,000	cyclo-pentane	WH	rad. in/2	250	*na*	1	2014
	17,000	cyclo-pentane	WH	rad. in/2	250	*na*	4	2015
Ormat [86–89]	1.2 – 4	trichlorobenzene	fossil	rad. in/1	220	2.5	950	1995 – 2014
	1,200	n-pentane	S	axial/*na*	180	*na*	1	2006
	400 – 3,500	n/iso-pentane	G	axial/1 – 4	130 – 170	*na*	70	1995 – 1999
	400 – 6,500	n/cyclo-pentane	WH	axial/1 – 5	130 – 190	*na*	20	1995 – 1999
	1,000 – 25,000	n-pentane/n-butane	G	axial/2 – 5	140 – 193	*na*	159	2000 – 2014
Tri-O-Gen [76, 90, 91]	80 – 160	toluene	WH, B	rad. in/1	325	32	30	2007 – 2014
Turboden [92–94]	100	siloxane	S	axial/2	250	10	1	2014

	200 – 500	siloxane	B, WH, G	axial/2 – 3	250	10	28	1998 – 2014
	500 – 1,000	siloxane/R134a	B, WH, G	axial/2 – 3	250	10 – 30	131	2001 – 2014
	1,001 – 1,500	siloxane/iso-butane	B, WH, G	axial/2 – 3	250	10 – 30	67	2003 – 2014
	1,501 – 2,000	siloxane	B, WH, G, S	axial/2 – 3	250	10	16	2007 – 2014
	2,001 – 4,000	siloxane/Solkatherm	B, WH, G	axial/2 – 3	250	10 – 30	17	2008 – 2014
	4,001 – 13,000	n/cyclo-pentane/R134a/245fa	B, WH, G	axial/2 – 3	250	10 – 30	11	2005 – 2014
GMK [95]	30 – 50	*na*	B, WH, G	*na*	*na*	*na*	13	2009 – 2014
	150 – 600	*na*	B, WH, G	*na*	*na*	*na*	6	2000 – 2014
	1,100 – 1,400	*na*	B, WH, G	*na*	*na*	*na*	13	2006 – 2014



(a) (b)

Fig. 4: Number of installed units per year (4a) and cumulative power capacity (4b) of the commercial ORC power plants commissioned between 1995 and the end of 2013, based on the data reported in table 3.

3 State of the art

The technological development of ORC power systems is evolving rapidly, and a considerable number of different and partly competing solutions for cycle configurations and main components can be observed. This variety and the significant role that ORC technology is achieving in the renewable energy scenario demand for a simple classification and shared terminology. The proposed classification is presented in table 4, and it refers to the main features of an ORC power plant.

Table 4: Proposed terminology for properties that can be used to classify ORC power plants. An ORC power plant can be extensively characterized by a combination of the properties reported here. Example: Biomass combustion ORC-CHP power plant of medium power capacity, based on a superheated and regenerated thermodynamic high-temperature cycle, using a linear siloxane as working fluid, indirectly heated, and adopting a multi-stage axial turbine.

Temperature max. cycle, °C		Power capacity	
High	> 250	Micro	< 3 kW
Medium	$150 - 250$	Mini	$3 - 50$ kW
Low	< 150	Small	$50 - 500$ kW
		Medium	$0.5 - 5$ MW
		Large	> 5 MW
Working fluid class		**Thermal energy source**	
Hydrocarbons (HC)	Alkanes, aromatics, alcohols	Geothermal	(Pressurized) water, steam
Fluorocarbons (FC)	Perfluorocarbons, hydrofluorocarbons	Biomass (solid or biogas)	Combustion
Siloxanes (Sil)	Cyclic, linear	Solar radiation	Parabolic trough, Fresnel
–	Carbon dioxide	Industrial heat	Process cooling, flares, landfill gas
Mixtures (mix)	Components also from different classes	Prime mover flue gas/cooling	Stationary, mobile
Configuration		**Working fluid cooling**	
Saturated	Simple, regenerated, multi-P levels	Air	
Superheated	Simple, regenerated, multi-P levels	Water	
Supercritical	Simple, regenerated, multi-P levels	Air with intermediate loop	
Cascaded	Combinations of cycle variants	Water (for CHP purposes)	
Expander type		**Working fluid heating**	
Turbine	Axial, radial inflow/outflow, mixed flow	Direct	
Volumetric expander	Scroll, screw, piston, vane	Indirect	Thermal oil loop, water loop
Turbine/generator connection		**Turbogenerator assembly**	
Direct	with inverter	Hermetic	
Indirect	with/without gearbox	Open	Shaft seals

A brief description of the most commonly adopted options encountered in commercially available systems is provided here; the sequential and iterative design process is often carried out in the order in which these are presented. The design of one system component strongly depends on the others, therefore a trend toward an increasingly integrated and automated approach is currently pursued [96–98]. The number of possible configurations applicable at system and component level is very large, and it explains why, even for similar specifications, the units that have reached commercial status can differ considerably. ORC modules can exhibit a certain level of standardization up to a power capacity of $2-3$ $\mathrm{MW_e}$, while larger power units are typically highly customized.

3.1 Technical options

The selection of the available solutions for the design of a system and its components depends on the initial specifications, which most often are (i) the type of thermal energy source in terms of average power capacity and temperature, and (ii) the available/usable cooling fluid and its average temperature.

Cycle configuration and working fluid

As treated in sec. 1, the design decisions about the cycle configuration and the working fluid are closely coupled, and have consequences on the choice and design of the components [2]. Currently, saturated and superheated cycle configurations are common. Note that a slight degree of superheating is needed in case the expander is a turbine, in order to avoid blades erosion. The supercritical cycle configuration has been adopted only in few exemplary/experimental cases [80, 99]. Two and three pressure levels in the evaporator have been adopted only in large geothermal power plants [100]. The supercritical cycle configuration might be optimal from a purely thermodynamic point of view, but the power consumption of the main feed pump becomes very large. Table 5 lists the working fluids that are most commonly employed, together with their main properties. Fluids that have been recently proposed to the market are also included. In general, fluids formed by more complex molecules are suitable for high-temperature applications (eg., siloxanes, toluene), and small-medium power capacity, while those formed by simpler molecules (e.g., refrigerants, alkanes) are adopted in low-temperature applications, and are suitable also for large power output.

Rotating equipment

In case of larger power plants, one of the advantages related to the selection of an optimal organic working fluid is that it is possible to design an efficient turbine for rotational speeds that allow for direct coupling to a synchronous generator (3,000/1,500 rpm if the grid frequency is 50 Hz, or 3,600/1,800 rpm if it is 60 Hz). If this is not possible or wanted, reduction gears can then be used. The shaft seal demands for attention in order to avoid excessive leakage. Oil is often used in a dedicated bearings system for the shaft, especially in slow-rotating turbines and pumps, whereby mechanical seals are adopted for the shaft. The expander, electrical generator, and feed pump can rotate independently from one another, or, in some cases and for systems rated at hundreds of $\mathrm{kW_e}$, they can share the same shaft [76, 82, 91]. In addition, thanks to the use of an inverter, the rotational speed of the turbine can be varied in order to match the machine optimum efficiency at the

Table 5: Main properties of the most common working fluids currently in use in ORC power plants, see also table 3. MW: molecular weight, T_{boil}: normal boiling temperature, $p_{\text{vap@80 °C}}$: vapor pressure at 80 °C. Data from Ref. [101]. Solkatherm SES36 is a mixture of 65% (mass) R365mfc (1,1,1,3,3-Pentafluorobutane), and 35% Galden® HT 55, which, in turn, is a mixture of 8 perfluoropolyethers with unpublished composition [102].

Fluid name	Chemical formula	Mol wt [g mol^{-1}]	T_{CR} [°C]	p_{CR} [bar]	ρ_{CR} [kg m^{-3}]	T_{boil} [°C]	$p_{\text{vap@80 °C}}$ [bar]
toluene	C_7H_8	92.1	318.6	41.26	278.8	110.6	0.389
cyclo-pentane	C_5H_{10}	70.1	238.5	45.15	272.6	49.2	2.522
iso-pentane	C_5H_{12}	72.1	187.2	33.78	215.7	27.8	4.575
iso-butane	C_4H_{10}	58.1	134.7	36.29	224.6	-11.8	13.438
MDM (octamethyltrisiloxane)	$C_8H_{24}Si_3O_2$	236.5	290.9	14.15	302.9	152.5	0.091
MM (hexamethyldisiloxane)	$C_6H_{18}OSi_2$	162.4	245.5	19.39	292.9	100.2	0.537
PP1 (perfluoro-2-methylpentane)	C_6F_{14}	338.0	182.15	19.23	635.0	57.0	2.06
R245fa (1,1,1,3,3-pentafluoropropane)	$C_3H_3F_5$	134.0	154.0	36.51	489.3	15.1	7.893
R134a (1,1,1,2-tetrafluoroethane)	$C_2H_2F_4$	102.0	101.1	40.59	545.6	-26.1	26.332
Solkatherm SES36	mix	184.9	176.1	28.49	538	35.3	3.840

given operating condition. An inverter would currently be too big and expensive for larger capacity systems.

Expander. ORC expanders are currently dynamic (turbines) in the vast majority of the cases, while volumetric (screw, scroll) expanders are in the pre-commercial or market-introduction phase. Turbo-expanders cover the power capacity (from approx. 100 kW to several MW), expansion ratio (approx. 5 to 100), and inlet temperature (approx. 120 to 350 °C) ranges typical of current commercial ORC power systems. Volumetric expanders are employed only in the low-temperature and low-capacity power systems (1 to approx. 100 kW) which are now being commercialized. Notable exceptions that might lead to interesting developments are the heat recovery systems manufactured and installed in Sweden [103], and the 1 MW_e screw expanders that have been recently installed in a low-temperature geothermal power plant in New Mexico [104]. The maximum volumetric expansion ratio of volumetric expanders at the present time prevents their use in high-temperature systems. These machines feature lower isentropic efficiency if compared to turbo-expanders, which in turn are not yet available with a power output of few kW. Screw and scroll expanders can be cost-effective because they are derived from volume-produced refrigerant compressors. A distinguishing technical feature of scroll and screw expanders is that they can tolerate a fraction of liquid working fluid, thus the simpler saturated cycle configuration with wet expansion can be adopted. Ref. [105] provides an overview on the main aspects of volumetric expanders for small ORC power systems.

ORC expanders are in general different from machines expanding steam, air or other gases, because dense vapor properties deviate largely from ideal gas behavior, and because the speed of sound is much lower than in light gases or steam, thus affecting nozzles design [106–108]. Axial turbines, see fig. 7, are commonly adopted for medium to large power output ORC systems in single or multi-stage arrangement (currently up to four/five). The isentropic efficiency in nominal conditions typically goes from 80% to less than 90%. In case of smaller-capacity systems, the radial inflow configuration is preferred because it allows to achieve high efficiency with one single stage, even in case of large expansion ratio/high TIT. A two-stage radial inflow turbine configuration has been recently implemented in a large ORC power plant [84]. Recently, systems based on turbines adopting the multi-stage radial outflow configurations, as suggested by several authors since the 70s [4, 109], have been successfully commercialized [81].

ORC turbines are usually made of alloy or stainless steel, but aluminum alloys are suitable construction materials if the turbine operates at low temperature and low rotational speed. Titanium is the material of choice for rotors of high-speed turbines operating at high temperature because the considerable mechanical stresses in this case demand for a material with comparably high mechanical resistance. The first ORC scroll expanders proposed to the market are either semi-hermetic or hermetic, the power output varies from 1 to 10 kW, the volumetric expansion ratio is at maximum $4-5$, while the rotational speed is between 1,500 and 6,000 rpm [110]. Screw expanders are in a slightly more advanced stage of development, and their power output reaches several hundreds kW. They feature either the single-screw or the double-screw configuration, and the maximum expansion ratio is slightly larger than that of scroll machines $(5-6)$ [105]. Their rotational speed can be as high as $10-12,000$ rpm in the smaller machines.

Bearings. Conventional oil bearings are typically used in case the electrical generator is external to the turbine casing. If the working fluid has good lubricant properties, especially designed fluid bearings are adopted, thus simplifying the turbine/generator assembly. These are often of the tilted pad type due to the high rotordynamic stability they offer. The high-speed hermetic turbogenerator assembly configuration also demands for special bearings, either electromagnetic [82], or lubricated with pressurized working fluid liquid [55, 111]. Electromagnetic bearings are utilized in some units that are in the initial commercialization phase with low turbine inlet temperature. The implementation of this technology in higher-temperature systems requires additional research.

Pump. The power consumption of an ORC pump is comparatively larger than that of a steam power plant pump because the ratio of the specific pump work to the specific turbine work is larger. For this reason, even though standard centrifugal water pumps are often adapted for the use in mainstream ORC systems, sometimes ad hoc pumps must be employed in order to achieve sufficient compression efficiency. The cost and comparatively low efficiency of multi-stage pumps is one of the main reasons why the supercritical cycle configuration is currently adopted only in very few cases [100].

Heat Exchangers

In general, the choice depends on the system capacity: compact heat exchangers are more commonly adopted in low-power output systems, while shell and tube in larger power plants.

Evaporator / Primary heater. The primary heat exchanger/evaporator can be of the once-through type [2, 76], or the shell and tube type, having the working fluid typically in the shell side [112, 113]. Thermal energy can be transferred directly from the heat source to the working fluid, or indirectly via an intermediate fluid loop. Direct heating in principle allows to achieve higher maximum fluid temperatures, thus increasing the conversion efficiency, while indirect heating demands for additional pumping power. The choice among the two solutions depends on many aspects: contractual issues, safety regulations, efficiency, and ease of control. In general, lowering the temperature of the working fluid is a way of prolonging its operational life, thereby lowering costs. As for this last aspect, indirect heating makes easier to reduce the presence of hot spots that increase the risk of working fluid decomposition.

Regenerator. The adoption of a regenerator depends on the selection of the working fluid, and optimal cycle configuration [1, 96, 97]. In some cases, the thermodynamic advantage can be quite limited, but the adoption of the regenerator can help reducing the size of the condenser, which is often a large cost component. In any case, regenerators are designed in order to limit as much as possible the pressure drop on the vapor side, which directly affects the turbine outlet pressure, and thus its power output. This becomes a critical aspect if the condenser operates at very low pressure. One of the adopted configurations features the co-location of regenerator and condenser within the same insulated housing, in order to realize more compact assemblies.

Condenser. Depending on the availability and regulations, water-cooled condensers are preferred because they allow to achieve higher net efficiency. Water cooling is also adopted if the ORC power plant cogenerates district or process thermal energy, or if it powers an absorption chiller or refrigerator. In case air cooling is the only possibility, the main choices are direct systems or air-coolers with an intermediate water/glycol loop. While the first ensures a comparatively better thermodynamic performance, the second allows to gain flexibility in equipment positioning. This last option proves particularly valuable in case the plant is situated in an environment whereby bulky components such as coolers and fans have to be placed far from the ORC turbogenerator (e.g., on the building roof).

3.2 Applications

The current applications of ORC power plants are listed here in order of relevance in terms of presently installed power capacity. ORC power systems are either the preferred or the only technology that can be adopted for the conversion into electricity of several types of relevant thermal renewable energy sources. For example, arguably most of the high temperature vapor-dominated geothermal reservoirs are already exploited, while the potential of liquid-dominated reservoirs with comparatively low capacity is still very large [43]. Similarly, in case of biomass combustion, the optimal plant capacity is typically limited by the cost of fuel gathering, to an extent that ORC systems are the preferable option. Moreover, for a small plant it is generally easier to find a suitable thermal utilization of condenser heat.

Geothermal Reservoirs

ORC power plants around the world are used mainly for the conversion of liquid-dominated geothermal reservoirs at temperatures of $120-150$ °C, though examples of operational plants fed by a mixture of steam and brine at higher temperature exist: Zunil - 20 MW_e (Guatemala), Ribeira Grande I and II - 14 MW_e (Portugal-Azores), Olkaria III - 120 MW_e and Oserian - 1.8 MW_e (Kenya) [113], and the Ngatamariki - 95 MW_e (New Zealand, see also fig. 7a). The geothermal fluid usually contains also a substantial amount of incondensible gases, which might form corrosive compounds. In case of two-phase geothermal fluid, the steam and the brine are separated, and the steam is used to evaporate the organic working fluid, while the brine is used for liquid working fluid preheating. The saturated cycle configuration with an alkane as a working fluid is the most common. Sometimes the system includes a regenerator. In case of a steam-dominated geothermal reservoirs of large capacity, whereby a steam power plant is used as the high-temperature conversion system, an ORC power plant as bottoming cycle results into an efficient combined cycle configuration [114]. Exemplary plants of this type are the Upper Mahiao - 125 MW_e (Philippines), the Mokai 1 and 2 - 130 MW_e, and the Puna - 30 MW_e (US-Hawaii) [113].

A novel concept has been tested at the liquid-dominated geothermal power plant of Thermo (US-Utah), whereby 50 standardized 220 kW_e turbogenerators have been installed [115]. These systems were derived from main-stream chillers for cost-effectiveness, whereby the radial-inflow turbine was redesigned starting from refrigerant compressors [116]. The working fluid is R245fa. This concept offers the advantage that skid mounted factory-assembled units could be transported and quickly connected on site. Additionally, a high level of flexibility in terms of power variation and maintenance is inherent. This attempt failed for reasons related to the adopted business model [117].

Solid biomass or biogas combustion

High-temperature ORC power plants in the MW_e power range fuelled with various types of solid biomass have been installed at increasing pace in Europe starting from the early 2000, thanks also to favorable legislation. More than 200 ORC gensets of this type are in operation. Most often these plants are integrated into wood-manufacturing sites, and feature the CHP (cogeneration of heat and power) arrangement, whereby the heat discharged by the ORC unit, at temperatures typically below 100 °C, is used for process purposes (e.g., wood drying), or district heating. Many of these power systems adopt a superheated and regenerated cycle configuration, indirect heating, two, or in few cases, three-stage axial turbines, and MDM as the working fluid. The rated net electrical efficiency is usually in the $15-20\%$ range, while the total energy efficiency can be as high as 90%. Information on exemplary biomass CHP power plants of this type can be found in Ref. [118] related to a 1 MW_e power plant in Lienz (Austria), in Ref. [93] for the 1.1 MW_e power plant in Tirano (Italy), and in Ref. [119] for that in Ostrow Wielkopolski (Poland), rated at 1.5 MW_e.

Flue Gas from Gas Turbines or Gas and Diesel Engines

Few ORC modules are installed as bottoming cycles of mechanical drive gas turbines [84], though the number of installations is increasing [120]. In the case of pipeline compressor stations 19 units of 5 to 6 MW_e are in operation in North America and Europe, the first one since 1999 [121]. Several examples of ORC turbogenerators used to recover waste heat from the exhaust of gas and Diesel engines already exist, and the number of these installations is also increasing. In cases in which the reciprocating engine or the gas turbine is fed with biogas, the addition of an ORC heat recovery system is often economically viable because of the subsidized value of the generated electricity. Few ORC plants are installed in landfill sites, whereby the combustion of landfill gas is the energy source, instead of simply be flared. Possibilities to use the flue directly as a heat source or in other energy conversion applications exist [122], but typically the gas is used in an internal combustion engine, while an ORC can be added as a heat recovery system for the engine exhaust [123]. Most of these ORC units have rather small capacity, e.g., the 160 kW_e power plants using toluene as working fluid installed in various locations in Europe [91], although it is possible to combine the exhaust gases of many gas engines to be fed to a single large ORC power plant.

Industrial Waste Heat

Opportunity for heat recovery in the manufacturing and process industry are countless, see, e.g., Ref. [124] for an analysis on European countries. The majority of the thermal energy is wasted at temperatures between 60 and 400 °C, with a capacity that monotonically increases toward vast quantities at low temperature, as shown in fig. 5.

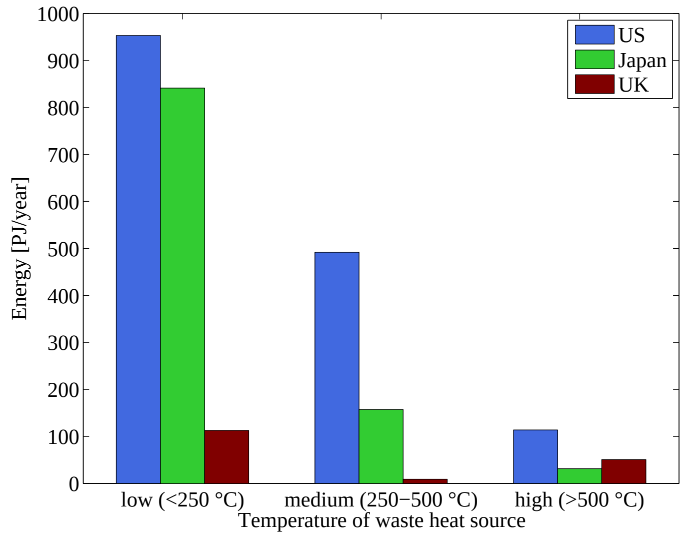


Fig. 5: Annual industrial waste heat in the US [125], Japan [126] and UK [127]. The data are not strictly homogeneous and are shown here together to indicate that the potential for useful conversion is in any case large.[5]

Only recently this enormous potential has attracted interest, and few ORC power plants recovering various forms of thermal energy otherwise wasted are now operational, while many feasibility studies are performed.

First examples of industrial waste heat recovery ORC power plants can be found in the cement industry [128]. Throughout the production of cement, about 40% of the process heat is wasted to the environment, mainly via the exhaust gases from the rotary kiln, coming from the limestone preheaters and also from the ambient air used for clinker cooling [129]. Depending on the cement plant configuration (e.g., number of preheating stages), and the process efficiency, waste heat streams are available at temperatures between approx. 200 and 400 °C [130, 131]. The first ORC heat recovery system in a cement factory was commissioned in 1998 at the Heidelberg Cement AG plant of Lengfurt (Germany) [132]. This 1.5 MW_e system proved to be extremely flexible and thus able to cope with the continuously fluctuating operating conditions of the heat source in terms of temperature and flow rate (for example, grate cooler air temperature fluctuating between 340 and 180 °C). Other successful examples are listed in Ref. [128]. Similar plants are under construction or commissioning are a 4 MW_e ORC plant in Alesd (Romania), a 5 MW_e plant in Rohoznik (Slovakia), and a 1.9 MW plant in Untervaz (Switzerland). Most of these installations use an intermediate thermal oil loop to transfer the thermal energy to the ORC working fluid.

In comparison to the quite standardized cement production process, steel manufacturing requires quite diverse processes.

[5] The data for the US industry summarize waste heat from selected process exhaust gases: iron/steel ovens and furnaces, industrial steam boilers, cement kilns, ethylene furnaces, glass furnaces, aluminum furnaces, and metal casting. The temperature ranges for the US data are defined as <230 °C (low), $230-650$ °C (medium) and >650 °C (high). The data for Japan comprise waste heat from the following industry: food, paper, petroleum, ferrous and non-ferrous, mechanics, transportation, electricity, fiber, chemical, ceramics, household appliance, gas and others. The data for the UK account for 73 unique industrial sites from 8 sectors: iron and steel, refineries, chemicals, cement, food and drinks, pulp and paper, glass, and ceramics.

The potential for heat recovery in the steel manufacturing industry by means of ORC power systems has been recently studied, and especially heat recovery from the exhaust gas of Electric Arc Furnaces (EAF) and rolling mills has been found promising [124]. One of the implemented arrangement features an intermediate loop, whereby saturated steam at temperatures around 300 °C is used in order to transfer the thermal energy of the furnace off-gas to the ORC working fluid [133]. A 3 MW_e unit is in operation since mid 2014 at the EAF of Elbe-Stahlwerke Feralpi in Riesa (Germany) as part of the European H-REII Demo project (Heat Recovery in Energy Intensive Industries) [134]. The first ORC power plant recovering heat from a rolling mill of a reheating furnace (700 kW_e) went into operation in April 2013 in Singapore. The heat transfer is performed by direct exchange between the exhaust gas and the ORC working fluid at temperatures around 400 °C.

The glass industry also offers vast opportunities for waste heat recovery by means of indirectly heated ORC power systems. An intermediate heat transfer loop can collect thermal energy from the hot gas exiting the oven that melts and refines the raw materials. The exhaust gas temperatures are relatively high ($400-500$ °C) [128]. Since 2012 one such system (1.3 MW_e) is in operation at the AGC floating glass production site in Cuneo (Italy). Other examples of successful ORC power plant installations for industrial heat recovery are at the urban solid waste incinerator plant in Roeselare (Belgium) - 3 MW_e, and at the sintered magnesite production site in Radenthein (Germany) - 1 MW. The Roeselare plant receives thermal energy at approximately 180 °C from a pressurized water loop transferring heat from the incineration furnace. The ORC system adopts a saturated configuration, axial turbine, synchronous generator, and an azeotropic mixture of pentafluorobutane and perfluoropolyethers as the working fluid [128].

Concentrated Solar Radiation

The design paradigm of CSP plants based on ORC engines is mainly related to the choice of the maximum plant temperature [135]. High temperature entails increased conversion efficiency, but calls for comparatively expensive solar collecting equipment and power block. The complementary approach consists in selecting a low maximum plant temperature which allows to adopt simpler technological solutions, but leads to lower conversion efficiency, which in turn demands for a larger solar field surface for a given power output. Within the STORES project in the US, a new paradigm for the successful deployment of thermal solar plants was investigated: economy of production can be achieved by means of high-volume manufacturing of small-capacity standard and modular systems, suitable for distributed energy conversion, instead of larger centralized power plants. ORC turbogenerators have been identified as the optimal conversion technology in this context, because of their performance and reliability [136, 137]. The main outcome of the study has been the construction of the first solar plant of this kind in the Saguaro Desert, Arizona. The plant, started operation in 2006, uses pentane as the working fluid and features a nominal power of 1 MW_e, with no need for on-site staff. The cycle efficiency is 21% with turbine-inlet and condensation temperatures equal to 204 and 15 °C. The reported average annual solar conversion efficiency is 12% [89].

More recently, a so-called hybrid ORC power plant has been put into operation in Ait Baha (Morocco), see also Fig. 7d. This plant combines heat recovery from waste heat of a cement factory (heat source cooled from 330 to 220 °C via an intermediate thermal oil loop) and a solar field of parabolic trough collectors including pebble stone thermal storage. The heat transfer fluid of the solar field is air at ambient pressure and inlet/outlet temperature of $270/570$ °C. The solar field generates a thermal power of 4 MW_{th} and the nominal power of the ORC turbine is 2 MW_e. The heat recovery unit of the ORC plant is in operation since 2012, while the start of the power generation of the solar field is currently under commissioning [138].

4 Future scenarios

Research and development activities are very lively because, together with the constant technological improvement related to current applications, new high-potential applications in the field of renewable energy and waste heat recovery are considered and actively studied and developed. The growth of the scientific and technical interest in ORC power systems is testified by the increase of scientific literature in this field, see fig. 6. The sudden increase of the number of publications related to ORC technology in the 80's and after 2000 can be correlated to the increase of oil prices, though the more recent trend is continuing notwithstanding the decrease and stabilization of oil prices of more recent years. It can be contended therefore that policy and strategic considerations are driving these studies. Nowadays, the application showing the highest

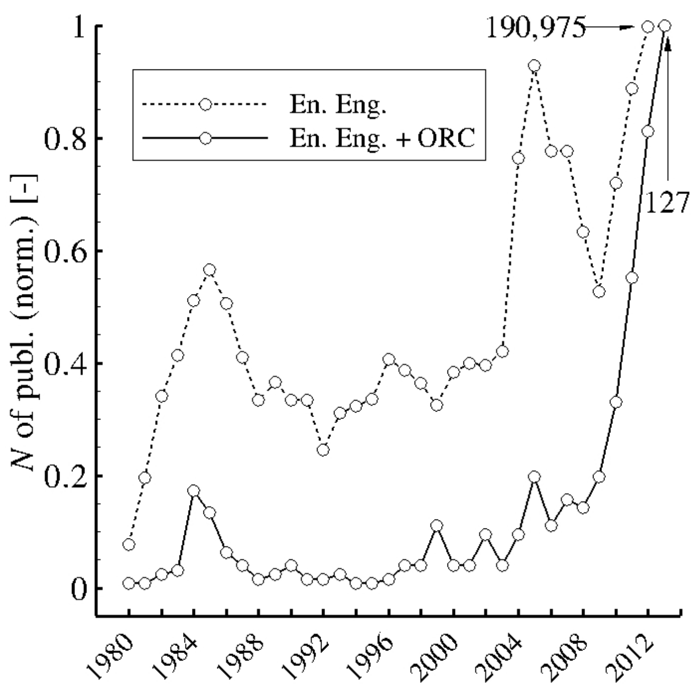


Fig. 6: Normalized number of published journal articles or conference papers in English per year since 1980. Dashed line: articles having as subject area *engineering* and *energy*. Solid line: articles on ORC power systems within the same subject area, i.e., with the acronym ORC appearing in the article title, abstract or among the keywords. The values are normalized with respect to the maximum value, which is indicated in the figure [139].

growth potential is arguably heat recovery at largely different capacity and temperature levels. All the applications of ORC power systems described in sec. 3.2 are undergoing a fast-pace growth, which will continue in the coming years, given the global turn toward renewable energy. Waste heat recovery by means of ORC power systems is actively researched in case of automotive engines (ORC unit from few up to 10 – 15 kW net power output) and starting to be applied in case of larger stationary reciprocating engines, but also as bottoming units for medium-size industrial gas turbines (ORC power plant up to approx. 20 MW), especially those used as mechanical drive in gas compression stations, and for power generation in the chemical and oil industry.

With reference to fig. 2, new applications of ORC power systems are located at the boundaries in terms of temperature and power capacities highlighted in the chart. At power levels of few kW, the conversion efficiency of low-temperature ORC systems is probably inherently too low for economic viability, though the system is feasible. A number of research efforts are ongoing aimed at developing Rankine cycle-based heat recovery systems for passenger vehicle applications, with a number of studies identifying ORC turbogenerators among the most promising solutions [140–142]. If the energy source is at high temperature, in the power range starting from hundreds of kW, both steam and ORC power systems are feasible and various economic and technical consideration drive the selection, though ORC power systems are more often preferred. It is only recently that, at this temperature range, ORC power systems are being developed at multi-megawatt capacity level, while for larger power capacity ORC power systems cannot compete with steam power plants. Unless other drivers are present which suggest the adoption of ORC (e.g. freezing issues in extreme climates), at medium temperatures of the energy source but large power capacity, ORC power plants are studied for the heat recovery from large processing units in the oil and gas industry [124], and other sectors of the chemical industry are also interested. At low temperature levels, currently the only large energy source that is driving some developments is the thermal gradient established in the water of tropical and equatorial ocean regions, see sec. 4.4.

As for the most relevant research topics, the supercritical cycle configuration is receiving attention because its thermodynamic merit needs careful evaluation, together with implications on turbomachinery design, due to dense-gas effects, and large expansion ratio [96, 97, 143]. In analogy to steam power plants, multiple pressure-level cycles and reheating of expanded vapor have been considered in order to boost efficiency [10, 144]. However, the feasibility of these solutions is challenged by the additional plant complexity they imply. The Lorentz thermodynamic cycle is known to be thermodynamically the best option for the exploitation of sensible heat sources and, to this end, different solutions adopting organic working fluids in so-called trilateral cycles have been proposed [145–147]. The criticality with such systems is related to the fully wet expansion process, still posing technological concerns regarding the expanding device, should it be a turbine. In case very high electrical efficiency is sought, the cascaded cycle configuration can be attractive and its evaluation has driven some interest, presenting several advantages if compared to a single cycle with large pressure ratio [10, 54, 137, 148].

Research on new working fluids can have a large impact, especially because fluids for high temperature applications that satisfy all requirements do not exist. However, fluid manufacturers are currently refraining from highly targeted development of new working fluids because the dimension of the market would require taking as a risk the large investments needed for R&D activities on new molecules, related new production processes, and new production plants. Large markets could arise as a result of the introduction of new optimal working fluids (e.g., automotive, naval and train-engine heat recovery), thus this circular situation has determined a stall so far. The merit of using fluid mixtures has been addressed already many years ago [149], and still stimulates many theoretical studies [150–152]. An innovative idea that very recently sparked some interest is the integration of the selection of the working fluid into the optimal automated cycle configuration design procedure [153]. The study of this idea is at a preliminary stage, but its potential could be high if competences on ORC system design can be successfully merged with knowledge at molecular level, and fluid manufacturing. Furthermore, new developments due to the advancements of simulation science promise to overhaul the traditional sequential and iterative design process. The new design paradigm can be termed *virtual prototyping*. The physics involved in an ORC power system is relatively well understood and therefore it can be accurately modeled. The power of modern software and computers are making it possible to develop and use a programming environment in which the entire system and its components can be modeled and simulated to the level of detail that is needed for preliminary design and optimization [154]. Dynamic simulation capabilities allow considering requirements on transient operation and control since early design stages [98, 155]. Applications that may feature critical control aspects are automotive heat recovery [142, 156, 157], and the conversion of concentrated solar radiation [158].

The fluid dynamics of expanders attracts considerable research efforts [159–161]: a sizable improvement of the fluid-dynamic performance of the expander directly affects the power output and thus the return on investment, more often without affecting the cost of each unit. On the contrary, improvement of the heat exchanging equipment can often be obtained only by increasing the heat transfer surface, therefore the cost of each unit. The non-conventional features of highly supersonic flows typical of high-temperature ORC turbines has driven even some fundamental experimental studies [162, 163].

All types of volumetric expanders for mini-ORC power systems are currently studied theoretically and experimentally. Piston expanders would be suitable for high-temperature applications, and they have recently been studied for truck engine heat recovery systems [164], though the need for a lubricant, and the high blow-by losses are difficult challenges to overcome. Predictive models for scroll expanders are actively studied [165, 166], and also experimental activities are pursued [110]. Models of single and twin-screw expanders [167, 168] are also under strong development.

Also the fluid-dynamic design of organic fluid pumps for high pressure levels and large compression ratio, whereby compressibility effects might play a role, should be considered, though no specific study is known to the authors.

The literature reports very few articles dealing with heat exchangers specifically designed for ORC power systems, see, e.g., Refs. [169, 170]. However, the design of more compact and lighter heat exchangers plays a very important role, particularly in the emerging field of mobile applications. To this end, several heat transfer enhancement techniques are investigated, leading to new concepts such as micro-channel [169, 171, 172] and porous [173, 174] heat exchangers. The addition of nano-particles to the working fluid might be beneficial for ORC power system for which ultra-high heat transfer to and from the working fluid is relevant [175]. Polymeric materials heat exchangers might also be an option in the future [176].

More detailed information on current and possible future research and development activities is given in the following sections, depending on the specific application. In this respect, one important factor that might influence the level and amount of future research is the recent interest in ORC technology by large global companies. This is testified either by the starting of R&D work devoted to new applications, see, e.g., Refs. [84, 164], or by the acquisition of companies that developed ORC technology [177].

4.1 Heat Recovery from Automotive Engines

The potential of recovering heat from the exhaust and the cooling system of automotive engines cannot be understated. The development strategy of this product is radically different from that of stationary units. In case of mini-ORC power systems for automotive engine heat recovery the paradigm is that of economy of production (large number of standardized units). If this industrial sector is successful, several new large markets for mini-ORC power systems could open up, see, e.g., sec. 4.2.

Recently, interest is being revived [178–182], and a considerable research and development effort by original equipment manufacturers (OEM) and tier-one suppliers has been focused especially on the waste heat recovery from long-haul truck engines [164]. In this case, as opposed to car engines [183], the amount of thermal power that can be recovered is arguably enough to allow for the design of an ORC system that does not incur into the limitations inherent to very small expanders. In addition, the large number of operating hours at cruising speed, plays an important role in the evaluation of the profitability of the investment. Feasibility studies on heat recovery from car engines have unveiled several limitations with current technological and economic conditions.

The first units that will be marketed are likely to be add-ons for existing trucks and their engines, employing ethanol as the working fluid and using high-speed turbines. Because the system is designed to fit existing truck frames and engines, strict requirements on the volume occupied by ORC components must be complied with. Regulations and requirements on the working fluids for the automotive sector are also quite stringent: aspects like toxicity, flammability, ODP and GWP are regulated. Even though a rational approach would require that these aspects are considered in relation to the corresponding indexes of the fuel, which is transported in quantities that are orders of magnitude larger. Very importantly, the freezing point of the working fluid must comply with the typical requirements of the automotive sector, therefore operation of the ORC system should be guaranteed for engine idle and startup temperatures as low as $-40\,^{\circ}\mathrm{C}$.

An interesting concept that might be successful in the longer run, is the *combined-cycle power train*: in this case the primary engine and its integrated heat recovery system are designed together in order to optimize all critical aspects: efficiency, volume, weight, reliability, etc. The potential for improvement with respect to the add-on approach can be large if one thinks about the similarity to the design methodology of combined-cycle power stations. In this case the gas and the steam turbine systems are optimized in an integrated fashion, aiming at maximizing the efficiency of the whole system, which often leads to a gas turbine which is less efficient than what is achievable with a simple Brayton cycle configuration [184]. In a combined cycle powertrain, also the relatively large amount of thermal energy dissipated by the engine cooling system could be recovered. Given the radical changes with respect to current practice that such a system could impose, it is likely that the whole cab and drivetrain should be designed around the new combined-cycle powertrain. Another interesting possibility is that the combined-cycle engine is part of a hybrid powertrain, thus generating electricity to power electric in-wheel motors and batteries [185].

In the authors' opinion, the development of mini-ORC power systems for the automotive sector has the potential to boost the advancements in many other fields of applications, see secs. 4.2 and 4.3.

4.2 Domestic CHP

The potential advantages of finely distributed cogeneration have been studied [25], especially in case of capillary natural-gas distribution, like in large parts of Europe. Besides the high utilization factor and total system efficiency, there might be a strategic interest in promoting a new business model of distributed power generation, due to the increasing difficulty to locate or refurbish power stations in densely populated areas because of permitting and public acceptance.

Among the technologies that are suitable for small-capacity electrical power conversion and cogeneration of heating, domestic ORC CHP units underwent research and development activities [186,187]. In comparison to Stirling and micro-gas turbine generators, ORC systems display some potential advantages. In case of recent developments, the power capacity is either very small, 1 kW [186], or small, $10-30$ kW [187], and the need to keep the cost low, especially in the case of a new application promoted by small companies, resulted in low-temperature cycles and the use of scroll expanders [188], whereby the electric efficiency is bound to be low ($5-10\%$). In any case the total energy efficiency can be very high (up to approximately $85-90\%$). The market for mini-ORC CHP units for domestic use could be very large (e.g., several millions unit per year in Europe only), but the higher investment cost compared to a traditional heater might be a barrier to widespread market introduction. In an increasing number of countries, however, mini-CHP systems are eligible for feed-in tariff schemes, which provide subsidy for early technology adopters. In the future, a large market might arise in developing countries where low-cost solid biomass fuel is locally available.

4.3 Concentrated Solar Power - CSP

The majority of the present research efforts are devoted to low-to-medium temperature solar ORC systems, aiming at using comparatively inexpensive solar collectors and at cogenerating heat and cooling. However, considering also the promising results achieved in the past [64, 70, 89], the investigation of higher temperature and thus high-efficiency systems might be worth more attention. ORC systems combined with solar-trough fields cannot compete in terms of cost and efficiency with solar-tower power plants for centralized power production. The advantage of solar ORC power systems is the possibility of locally integrating thermal storage and cogenerating heat and cooling, and still achieving an electric efficiency that is competitive with photo-voltaic panels, at the cost of a more complex system, possibly requiring more maintenance. The potential market of distributed solar cogeneration is very large, e.g., for buildings in the solar belt. In this respect, innovative concepts aimed at including thermal storage, while simplifying plant layout and operation, and preserving or improving performance might be successful [189]. the use of small-capacity solar or biomass-fueled ORC modules to power the electrification of remote areas has been envisaged since the first studies on this technology [36, 46], and this research field is still actively investigated [148, 190]. The combination of solar power conversion with other functions has also been studied: examples are desalinized water, or combination with cooling by means of absorption chillers [6, 191–194]. Also the hybridization with other energy sources seems promising; this is the case of systems integrating concentrated solar input with biomass combustion [195], industrial waste heat recovery [138], geothermal energy [196], or ocean thermal energy [10].

4.4 Ocean Thermal Energy Conversion - OTEC

An ORC power plant could be suitable for the conversion of the energy deriving from the temperature difference between surface and deep ocean water ($600-1000$ m), which is in the range $20-25$ °C in various parts of the tropical and equatorial belt. The OTEC concept has been studied for a long time [197], though no commercial application exists, the very low power density being the main technical and economic challenge. Recently, experimental research has been resumed and pilot plants have been built, utilizing ammonia as the working fluid in a saturated cycle configuration [198]. An ORC system utilizing a refrigerant or a hydrocarbon as working fluid are options, compared to the more conventional and studied ammonia Rankine cycle OTEC plant, or to the potentially more efficient Kalina or Uheara cycle power plants [198–200]. Note that ammonia-water mixtures implies lower heat transfer coefficient than pure fluids, thus possibly much larger heat exchangers. Technical problems related to deep-water pipes and pumps can now be solved because of advancements in off-shore technology. Economic viability might be achieved in the future, depending on energy value and policy, arguably only with large installations (many tens to hundreds or more MW) [201]. Such conditions push for the highest possible efficiency. The co-production of other goods or utilities (e.g. desalinated water) could also positively influence the economic feasibility. An interesting overview of various aspects related to OTEC power plants can be found in Ref. [10], together with the illustration of a study on the hybridization of an OTEC power plant with the addition of solar concentrators, and the utilization of complex configuration (multiple pressure level) for maximum thermodynamic efficiency.

4.5 Other applications

Other niche applications attracted some research efforts because the use of an ORC power system implies several advantages. An example is the heat recovery from high-temperature fuel cells. Molten Carbonate Fuel Cell (MCFC) and Solid Oxide fuel cell (SOFC) discharge flue gases at temperatures around 400 to 600 °C, and can achieve extremely high electrical efficiency (50% to 60%). They have not reached widespread market introduction because of the very high cost per kilowatt and because of long-term reliability and maintenance issues. The first commercialized MCFC units are in the 300 kW_e $-$ 3 MW_e power range, and an ORC power system is the heat recovery system of choice, not only because of technical reasons, but also because its cost per kilowatt is bound to be lower than that of the fuel cell, thus inherently improving the return on investment of the total system [202–204].

ORC turbogenerators are increasingly studied also as bottoming cycles in combined systems for advanced power conversion facilities. According to several authors, this can be the solution of choice to recover power from the exhaust of high efficiency small and medium-size gas turbines, in order to exceed 50% efficiency at power levels as low as 5 MW_e [205,206]. Similar systems are being considered also for CBC-based plants proposed for next generation nuclear and CSP applications [207].

Another notable application that has been studied in the past and that might attract attention in the future is the conversion from solar radiation in space. At the time of the initial activities aimed at the development of the International Space Station, together with Stirling engines and closed Brayton cycle gas turbines, ORC power systems were much studied, also experimentally [67,208,209]. It is well possible that the increasing presence of devices orbiting around the earth and further space exploration will drive the development of special solar or nuclear-powered ORC systems, whereby the main advantage with respect to photovoltaic panels could be the possibility of efficiently cogenerating the heat needed for the thermal control of on-board equipment.

5 Conclusions

The concept of the organic Rankine cycle engine is almost coeval with that of the steam engine. Similarly to steam engines, the concept has been implemented into actual power systems with an impressive growth of technological sophistication. The main cause of the recent success of ORC power systems is possibly their very high flexibility, and their relatively high conversion efficiency in the low power range. It is a technology that can be used to convert external sources of thermal energy at widely different temperature levels, and at an equally wide range of capacities. This characteristic places ORC power systems in a prominent position among the technologies that are suitable for renewable of renewable-equivalent thermal energy conversion (geothermal reservoirs, biomass combustion, concentrated solar radiation, industrial waste-heat recovery, waste heat recovery from reciprocating engines and gas turbines, ocean thermal gradient). ORC power systems can also co-generate heat and cooling, thus are inherently suitable for distributed energy conversion with unequaled total thermal efficiency.

Technical solutions have been developed out of scientific and technical research, and sometimes quite fundamental investigation paved the way to highly innovative improvements. This is the case, for instance, of the study on new fluids, and their modeling, and the study of the complex gasdynamics of dense vapors and supercritical fluid flows of organic substances. Equally important were technical inventions related to the various components of the system, and the hermetic turbogenerator, or the recently re-descovered radial outflow turbine are good examples. Design problems are quite complex because fundamental aspects, e.g., those related to thermodynamic cycles, and fluid dynamics, cannot be studied without taking into account realistic technical constraints at the same time. The development of new technology benefits today from the application of the most advanced engineering methods, like high-fidelity simulations of fluid flows and complex multi-physics and system and component optimization.

The cumulative installed capacity (CIC) of ORC power plants have been growing at a sustained rate starting from the first years of the new millennium, as well as the number of ORC power systems. The current CIC is over $2,000$ $\mathrm{MW_e}$ and close to a hundred units are commissioned every year. The number of vendors is increasing, and large manufactures of conventional power equipment are entering the market, together with several new dynamic enterprises. The trend might be similar to that of the CIC of wind power plants, if one looks at some ten to fifteen years ago. The analysis of the available information about commercial power plants shows that the range of power outputs of ORC units that enter into operation is becoming both smaller and larger, if compared to few years ago. The application of ORC technology to geothermal heat and biomass combustion conversion, the two applications that sparked the growth of ORC installations, continues the trend, whereby the power output of geothermal ORC power plants is increasing (the plants that were recently commissioned feature capacities from several tens of MW up to the last one, which is approximately 100 MW). Biomass-fuelled ORC power plants are still spreading in Europe, where policy is favorable, but the situation is not yet equally favorable in other continents. Waste heat recovery from prime movers and industrial processes by means of ORC power plants has also started to grow in recent years, and it is the application with arguably the highest potential in the foreseeable future.

Very recently, a considerable amount of research and development efforts are dedicated to the development of ORC systems for applications suitable for high-volume production, and heat recovery from automotive engines stands out. The automotive industry is committed to the initiative. Several solutions are investigated, different above all with respect to the expander. Volumetric (piston, screw, scroll) expanders are attractive, as much knowledge from small refrigeration compressors is available, but limitations related to the maximum expansion ratio and inlet temperature are difficult to overcome. High-speed turbines are very promising given their ability to expand vapors from high temperature and to handle large expansion ratio. In addition they potentially offer a high degree of reliability, given their simplicity, as it can be extrapolated from the experience with turbo-chargers. The first models of mini-ORC turbogenerators for heat recovery from the exhaust of truck engines will likely be commercialized in the next few years. If successful, the production of a large number of standardized and cost-effective units could promote the adoption of mini-ORC power systems in many other high-volume applications. Examples are domestic CHP, distributed solar power plants cogenerating heat and/or cooling with thermal storage, and capillary waste heat recovery. The possibility that ORC power blocks will make OTEC plants a viable solution for base-load energy conversion in the tropical oceans is also worth consideration.

The increase in interest and technological development around ORC power system resulted in the consolidation of a community of technical professionals who met for the first time in 2011 at the first international seminar on ORC power systems, held at the Delft University of Technology. The success of the initiative resulted in the establishment of the ORC Power Systems committee within the ASME International Gas Turbine Institute. The committee has in the website of the Knowledge Center on organic Rankine cycle technology its hub for the dissemination of information [210]. The committee now organizes the bi-annual ASME ORC conference.

As a final remark, it is worth noting that modern technological progress is often due to strong collaboration between academia and industry. Academics shall continue to strive with their role of looking at high-risk high-reward research, especially now that the technology grew further from its infancy. The level of research and development should reach those of more mature energy conversion technologies, like, e.g., gas turbines or reciprocating engines. The companies that have been on the market since the beginning of the diffusion of ORC power systems, and those that are now entering the market, shall therefore maintain or increase their attitude toward research and innovation, without which the solutions needed in order to fulfill the high potential of current and future applications cannot be obtained.

Aknowledgements

The authors are very grateful for the large amount of specific information that was contributed by many colleagues and professionals in the field. In particular, we thank Dr. Lucien Bronicki, Prof. Jos van Buijtenen, and Prof. Mario Gaia for the many interesting discussions and email exchanges we entertained during the years that led to the completion of this article. A special mention goes to the late Prof. Angelino who inspired so much of its content.

References

[1] Tabor, H., and Bronicki, L., 1964. "Establishing criteria for fluids for small vapor turbines". *SAE Technical Paper,* **640823**.

[2] Angelino, G., Gaia, M., and Macchi, E., 1984. "A review of Italian activity in the field of organic Rankine cycles". In VDI Berichte - Proceedings of the International VDI Seminar, Vol. 539, VDI Verlag, pp. 465–482.

[3] Adam, A. W., 1995. *Encyclopedia of Energy Technology and the Environment*. John Wiley & Sons, ch. Organic Rankine Engines, pp. 2157–2161.

[4] Macchi, E., 1977. "Design criteria for turbines operating with fluids having a low speed of sound". In Lecture Series 100 on Closed Cycle Gas Tubines, Von Karman Institute for Fluid-Dynamics.

[5] Verneau, A., 1987. "Supersonic turbines for organic fluid Rankine cycles from 3 to 1300 kW". In Lecture series 1987-07 Small High Pressure Ratio Turbines, Von Karman Institute for Fluid Dynamics.

[6] Quoilin, S., Broek, M. V. D., Declaye, S., Dewallef, P., and Lemort, V., 2013. "Techno-economic survey of Organic Rankine Cycle (ORC) systems". *Renew. Sust. Energ. Rev.,* **22**, pp. 168 – 186.

[7] Invernizzi, C. M., 2013. *Closed Power Cycles - Thermodynamic Fundamentals and Applications*. No. 11 in Lecture Notes in Energy. Springer-Verlag.

[8] Di Nanno, L., Di Bella, F., and Koplow, M., 1983. An RC-1 organic Rankine bottoming cycle for an adiabatic Diesel engine. Tech. Rep. DOE/NASA/0302-1, NASA, Lewis Research Center.

[9] Fergason, S., Guardone, A., and Argrow, B., 2003. "Construction and validation of a dense gas shock tube". *J. Thermophys. Heat Transfer,* **17**(3), pp. 326–333.

[10] Bombarda, P., Invernizzi, C., and Gaia, M., 2013. "Performance analysis of OTEC plants with multilevel organic Rankine cycle and solar hybridization". *J. Fluid Eng.-T. ASME,* **135**(4).

[11] Gaia, M., 2011. "30 years of ORC development". Keynote lecture at the ORC2011 - 1st International Seminar on ORC Power Systems - Delft (NL), September 22-23. Available online: www.kcorc.org/en/literature.

[12] Kalina, I. A., 1984. "Combined cycle system with novel bottoming cycle". *J. Eng. Gas Turb. Power - Trans. ASME,* **106**, pp. 737–742.

[13] Bombarda, P., Invernizzi, C., and Pietra, C., 2010. "Heat recovery from Diesel engines: A thermodynamic comparison between Kalina and ORC cycles". *Appl. Therm. Eng.,* **30**, pp. 212 – 219.

[14] Stone, K., Leingang, E., Liden, B., Ellis, E., Sattar, T., Mancini, T., and Nelving, H., 2001. "SES/Boeing dish Stirling system operation". In Proceedings of the ASME International Solar Energy Conference, Washington (US-DC), April 21-25, pp. 105–110.

[15] Reinalter, W., Ulmer, S., Heller, P., Rauch, T., Gineste, J. M., Ferriere, A., and Nepveu, F., 2007. "Detailed performance analysis of a 10 kW dish Stirling system". *J. Sol. Energ. - Trans. ASME,* **130**(011013).

[16] Carlsen, H., and Fentz, J., 2004. "Development of a 9 kW Stirling engine". In Proceedings of the International Gas Research Conference, Vancouver (CA), November.

[17] Conroy, G., Duffy, A., and Ayompe, L., 2013. "Validated dynamic energy model for a Stirling engine μ-CHP unit

using field trial data from a domestic dwelling". *Energy Build.,* **62**, pp. 18–26.

[18] Angelino, G., and Invernizzi, C., 2000. "Real gas effects in Stirling engines". In Proceedings of the 35th Intersociety Energy Conversion Engineering Conference & Exhibit (IECEC), Las Vegas (US-NV), July 24-28, pp. 69–75.

[19] Anon., 2008. "Global monitor: Sandia, Stirling energy systems set new world record". *Power,* **152**(4).

[20] Angelino, G., 1968. "Carbon dioxide condensation cycles for power production". *J. Eng. Power - T. ASME,* **10**, July, pp. 287–295.

[21] Dostal, V., Hejzlar, P., and Driscoll, M. J., 2006. "High-performance supercritical carbon dioxide cycle for next-generation nuclear reactors". *Nucl. Technol.,* **154**(3), pp. 265–282.

[22] Iverson, B., Conboy, T., Pasch, J., and Kruizenga, A., 2013. "Supercritical CO_2 Brayton cycles for solar-thermal energy". *Appl. Energ.,* **111**, pp. 957–970.

[23] Bram, S., De Ruyck, J., and Novak-Zdravkovic, A., 2005. "Status of external firing of biomass in gas turbines". *Proc. IMechE Part A: J. Power and Energy,* **219**(2), pp. 137–145.

[24] Heller, P., Pfänder, M., Denk, T., Tellez, F., Valverde, A., Fernandez, J., and Ring, A., 2006. "Test and evaluation of a solar powered gas turbine system". *Sol. Energy,* **80**(10), pp. 1225–1230.

[25] Pehnt, M., Praetorius, B., Schumacher, K., Fischer, C., Schneider, L., Cames, M., and Voß, J.-P., 2006. *Micro Cogeneration: Towards Decentralized Energy Systems*. Springer.

[26] Galloway, E., and Hebert, L., 1836. *History and progress of the steam engine: with a practical investigation of its structure and application*. Printed for Thomas Kelly, R. Clay printer.

[27] Ofeldt, F. W., 1898. "Engine". Patent US611792 A.

[28] Durant, K., 1976. *The Naphtha Launch*. Monographs. Adirondack Museum.

[29] Towne, P., 1991. "The naphta engine". *Gas Engine Magazine*, October/November.

[30] Shuman, F., 1907. The direct acting solar engine - the prime mover of the immediate future. Tech. rep., The Sun Power Company. Review Publishing & Printing Company, Philadelphia (US-PA).

[31] Tissandier, G., and de Parville, H., 1888. "Moteurs a vapeurs volatiles". *La Nature*(790), July 21, pp. 113–114.

[32] Esher Wyss AG, 1912. Motorboote und motoryachten. Reprinted by Brian Hillsdon and Jim White in 1982. Catalogue.

[33] Anon., 1904. "Naphta launch ablaze". *The New York Times*, 26 July.

[34] Pytilinski, J., 1978. "Solar energy installations for pumping irrigation water". *Sol. Energy,* **21**(4), pp. 255 – 262.

[35] Spencer, L., 1989. "A comprehensive review of small solar-powered heat engines: Part I. a history of solar–powered devices up to 1950". *Sol. Energy,* **43**(4), pp. 191 – 196.

[36] D'Amelio, L., 1935. *Impiego di vapori ad alto peso molecolare in piccole turbine e utilizzazione del calore solare per energia motrice*. Industria Napoletana Arti Grafiche.

[37] D'Amelio, L., 1936. "La turbina a vapore ed i cicli binari con fluidi diversi dall'acqua fra le isoterme inferiori". *L'Elettrotecnica,* **XXIII**(9), pp. 250–257.

[38] D'Amelio, L., 1936. "La turbina a vapore ed i cicli binari con fluidi diversi dall'acqua fra le isoterme inferiori". *L'Elettrotecnica,* **XXIII**(10), pp. 286–292.

[39] D'Amelio, L., 1939. *I combustibili nazionali ed il loro impiego*. Reale accademia delle scienze di Torino, ch. Le acque termali come fonti di energia, pp. 293–307.

[40] Dornig, M., 1959. *Trattato generale delle macchine termiche ed idrauliche: Macchine a vapore*. Libreria editrice politecnica C. Tamburini, ch. 2, p. 246.

[41] D'Amelio, L., 1958. "A steam engine using a mixture of vapours from non-miscible fluids as a solar engine with flat plate collectors". In Proceedings of the 1955 International Conference on the Use of Solar Energy - the Scientific Basis. Tucson (US-AZ), Oct. 31 - Nov. 1, E. F. Carpenter, ed., Association for Applied Solar Energy, Arizona Unversity Press.

[42] D'Amelio, L., 1963. "Thermal machines for the conversion of solar energy into mechanical power (presented at the United Nations conference on new sources of energy, Rome, 1961, 12 p.)". *Sol. Energy,* **7**(2), p. 82.

[43] DiPippo, R., 2012. *Geothermal Power Plants*, third ed. Butterworth-Heinemann, Boston, ch. 8, p. 152.

[44] Povarov, O., Saakyan, V., Nikolski, A., Luzin, V., Tomarov, G., and Sapozhnikov, M., 2003. "Experience of creation and operation of geothermal power plants at Mutnovsky geothermal field, Kamchatka, Russia". In Proceedings of the International Geothermal Conference, no. S01P52, pp. 1–56.

[45] Tomarov, G. V., Nikolsky, A. A., Semenov, V. N., and Shipkov, A. A., 2010. "Recent geothermal power projects in Russia". In Proceedings of the World Geothermal Congress, pp. 1–7.

[46] Tabor, H., and Bronicki, L., 1963. "Small turbine for solar energy power package". *Sol. Energy,* **7**(2), p. 82. Presented at the 1961 United Nations Conference on New Sources of Energy, Rome.

[47] Ray, S. K., and Moss, G., 1966. "Fluorochemicals as working fluids for small Rankine cycle power units". *Adv. Energy Convers.,* **6**, pp. 89–102.

[48] Spencer, L., 1989. "A comprehensive review of small solar-powered heat engines: Part II. research since 1950 – "conventional engines" up to 100 kW". *Sol. Energy,* **43**(4), pp. 197 – 210.

[49] Bronicki, L., 1972. "The Ormat Rankine power unit". In Proceedings of the IECEC Conference, pp. 327–334.

[50] Anon., 1972. "Turbo-generator provides 2,000 watts remote power". *World Oil,* **175**(7), pp. 67–69.

[51] Bronicki, L., 1968. "Ten years of research, development and operation of Rankine cycle power units in Israel". In Proceedings of IECEC.

[52] Einav, A., 2004. "Solar energy research and development achievements in Israel and their practical significance". *J. Sol. Energ. - Trans. ASME,* **126**(3), pp. 921–928.

[53] Bronicki, L. Y., 2007. "Organic Rankine cycles in geothermal power plants: 25 years of Ormat experience". In GRC transactions, Vol. 31, Geothermal Resources Council, pp. 499–502.

[54] DiPippo, R., 2012. *Geothermal Power Plants*, third ed. Butterworth-Heinemann, Boston, ch. 18, pp. 362–374.

[55] Larjola, J., 1988. "ORC power plant based on high speed technology". In Proceedings of the Conference on High Speed Technology, no. ENTE D-15, Lappeenranta University of Technology, pp. 63–77.

[56] Platell, O. B., 1976. "Progress of Saab Scania's steam power project". *SAE Technical paper,* **760344**.

[57] Luchter, S., and Renner, R., 1977. Assessment of the technology of Rankine engines for automobiles. Tech. Rep.

ERDA-77-54, US Energy Research and Development Administration.

[58] DiBella, F. A., DiNanno, L. R., and Koplow, M. D., 1983. "Laboratory and on-highway testing of Diesel organic Rankine compound long-haul vehicle engine". *SAE Technical paper,* **830122**.

[59] Werner, D., and Barber, R., 1973. "Working fluid selection for a small Rankine cycle total energy system for recreation vehicles". pp. 146–151. Proceedings of the 8th Intersoc. Energy Convers. Eng. Conf. - Philadelphia (US-PA), August 13-17.

[60] Barber, R., 1974. "Potential of Rankine engines to produce power from waste heat streams.". pp. 508–514. Proceedings of the 9th Intersoc. Energy Convers. Eng. Conf. - San Francisco (US-CA), August 26-30.

[61] Prigmore, D., and Barber, R., 1975. "Cooling with the sun's heat design considerations and test data for a Rankine cycle prototype". *Sol. Energy,* **17**(3), pp. 185 – 192.

[62] Abbin, J., 1978. Solar total energy test facility project test summary report: Rankine cycle energy conversion subsystem. Tech. Rep. SAND-78-0396, Sandia Labs., Albuquerque (US-NM).

[63] Barber, R., and Batton, W., 1988. "Development of a 25 kW solar electric-power-generation unit.". pp. 237–243. Proceedings of the 10th ASME Solar Energy Conference - Denver (US-CO), Code 11306.

[64] Jaffe, L. D., 1988. "Review of test results on parabolic dish solar thermal power modules with dish-mounted Rankine engines and for production of process steam". *J. Sol. Energ. - Trans. ASME,* **110**(4), pp. 275–281.

[65] Prasad, A., 1980. "Field testing of a 600 kW organic Rankine cycle waste recovery system: Results to date.". *Energy Technology: Proceedings of the Energy Technology Conference,* **1**, pp. 482–494.

[66] Boretz, J. E., 1986. "Supercritical organic Rankine engines (SCORE)". In 21st Intersociety Energy Conversion Engineering Conference (IECEC), Vol. 3, ACS, pp. 2050–2054.

[67] Angelino, G., and Invernizzi, C., 1993. "Cyclic Methylsiloxanes as Working Fluids for Space Power Cycles". *J. Sol. Energ. - Trans. ASME,* **115**(3), pp. 130–137.

[68] Bado, G., Tomei, G., Angelino, G., Gaia, M., and Macchi, E., 1979. "The Ansaldo 35 kW solar power system". In Sun II, Proceedings of the Silver Jubilee Congress, Atlanta - GA, Vol. 2, Pergamon Press, pp. 1090–1094.

[69] Angelino, G., Gaia, M., Macchi, E., Barutti, A., Maccio, C., and Tomei, G., 1982. "Test results of a medium temperature solar engine.". *Int. J. Ambient Energy,* **3**(3), pp. 115–126.

[70] Barutti, A., Pedrick, W., Angelino, G., Gaia, M., and Macchi, E., 1984. "Ansaldo solar thermal and photovoltaic plants located at Ballajura, Western Australia.". In Proceedings of the 8th Solar World Congress 1983, Biennial Congress of the International Solar Energy Society, Perth (AU), Vol. 3, pp. 1572–1576.

[71] Gaia, M., Angelino, G., Macchi, E., DeHerring, D., and Fabry, J., 1984. "Experimental results of the ORC engine developed for the Borj Cedria solar plant.". In Proceedings of the 8th Solar World Congress 1983, Biennial Congress of the International Solar Energy Society, Perth, Australia, Vol. 3, pp. 1460–1464.

[72] Angelino, G., Invernizzi, C., and Macchi, E., 1991. *Organic Working Fluid Optimization for Space Power Cycles*. Springer New York, ch. 16, pp. 297–326.

[73] Jokinen, T., Larjola, J., and Mikhaltsev, I., 1998. "Power unit for research submersible". In ElecShip 98, International

Conference on electric ship, pp. 114–118.

[74] Bronicki, L., 1988. "Experience with high speed organic Rankine cycle turbomachinery". In Proceedings of Conference on High Speed Technology, no. ENTE D-15, Lappeenranta University of Technology, pp. 44–61.

[75] Larjola, J., 1984. "ORC-plant with high-speed gas lubricated turbogenerator". In VDI Berichte - Proceedings of the International VDI Seminar, Vol. 539, VDI Verlag, pp. 697–705.

[76] van Buijtenen, J., Larjola, J., Turunen-Saaresti, T., Honkatukia, J., Esa, H., Backman, J., and Reunanen, A., 2003. "Design and validation of a new high expansion ratio radial turbine for ORC application". In Proceedings of the 5th European Conference on turbomachinery.

[77] Curran, H., 1981. "Use of organic working fluids in Rankine engines". *Journal of Energy,* **5**(4), pp. 218–223.

[78] Atlas Copco - Expanders, 2014. Official website: www.atlascopco-gap.com/products/expanders/eg-egi-eegi-series/ [Last accessed November 2014].

[79] Exergy, 2014. Official website: exergy-orc.com.

[80] Spadacini, C., Centemeri, L., Xodo, L. G., Astolfi, M., Romano, M. C., and Macchi, E., 2011. "A new configuration for organic Rankine cycle power systems". ORC2011 - 1st International Seminar on ORC Power Systems - Delft (NL), September 22-23. Available online: www.kcorc.org/en/literature.

[81] Spadacini, C., Rizzi, D., Saccilotto, C., Salgarollo, S., and Centemeri, L., 2013. "The radial outflow turbine technology". ASME ORC2013 - 2nd International Seminar on ORC Power Systems - Rotterdam (NL), October 7-8. Available online: www.kcorc.org/en/literature.

[82] Hawkins, L., Lei, Z., Blumber, E., Mirmobin, P., and Erdlac, R., 2012. "Heat-to-electricity with high-speed magnetic bearing/generator system". In Geothermal Resources Council Annual Meeting, Vol. 36, pp. 1073–1078.

[83] GE Oil & Gas - ORegen, 2014. Official website: www.ge-energy.com/products_and_services/services/oil_and_gas_services/oregen.jsp [Last accessed November 2014].

[84] Del Turco, P., Asti, A., Del Greco, A., Bacci, A., Landi, G., and Seghi, G., 2011. "The ORegen waste heat recovery cycle: Reducing the CO_2 footprint by means of overall cycle efficiency improvement". In Proceedings of ASME Turbo Expo 2011, Vancouver (CA), June 6-10, pp. 547–556.

[85] Burrato, A., 2013. "ORegen™waste heat recovery: Development and applications". ASME ORC2013 - 2nd International Seminar on ORC Power Systems - Rotterdam (NL), October 7-8. Available online: www.kcorc.org/en/literature.

[86] Ormat Technologies Inc., 2014. Official website: www.ormat.com.

[87] Bronicki, L., 2013. "Short review of the long history of ORC power systems". Keynote lecture at the ASME ORC2013 - 2nd International Seminar on ORC Power Systems - Rotterdam (NL), October 7-8. Available online: www.kcorc.org/en/literature.

[88] Bronicki, L., 2013. Personal communication.

[89] Canada, S., Brosseau, D., and Price, H., 2006. "Design and construction of the APS 1-MW_E parabolic trough power plant". In Proceedings of the ASME International Solar Energy Conference 2006.

[90] Triogen BV., 2014. Official website: www.triogen.nl.

[91] van Buijtenen, J., Eppinga, Q., and Ganassin, S., 2013. “Development and operation of a high temperature high speed organic Rankine cycle system”. ASME ORC2013 - 2nd International Seminar on ORC Power Systems - Rotterdam (NL), October 7-8. Available online: www.kcorc.org/en/literature.

[92] Turboden s.r.l., 2014. Official website: www.turboden.eu.

[93] Bini, R., Duvia, A., Schwarz, A., Gaia, M., Bertuzzi, P., and Righini, W., 2004. “Operational results of the first biomass CHP plant in Italy based on organic Rankine cycle turbogenerator and overview of a number of plants in operation in Europe since 1998”. In Proceedings of the 2nd World Biomass Conference, pp. 1716–1721.

[94] Bini, R., and Viscuso, F., 2011. “High efficiency (25%) ORC for power-only generation mode in the range 1-3 MW: an already proven technology also available for partially cogenerative applications”. In ORC2011 - 1st International Seminar on ORC Power Systems - Delft (NL), September 22-23. Available online: www.kcorc.org/en/literature, Delft Univeristy of Technology.

[95] GMK, Gesellschaft fur Motoren und Kraftanlangen GmbH, 2014. Official website: www.gmk.info [Last accessed February 2014].

[96] Astolfi, M., Romano, M., Bombarda, P., and Macchi, E., 2014. “Binary ORC (organic Rankine cycles) power plants for the exploitation of medium-low temperature geothermal sources - Part A: Thermodynamic optimization”. *Energy,* **66**, pp. 423–434.

[97] Astolfi, M., Romano, M., Bombarda, P., and Macchi, E., 2014. “Binary ORC (organic Rankine cycles) power plants for the exploitation of medium-low temperature geothermal sources - Part B: Techno-economic optimization”. *Energy,* **66**, pp. 435–446.

[98] Pierobon, L., Casati, E., Casella, F., Haglind, F., and Colonna, P., 2014. “Design methodology for flexible energy conversion systems accounting for dynamic performance”. *Energy,* **68**, pp. 667–679.

[99] Astolfi, M., Bini, R., Macchi, E., Paci, M., Pietra, C., Rossi, N., and Tizzanini, A., 2013. “Testing of a new supercritical ORC technology for efficient power generation from geothermal low temperature resources”. ASME ORC2013 - 2nd International Seminar on ORC Power Systems - Rotterdam (NL), October 7-8. Available online: www.kcorc.org/en/literature.

[100] Bronicki, L., 2007. “Organic Rankine cycles in geothermal power plants 25 years of Ormat experience”. *Transactions - Geothermal Resources Council,* **31**, pp. 499–502.

[101] Colonna, P., van der Stelt, T. P., and Guardone, A., 2012. FluidProp (Version 3.0): A program for the estimation of thermophysical properties of fluids. A program since 2004.

[102] Fröba, A., Kremer, H., Leipertz, A., Flohr, F., and Meurer, C., 2007. “Thermophysical properties of a refrigerant mixture of R365mfc (1,1,1,3,3-pentafluorobutane) and Galden® HT 55 (perfluoropolyether)”. *Int. J. Thermophys.,* **28**(2), pp. 449–480.

[103] Opcon Energy Systems, 2015. Official website: http://www.opcon.se/web/oes_en.aspx.

[104] Biederman, T., and Brasz, J., 2014. “Geothermal ORC systems using large screw expanders”. 22nd International

Compressor Engineering Conference, West Lafayette (US-IN), July 14-17.

[105] Lemort, V., Guillaume, L., Legros, A., Declaye, S., and Quoilin, S., 2013. "A comparison of piston, screw and scroll expanders for small scale Rankine cycle systems". In Proceedings of the 3rd International Conference on Microgeneration and Related Technologies, Naples (IT), April 5 – 17.

[106] Colonna, P., and Rebay, S., 2004. "Numerical simulation of dense gas flows on unstructured grids with an implicit high resolution upwind Euler solver". *Int. J. Numer. Meth. Fl.,* **46**(7), pp. 735–765.

[107] Colonna, P., Harinck, J., Rebay, S., and Guardone, A., 2008. "Real-gas effects in organic Rankine cycle turbine nozzles". *J. Propul. Power,* **24**(2), March–April, pp. 282–294.

[108] Harinck, J., Colonna, P., Guardone, A., and Rebay, S., 2010. "Influence of thermodynamic models in 2D flow simulations of turboexpanders". *J. Turbomach. - T. ASME,* **132**(1), January, pp. 011001–17.

[109] Angelino, G., Ferrari, P., Giglioli, G., and Macchi, E., 1976. "Combined thermal engine-heat pump systems for low-temperature heat generation.". *Inst. Mech. Eng. Proc.,* **190**(27), pp. 255–265.

[110] Song, P., Wei, M., Shi, L., Danish, S., and Ma, C., 2014. "A review of scroll expanders for organic Rankine cycle systems". *Appl. Therm. Eng.* Article in Press.

[111] van Buijtenen, J., 2009. "The Tri-O-Gen organic Rankine cycle: development and perspectives". *Power Engineer: Journal of the Institution of Diesel and Gas Turbine Engineers,* **13**(1).

[112] Bini, R., and Manciana, E., 1996. "Organic Rankine cycle turbogenerators for combined heat and power production from biomass". In 3rd Munich Discussion Meeting Energy Conversion from Biomass Fuels Current Trends and Future Systems.

[113] Bronicki, L., 2008. "Advanced power cycles for enhancing geothermal sustainability, 1,000 MW deployed worldwide". In Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century, 2008 IEEE.

[114] Krieger, Z., and Kaplan, U., 2000. Patent 6009711: *Apparatus and method for producing power using geothermal fluid*.

[115] Brasz, J., 2011. "Low temperature/small capacity ORC system development". Keynote lecture at the ORC2011 - 1st International Seminar on ORC Power Systems - Delft (NL), September 22-23. Available online: www.kcorc.org/en/literature.

[116] Brasz, J., and Holdmann, G., 2005. "Power production from a moderate - temperature geothermal resource". *Transactions - Geothermal Resources Council,* **29**, pp. 729–733.

[117] Levy, C. E., 2011. Lessons learned from Raser Technologies' "revolutionary" project. Available online: www.breakingenergy.com/2011/10/20/lessons-learned-from-raser-technologies-revolutionary-project/ [Last accessed June 2014].

[118] Obernberger, I., Thonhofer, P., and Reisenhofer, E., 2002. "Description and evaluation of the new ORC process". *Euroheat and Power International,* **31**(10), pp. 18–25.

[119] Duvia, A., Guercio, A., and Rossi, C., 2009. "Technical and economic aspects of biomass fuelled CHP plants based on ORC turbogenerators feeding existing district heating networks". In Proceedings of the 17th European Biomass Conference,, pp. 2030–2037.

[120] Hedman, B. A., 2009. Status of waste heat to power projects on natural gas pipeline. Tech. rep., Interstate Natural Gas Association of America (INGAA). Available online: www.ingaa.org/11885/reports/9371.aspx.

[121] Bronicki, L., and Schochet, D., 2005. "Bottoming organic cycle for gas turbines". In Proceedings of ASME Turbo Expo 2005, Reno (NV), June 6-9, Vol. 5, pp. 79–86.

[122] Bove, R., and Lunghi, P., 2006. "Electric power generation from landfill gas using traditional and innovative technologies". *Energ. Convers. Manage.,* **47**(11-12), pp. 1391 – 1401.

[123] Gewald, D., Siokos, K., Karellas, S., and Spliethoff, H., 2012. "Waste heat recovery from a landfill gas-fired power plant". *Renew. Sust. Energ. Rev.,* **16**(4), pp. 1779 – 1789.

[124] Campana, F., Bianchi, M., Branchini, L., De Pascale, A., Peretto, A., Baresi, M., Fermi, A., Rossetti, N., and Vescovo, R., 2013. "ORC waste heat recovery in European energy intensive industries: Energy and GHG savings". *Energ. Convers. Manage.,* **76**, pp. 244–252.

[125] US Department of Energy, 2008. Waste Heat Recovery: Technology and Opportunities in US Industry. Tech. rep.

[126] Sumitomo, H., Kado, S., Nozaki, T., Fushinobu, K., and Okazaki, K., 2005. "Exergy enhancement of low temperature waste heat by methanol steam reforming for hydrogen production". In Proceedings of the 8th Asian Hydrogen Energy Conference.

[127] Department of Energy and Climate Change (DECC), 2014. The potential for recovering and using surplus heat from industry. Tech. rep.

[128] Vescovo, R., 2009. "ORC recovering industrial heat - power generation from waste energy streams". *Cogeneration and On-Site Power Production*, March-April.

[129] Madlool, N., Saidur, R., Hossain, M., and Rahim, N., 2011. "A critical review on energy use and savings in the cement industries". *Renew. Sust. Energ. Rev.,* **15**(4), pp. 2042 – 2060.

[130] Engin, T., and Ari, V., 2005. "Energy auditing and recovery for dry type cement rotary kiln systems - a case study". *Energ. Convers. Manage.,* **46**(4), pp. 551 – 562.

[131] Karellas, S., Leontaritis, A.-D., Panousis, G., Bellos, E., and Kakaras, E., 2013. "Energetic and exergetic analysis of waste heat recovery systems in the cement industry". *Energy,* **58**(0), pp. 147 – 156.

[132] Legmann, H., 2002. "Recovery of industrial heat in the cement industry by means of the ORC process". In Proceedings of the IEEE Cement Industry Technical Conference, pp. 29–35.

[133] Born, C., and Granderath, R., 2011. "Analysis of potential and specific problems of heat recovery in the EAF". *Steel Times International,* **35**(5), pp. 45–48+51.

[134] Bause, T., Campana, F., Filippini, L., Foresti, A., Monti, N., and Pelz, T., 2014. "Cogeneration with ORC at Elbe-Stahlwerke Feralpi EAF Shop". In Proceedings of the AISTech 2014 Conference.

[135] Tabor, H., 1962. "Use of solar energy for production of mechanical power and electricity by means of piston engines

and turbines". *Sol. Energy,* **6**(3), pp. 89 – 93.

[136] Price, H., and Hassani, V., 2002. Modular trough power plant cycle and system analysis. Tech. Rep. NREL/TP-550-31240, US National Renewable Energy Laboratory.

[137] Prabhu, E., 2006. Solar trough organic Rankine electricity system (STORES) stage 1: Power plant optimization and economics. Tech. Rep. NREL/SR-550-39433, US National Renewable Energy Laboratory.

[138] Turboden, 2013. Turboden Solar Thermal Power Applications. Available online: www.turboden.eu/en/public/downloads/12-COM.P-23-rev.6.pdf? [Last accessed November 2014].

[139] Elsevier B.V., 2014. Scopus: abstract and citation database of peer-reviewed literature, scientific journals, books and conference proceedings. Available online: www.scopus.com.

[140] Saidur, R., Rezaei, M., Muzammil, W., Hassan, M., Paria, S., and Hasanuzzaman, M., 2012. "Technologies to recover exhaust heat from internal combustion engines". *Renew. Sust. Energ. Rev.,* **16**(8), pp. 5649 – 5659.

[141] Boretti, A. A., 2012. "Transient operation of internal combustion engines with Rankine waste heat recovery systems". *Appl. Therm. Eng.,* **48**(0), pp. 18 – 23.

[142] Horst, T., Tegethoff, W., Eilts, P., and Koehler, J., 2014. "Prediction of dynamic Rankine cycle waste heat recovery performance and fuel saving potential in passenger car applications considering interactions with vehicles' energy management". *Energ. Convers. Manage.,* **78**, pp. 438–451.

[143] Maraver, D., Royo, J., Lemort, V., and Quoilin, S., 2014. "Systematic optimization of subcritical and transcritical organic Rankine cycles (ORCs) constrained by technical parameters in multiple applications". *Appl. Energ.,* **117**(0), pp. 11 – 29.

[144] DiGenova, K., Botros, B., and Brisson, J., 2013. "Method for customizing an organic Rankine cycle to a complex heat source for efficient energy conversion, demonstrated on a Fischer Tropsch plant". *Appl. Energ.,* **102**(0), pp. 746 – 754.

[145] Smith, I., and da Silva, R. M., 1994. "Development of the trilateral flash cycle system. Part 2: Increasing power output with working fluid mixtures". *Proc. IMechE Part A: J. Power and Energy,* **208**(2), pp. 135–144.

[146] Boyle, P., Hays, L., Kaupert, K., and Welch, P., 2013. "Performance of variable phase cycle in geothermal and waste heat recovery applications". In Transactions - Geothermal Resources Council, Vol. 37, pp. 679–685.

[147] Ho, T., Mao, S., and Greif, R., 2012. "Comparison of the organic flash cycle (OFC) to other advanced vapor cycles for intermediate and high temperature waste heat reclamation and solar thermal energy". *Energy,* **42**(1), pp. 213 – 223.

[148] Kane, M., Larrain, D., Favrat, D., and Allani, Y., 2003. "Small hybrid solar power system". *Energy,* **28**(14), pp. 1427 – 1443.

[149] Angelino, G., and Colonna, P., 1998. "Multicomponent working fluids for organic Rankine cycles (ORCs)". *Energy,* **23**(6), pp. 449–463.

[150] Chen, H., Goswami, D., Rahman, M., and Stefanakos, E., 2011. "A supercritical Rankine cycle using zeotropic mixture working fluids for the conversion of low-grade heat into power". *Energy,* **36**(1), pp. 549–555.

[151] Heberle, F., Preißinger, M., and Brüggemann, D., 2012. "Zeotropic mixtures as working fluids in Organic Rankine

Cycles for low-enthalpy geothermal resources". *Renew. Energ.,* **37**(1), pp. 364–370.

[152] Trapp, C., and Colonna, P., 2013. "Efficiency improvement in precombustion CO_2 removal units with a waste-heat recovery ORC power plant". *J. Eng. Gas Turb. Power - T. ASME,* **135**(4).

[153] Lampe, M., Groß, J., and Bardow, A., 2014. "Simultaneous process and working fluid optimisation for Organic Rankine Cycles (ORC) using PC-SAFT". *Computer Aided Chemical Engineering,* **30**, pp. 572 – 576.

[154] The Modelica Association, 2013. Modelica - A unified object-oriented language for physical systems modeling - Language specification version 3.2 revision 2. Available online www.modelica.org.

[155] Casella, F., Mathijssen, T., van Buijtenen, J., and Colonna, P., 2013. "Dynamic modeling of ORC power systems". *J. Eng. Gas Turb. Power - Trans. ASME,* **135**(042310).

[156] Kadota, M., and Yamamoto, K., 2009. "Advanced transient simulation on hybrid vehicle using Rankine cycle system". *SAE International Journal of Engines,* **1**(1), pp. 240–247.

[157] Quoilin, S., Aumann, R., Grill, A., Schuster, A., Lemort, V., and Spliethoff, H., 2011. "Dynamic modeling and optimal control strategy of waste heat recovery organic Rankine cycles". *Appl. Energ.,* **88**(6), pp. 2183 – 2190.

[158] Casati, E., Desideri, A., Casella, F., and Colonna, P., 2012. "Preliminary assessment of a novel small CSP plant based on linear collectors, ORC and direct thermal storage". Proceedings of the 18th SolarPACES conference, Marrakech (MO), 11–14 September.

[159] Harinck, J., Pasquale, D., Pecnik, R., van Buijtenen, J., and Colonna, P., 2013. "Performance improvement of a radial ORC turbine by means of automated design". *Proc IMechE Part A: J Power and Energy,* **227**(6), pp. 637–645.

[160] Casati, E., Vitale, S., Pini, M., Persico, G., and Colonna, P., 2014. "Centrifugal turbines for mini-organic Rankine cycle power systems". *J. Eng. Gas Turb. Power - Trans. ASME,* **136**(12), pp. 122607–122607.

[161] Sciacovelli, L., and Cinnella, P., 2014. "Numerical study of multistage transcritical organic Rankine cycle axial turbines". *J. Eng. Gas Turb. Power - Trans. ASME,* **136**(8).

[162] Spinelli, A., Pini, M., Dossena, V., Gaetani, P., and Casella, F., 2013. "Design, simulation, and construction of a test rig for organic vapors". *J. Fluid Eng.-T. ASME,* **135**(4).

[163] Mathijssen, T., Casati, E., Gallo, M., Nannan, N., Zamfirescu, C., Guardone, A., and Colonna, P., 2014. "Flexible asymmetric shock tube (FAST): Commissioning of a high temperature Ludwieg tube for wave propagation measurements". Submitted for publication to *Exp. Fluids*.

[164] Seher, D., Lengenfelder, T., Gerhardt, J., Eisenmenger, N., Hackner, M., and Krinn, I., 2012. "Waste heat recovery for commercial vehicles with a Rankine process". In 21st Aachen Colloquium on Automobile and Engine Technology, Aachen (DE).

[165] Bell, I. H., Groll, E. A., Braun, J. E., and Horton, W. T., 2013. "A computationally efficient hybrid leakage model for positive displacement compressors and expanders". *Int. J. Refrig.,* **36**(7), pp. 1965 – 1973. New Developments in Compressor Technology.

[166] Giuffrida, A., 2014. "Modelling the performance of a scroll expander for small organic Rankine cycles when changing the working fluid". *Appl. Therm. Eng.,* **70**(1), pp. 1040–1049.

[167] Ziviani, D., Bell, I., de Paepe, M., and van der Broek, M., 2014. "Comprehensive model of a single screw expander for ORC-systems". Proceedings of the 22nd International Compressor Engineering Conference - Purdue (US-IN), July 14-17.

[168] Smith, I., Stosic, N., and Kovacevic, A., 2014. *Power recovery from low grate heat by means of screw expanders*. Chandos Publishing.

[169] Wang, H., and Peterson, R., 2011. "Performance enhancement of a thermally activated cooling system using microchannel heat exchangers". *Appl. Therm. Eng.,* **31**(14-15), pp. 2951–2962.

[170] Karellas, S., Schuster, A., and Leontaritis, A.-D., 2012. "Influence of supercritical ORC parameters on plate heat exchanger design". *Appl. Therm. Eng.,* **33-34**(1), pp. 70–76.

[171] Harris, C., Kelly, K., Wang, T., McCandless, A., and Motakef, S., 2002. "Fabrication, modeling, and testing of micro-cross-flow heat exchangers". *J. Microelectromech. S.,* **11**(6), pp. 726–735.

[172] Ohadi, M., Choo, K., Dessiatoun, S., and Cetegen, E., 2013. *Next Generation Microchannel Heat Exchangers*. Springer.

[173] Boomsma, K., Poulikakos, D., and Zwick, F., 2003. "Metal foams as compact high performance heat exchangers". *Mechanics of Materials,* **35**(12), pp. 1161–1176.

[174] Muley, A., Kiser, C., Sundn, B., and Shah, R., 2012. "Foam heat exchangers: A technology assessment". *Heat Transfer Eng.,* **33**(1), pp. 42–51.

[175] Godson, L., Raja, B., Mohan Lal, D., and Wongwises, S., 2010. "Enhancement of heat transfer using nanofluids-an overview". *Renew. Sust. Energ. Rev.,* **14**(2), pp. 629–641.

[176] Cevallos, J., Bergles, A., Bar-Cohen, A., Rodgers, P., and Gupta, S., 2012. "Polymer heat exchangers-history, opportunities, and challenges". *Heat Transfer Eng.,* **33**(13), pp. 1075–1093.

[177] Turboden, 2009. Agreement for Pratt & Whitney Power Systems, a United Technologies Corporation company, to purchase majority interest in Turboden. Press release, available online: www.turboden.eu/en/public/press/20090629_turboden_pratt_ENG.pdf [Last accessed November 2014].

[178] Sprouse, C., and Depcik, C., 2013. "Review of organic Rankine cycles for internal combustion engine exhaust waste heat recovery". *Appl. Therm. Eng.,* **51**(1-2), pp. 711 – 722.

[179] Teng, H., Regner, G., and Cowland, C., 2007. "Waste heat recovery of heavy-duty Diesel engines by organic Rankine cycle part I: Hybrid energy system of Diesel and Rankine engines". *SAE Technical paper,* **01-0537**.

[180] Teng, H., Regner, G., and Cowland, C., 2007. "Waste heat recovery of heavy-duty diesel engines by organic Rankine cycle part II: Working fluids for WHR-ORC". *SAE Technical paper,* **01-0543**.

[181] Freymann, R., Strobl, W., and Obieglo, A., 2008. "The Turbosteamer: a system introducing the principle of cogeneration in automotive applications". *MTZ,* **5**, pp. 20–27.

[182] Lang, W., Almbauer, R., and Colonna, P., 2013. "Assessment of waste heat recovery for a heavy-duty truck engine using an ORC turbogenerator". *J. Eng. Gas Turb. Power - T. ASME,* **135**(4), April, pp. 042313–1–10.

[183] Endo, T., Kawajiri, S., Kojima, Y., Takahashi, K., Baba, T., Ibaraki, S., Takahashi, T., and Shinohara, M., 2007. "Study

on maximizing exergy in automotive engines". *SAE Technical Paper,* **01-0257**.

[184] Nag, P., 2008. *Power Plant Engineering*, 3 ed. Tata McGraw Hill Education Private Limited.

[185] Lin, C.-C., Peng, H., and Grizzle, J. W., 2003. "Power management strategy for a parallel hybrid electric truck". *IEEE trans. on control systems technology,* **11**(6), November.

[186] Dettmer, R., 2010. "The mighty micro". *Engineering and Technology,* **5**(3), pp. 42–45.

[187] Kane, M., 2011. "Micro-cogeneration based organic Rankine cycle (ORC) system in a district heating network: A case study of the Lausanne city swimming pool". ORC2011 - 1st International Seminar on ORC Power Systems - Delft (NL), September 22-23. Available online: www.kcorc.org/en/literature.

[188] Zanelli, R., and Favrat, D., 1994. "Experimental investigation of a hermetic scroll expander-generator". In Proceedings of the 12th International Compressor Engineering Conference, W. Soedel, ed., pp. 459–464.

[189] Casati, E., Galli, A., and Colonna, P., 2013. "Thermal energy storage for solar-powered organic Rankine cycle engines". *Sol. Energy,* **96**, pp. 205 – 219.

[190] Quoilin, S., Orosz, M., Hemond, H., and Lemort, V., 2011. "Performance and design optimization of a low-cost solar organic Rankine cycle for remote power generation". *Sol. Energy,* **85**(5), pp. 955–966.

[191] Schuster, A., Karellas, S., Kakaras, E., and Spliethoff, H., 2009. "Energetic and economic investigation of organic Rankine cycle applications". *Appl. Therm. Eng.,* **29**(8-9), pp. 1809–1817.

[192] Tchanche, B., Lambrinos, G., Frangoudakis, A., and Papadakis, G., 2011. "Low-grade heat conversion into power using organic Rankine cycles - A review of various applications". *Renew. Sust. Energ. Rev.,* **15**(8), pp. 3963–3979.

[193] Vélez, F., Segovia, J. J., Martín, M. C., Antolín, G., Chejne, F., and Quijano, A., 2012. "A technical, economical and market review of organic Rankine cycles for the conversion of low-grade heat for power generations". *Renew. Sust. Energ. Rev.,* **16**(6), pp. 4175 – 4189.

[194] Wang, L., Roskilly, A., and Wang, R., 2014. "Solar powered cascading cogeneration cycle with ORC and adsorption technology for electricity and refrigeration". *Heat Transfer Eng.,* **35**(11-12), pp. 1028–1034.

[195] Jradi, M., and Riffat, S., 2013. "Modelling and testing of a hybrid solar-biomass ORC-based micro-CHP system". *Int. J. of Energy Res.* Article in Press.

[196] Astolfi, M., Xodo, L., Romano, M., and Macchi, E., 2011. "Technical and economical analysis of a solar-geothermal hybrid plant based on an organic Rankine cycle". *Geothermics,* **40**(1), pp. 58–68.

[197] Avery, W., and Wu, C., 1994. *Renewable Energy from the Ocean: A Guide to OTEC*. Oxford University Press.

[198] Ikegami, Y., and Morisaki, T., 2012. "Research on double stage-Rankine cycle for ocean thermal energy conversion using ammonia as working fluid". *Proceedings of the 22nd International Offshore and Polar Engineering Conference - Rhodes (GR), June* 17 – 22.

[199] Sun, F., Ikegami, Y., Jia, B., and Arima, H., 2012. "Optimization design and exergy analysis of organic Rankine cycle in ocean thermal energy conversion". *Appl. Ocean Res.,* **35**(0), pp. 38 – 46.

[200] Yang, M.-H., and Yeh, R.-H., 2014. "Analysis of optimization in an OTEC plant using organic Rankine cycle". *Renew. Energ.,* **68**(0), pp. 25 – 34.

[201] Vega, L., 2010. "Economics of ocean thermal energy conversion (OTEC): An update". *Proceedings of the Offshore Technology Conference (OTC)*. Paper number OTC 21016.

[202] Angelino, G., and Colonna, P., 2000. "Air cooled siloxane bottoming cycle for molten carbonate fuel cells". In Fuel Cell Seminar, pp. 667–670.

[203] De Servi, C., Campanari, S., Tizzanini, A., and Pietra, C., 2013. "Enhancement of the electrical efficiency of commercial fuel cell units by means of an organic Rankine cycle: A case study". *J. Eng. Gas Turb. Power - T. ASME,* **135**(4).

[204] Akkaya, A., and Sahin, B., 2009. "A study on performance of solid oxide fuel cell-organic Rankine cycle combined system". *Int. J. of Energy Res.,* **33**(6), pp. 553–564.

[205] Chacartegui, R., Snchez, D., noz, J. M., and Sánchez, T., 2009. "Alternative ORC bottoming cycles for combined cycle power plants". *Appl. Energ.,* **86**(10), pp. 2162 – 2170.

[206] Kusterer, K., Braun, R., Köllen, L., Sugimoto, T., Tanimura, K., and Bohn, D., 2013. "Combined solar thermal gas turbine and organic Rankine cycle application for improved cycle efficiencies". In Proceedings of the ASME Turbo Expo, Vol. 4.

[207] Dunham, M., and Iverson, B., 2014. "High-efficiency thermodynamic power cycles for concentrated solar power systems". *Renew. Sust. Energ. Rev.,* **30**, pp. 758–770.

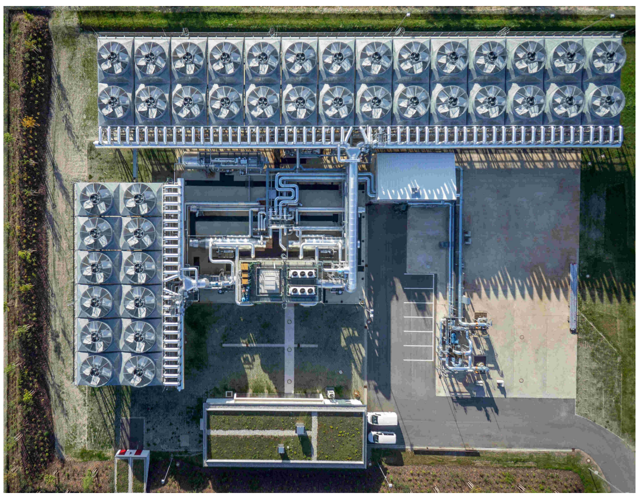
[208] Nored, D. L., and Bernatowicz, D. T., 1986. "Electrical power system design for the US space station". In Proceedings of the Intersociety Energy Conversion Engineering Conference, pp. 1416–1422.

[209] Farina, F., Mao, C., and Tuninetti, G., 1987. "Organic Rankine cycle power conversion systems for space applications". In Photovoltaic Generators in Space, Proceedings of the Fifth European Symposium, European Space Agency, (Special Publication) ESA SP, pp. 225–230.

[210] KCORC - Knowledge Center on organic Rankine cycle technology - ASME International Gas Turbine Institute. Official website: www.kcorc.org.

(a)

(b)



(c)

(d)

(e)

(f)

Fig. 7: Exemplary ORC power plants. Large systems - courtesy of Ormat Technologies Inc. [86]: 7a aerial view of the Ngatamariki 100 MW_e geothermal plant (NZ), featuring four 25 MW_e units. Geothermal fluid is available at 192 °C, brine and condensate return at 90 °C; 7b turbines of the axial type for similar applications during the assembly phase, approx. 15 MW_e power output each. Medium scale systems - courtesy of Turboden s.r.l. [92]: 7c aerial view of a 5,600 kW_e geothermal plant installed in Germany; 7d 2 MW_e ORC unit, i.e. turbine and regenerator/condenser, for the hybrid plant built in Ait Baha (MO), recovering heat from a cement plant and integrating it with a solar thermal source. Small scale systems - courtesy of Triogen BV. [90]: 7e 160 kW_e unit installed in Belgium, recovering thermal power from a biogas engine; 7f hermetic turbo-generator assembly for the same system, with single stage radial expander.