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Energy Procedia 82 (2015) 994 – 1001

Energy Procedia

ATI 2015 - 70th Conference of the ATI Engineering Association

State of art on ORC applications for waste heat recovery and micro-cogeneration for installations up to 100kWe

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Abstract

The growing cost for energy production and distribution as well as problems related to environmental pollution have induced an increasing interest in the research of alternative solutions and in particular innovative technologies capable of compromising energy production cost, optimization and guaranteeing environmental sustainability. One of the technologies of increasing interest in recent years is the Organic Rankine Cycle (ORC). These systems are generally suitable for the recovery of low grade heat at low pressure this is a major advantage of the system in terms of safety and management. Furthermore, they enhance simple operation, low maintenance, and the use of a working fluid that is environmentally friendly. This paper presents a comprehensive and current literature overview of micro generation systems up to 100kWe. A working fluid screening criteria has been discussed taking into account the environmental impact as well as the thermo-physical properties of various potential working fluids. From the analyses it emerges that the fluid most used in installed ORC systems is the R245fa also confirmed by means of a computational code developed for micro-systems of the size range. Components and expander selection has also been examined, the study reveals that the most suitable expander for the applications of these plant size ranges are the scroll for small installations and the vane or screw expanders for larger installations. Finally a detailed list of characteristics of both industrial and experimental prototype application is presented with references to their manufacturers.

Peer-review under responsibility of the Scientific Committee of ATI 2015

*Keywords:*distributed generation; waste recovery systems; ORC applications; expanders; working fluids; ORC modeling.

1. Introduction

The Steam Rankine Cycle remains the widest used technology for power generation and the Organic Rankine Cycle differsform it in the cycle working fluid [1], the working fluid in these cycles determines the type of technology to be applied; power generation or an energy recovery system [2].Advantages of the ORC include low maintenance, favorable operating pressures and autonomous operation. Tchanche *et*

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1876-6102
Peer-review under responsibility of the Scientific Committee of ATI 2015
doi:10.1016/j.egypro.2015.11.857

al[3] underlined some advantages achievable from power plants operating with an organic fluid. Early system architecture and component lay-out are available in[4], a recent and extensive publication on system architecture is discussed in[5]. Several authors have documented on working fluid screening methods as in[6], a list of potential working fluids for ORC applications is also presented. Plant design specifications and financial aspects have been dealt with by Lecompte and Cayer [7] who also addressed performance parameters like expander isentropic efficiency, pinch point temperature differences as well as the heat source temperatures in [8] suggesting different common architectures. Studies on ORC expanders have been covered in[9], different expander types have been investigated including traditional expanders as well as the use of other devices like compressors. Trends in developing a dynamic ORC model is proposed by Quoilin [10]. Other recent studies on dynamic modeling and control strategy of ORC are presented in[11].

A summary of different potential working fluids and substances commercially available for small ORC is presented in this article and suggestions on their choice depending on the target application; a thermodynamic model for the target applications has also been developed. ORC applications and heat resources are also examined, some references are also provided on the degree of maturity of various applications, to conclude, reference installations and manufacturers are provided with indication of their working conditions.

Nomenclature

CHP	Combined Heat and Power	CSHP	Combined Solar Heat and Power
EES	Engineering Equation Solver	ICE	Internal Combustion Engine
HVAC	Heating, Ventilation and Air Conditioning	HMDSO	Hexamethyldisiloxane
OMTS	Octamethyltrisiloxane	ORC	Organic Rankine Cycle
OTEC	Ocean Thermal Energy Conversion	RORC	Regenerative ORC
T_{cond}	Condensing temperature	SORC	Standard ORC without regeneration
WHR	Waste Heat Recovery	T_{evap}	Evaporation temperature
$\eta_{\_th}$	thermal efficiency	$\eta_{\_exp}$	expander efficiency

2. Working fluids in ORC

The working fluid is very essential for the definition of the thermodynamic properties, economical and technical flexibility of the plant in every power cycle. The selection criteria and the choice of a suitable working fluid must satisfy the thermodynamic requirements, compatibility, cost and be environmentally friendly [12]. An interesting study on fluid selection is presented by Chen [13]. A recent study on ORC working fluids is provided by Guo [14], while in [15] the comparison on the thermo-physical properties for different working fluids is presented. In[16]it was showed that fluid mixtures improve the cycle performance. In [17] the advantages of fluid mixtures over pure fluids in terms of safety and volumetric efficiencies are discussed. Tchanche [3] presented a list of substances identified as potential working fluids suitable for different applications in the ORC technology, a comparison of the choice of working fluids in ORC systems for three different characteristics; the target destination, the temperature ranges of evaporation and condensation is presented in table1, a further analyses on fluid selection was performed by Jinliang [18];

Table 1 Potential working fluids for ORC applications elaborated from [19]

Application	T_{cond} [°C]	T_{evap}[°C]	Considered fluids	Recommended fluids
WHR	30-50	120	R11, R113, R114	R113
n/a	35-60	80-110	Non-conventional working fluids	RC123, R124
WHR	30	150-200	RC123, HFE 7100, benzene, Toluene, p-xylene	Benzene, Toluene, RC123
ICE	55 , 100	60-150	H_2O, RC123, Isopentane, R245ca, R245fa, Butane, Isobutane, R152a	H_2O, R245ca, Isobutane

CHP	90	250-350	Butyl-benzene, propyl-benzene, ethyl-benzene, Toluene, OMTS, Ammonium, R123, PF5050	Butyl-benzene
n/a	40-60	220-350	HMDSO, OMTS, HMDSO/OMTS	HMDSO/OMTS
Geothermal	30	100	Alkanes, Fluoro-alkanes, Ethers, Fluoro-ethers	RE133, R245, R600, R245fa, R245ca, R601
Geothermal	25	80-115	Propylene, R227ea, RC318, R236fa, Isobutane, R245fa	Propylene, R227ea, R245fa
WHR	25	100-210	R113, R123,R245fa, Isobutane	R113
Solar	35	60-100	Refrigerant	R152a, R600,R290
Solar	45	120-230	H_2O, n-pentane	n-dodecane
WHR	25	145	H_2O, NH_4, butane, Isobutane, R11, RC123, R141B	R236A
WHR	50	80-220	R600a, R245fa, RC123, R113	R113, RC123
CHP	50	170	R365mfc, heptane, Pentane, R12, R141b, Ethanol	Ethanol
ICE- WHR	76	n/a	R124 R134a, R245fa, R600, R600a, R1234yf	R134a
ICE- WHR	95	n/a	R125, R143a, R218	R134a
Geothermal	30	150	R1225yeZ, R1234yf, R1234zeE, R1234zeZ, R1234zf, R1225yeE, R1225zc, R1234yeE	R1234yf, R1225yeE
WHR	20-35	150	R245fa, R245fa/R152a, R245fa/R600a, R113/R245fa, R601a/R600a, R236ea	n/a
ICE_WHR	35	96-221	R134, R11, benzene	Benzene
WHR	n/a	120	R290, R600a, R601, R134a, R227ea, R245fa, R600a/R601, R290/R600a, R134a/R245fa	R600a/R601
WHR	27-87	327	R245fa, R245ca, R236ea, R141b, R114, RC123, R113, R11, butane	R11, R141b, R113, RC123, R245fa, R245ca
WHR	n/a	277	R12, RC123, R134a, R717	RC123
Solar	30	150	n-pentane, SES36, R245fa, R134a	R245fa, R134a

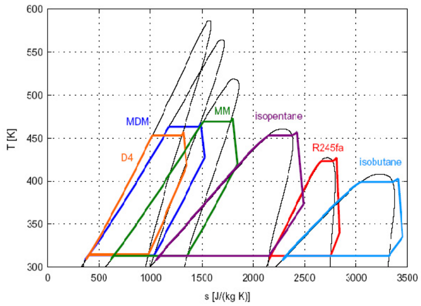


Figure 1. T-s diagram for some working fluids used in WHR

In order to investigate the ORC system performances parameters, a simulation model has been developed using the EES platform, the model will be described in a successive article under development. R245fa already abundantly discussed in literature has been confirmed to be a suitable working fluid candidate for waste heat recovery (low grade heat) systems, chosen according to the above mentioned selection criteria; heat source temperatures, system maximum pressure, safety, toxicity and the legislations imposed on the characteristics of a good working fluid. The results of a preliminary simulation have been provided as in figure 1, where it is visible the thermodynamic cycle diagram on the T-s plane for the 6 working fluids considered. The code has been validated using experimental data obtained from an available 2kWe ORC prototype driven by a scroll expander and running with R245fa, furthermore the code will be used for the assessment of system parameters for coupling the micro-generator with different heat sources as well as optimization of the prototype and system performances parameters computation for other working fluids.

3. Applications of ORC for small scale and distributed generations

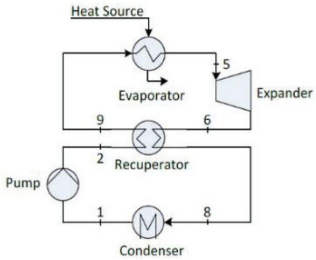


Figure 2 Configuration of an ORC facility with recuperator

A general description of the various potential uses of this technology is presented, with particular focus on small and medium sized applications, without ignoring some large installations. The cycle architecture of an ORC is simple, its' basic configuration is made of four main components: the feed pump, the evaporator, the expander and the condenser; however a recuperator (regeneration) can be integrated in the circuit as a preheater between the feed pump and the evaporator on one side and between the expander and the condenser on the other side as in figure 2.

3.1 Geothermal Energy

A geothermal system can be coupled to an ORC unit to serve as the heat source using as energy vector rain water for the heat extraction, the rain water is extracted at high pressures and temperature say up to 300°C and exploited for small and medium scale electric power generation [20]. Tchanche [3] underlined the total number of existing geothermal installations and the total energy capacity obtained from these installations, a classification of geothermal plants is also presented by Villani [21]. Small scale installations, for power range up to about 10 kW, can be cost-effective if and only if components with large production and market diffusion such as devices derived from the Heating, Ventilation and Air Conditioning (HVAC) field, are used [3].

3.2 Solar Energy

Solar systems provide a great opportunity for the coupling of an ORC since they are generally characterized with temperatures usually lower than 300°. The main advantages of a solar system have been summarized in [3], benefits offered by a solar ORC are found in [22]. Both flat and concentrated solar panels can be coupled with an ORC system, depending on the applications and the installations site: while flat plate collectors require a lower capital investment [23], concentrating collectors ensure a higher total amount of produced energy throughout the panel operating life, especially if equipped with sun tracking systems as featured by Delgado Torres and Garcia-Rodriguez in [24]. Wang [25]made a comparison between a flat plate and the evacuated tube type collectors in a solar ORC running with R245fa, and achieved a higher conversion efficiency with the evacuated tube collectors. In a successive article[26], he tested both pure substances and mixtures on an ORC prototype equipped with flat plate collectors. Jing [27] developed a simulation model of a solar ORC system with dedicated submodels for solar radiation, collectors behavior, and thermodynamic cycle performance. Kane *et al*[28] designed, built and optimized a mini-hybrid solar power system suitable for installation in remote areas of developing countries, the field tests confirmed the possibility of achieving acceptable performances with the prototype

3.3 Desalination systems

Water desalination coupled with an ORC offers notable benefits, the solar RO-ORC desalination technology is widely studied today, aiming to reach the economic competitiveness and to design low cost systems suitable for applications in developing countries especially with harsh climate[28]. In order to reduce the environmental impact of a RO (Reversed Osmosis) desalination system, the power needed for pumping should be provided from renewable sources.

3.4 Biomass Power plants

Biomass is an abundant heat resource, although it presents enormous difficulties in transportation due to its low energy density, it is locally the most adapted for micro scale distributed CHP generation as reported in [29]. For the small size biomass CHP systems, coupling with combustion engines or ORC technologies is rapidly gaining considerable interests. In the second case, a typical system is made of a biomass feed boiler capable of burning solid fuels and an ORC module coupled through a thermal oil loop. The need for an intermediate heat transfer medium, which gradually cools down in the vapor generator provides a number of advantages such as; low pressure in the boiler, larger thermal inertia and lower sensitivity to load changes, simpler and safer control and operations [3]. Regarding the working parameters, they are different from other ORC applications: in particular, the maximum cycle temperature could be close to flame temperature, compatibly with the chemical stability of the working fluid, allowing also higher condensation temperature and a higher quality of the cogenerated heat, without excessive penalizations in the power cycle efficiency [30]. From an economic point of view Dong [29] underlined that small scale biomass ORC systems for domestic installation are still under development and not convenient due to high investment cost and long payback periods compared to medium size plants.

3.5 Energy Recovery from internal combustion engines (ICE)

Internal combustion engines are characterized by efficiencies closer to 50% in the cases of very big installations, this efficiency is associated to the amount of waste heat involved in the engine operations. The recovery of the thermal energy both from the exhaust gases and cooling circuit to produce useful mechanical work is of growing interest. Amongst other technologies such as: thermo-electricity and absorption cycle air conditioning, ORCs appear to be the most prominent solution for such applications as reported in the study by [31] showing how coupling of an ICE with an ORC for heat recovery could improve the overall net power and hence cycle efficiency. Zhang *et al*[32] presented thermodynamic analyses on bottoming ORC with an ICE for different system architectures. Considering only the design conditions, the authors concluded that the regenerated cycle was preferable as bottoming cycle for the studied engines.

Table 2 Small scale ORC manufacturers' website [33]

Website	Expander	Size [kW]	Website	Expander	Size [kW]
www.electratherm.com	Screw	50	www.e-rational.net	Screw	50-100
www.barber-nichols.com	Turbine	15-100	www.eneftech.com	Scroll	5-30
www.gmk.info	Turbine	50-100	www.koehler-ziegler.de	Screw	50-100
www.freepower.co.uk	Turbine	60-100	www.enerbasque.com	n/a	20-100
www.durr-cyplan.com	Turbogenerator	70	www.termocycle.com	Turbine	50-100
www.ener-g-rotors.com	Gear	40-60	www.entrans.se	n/a	50-100
www.transpacenergy.com	Turbine	100	www.enogia.com	Turboexpander	5-100
www.infinityturbine.com	Screw	10-100	www.verdicorp.com	Turbocorp compressor	20-100
www.aqylon.com	Turbine	100	www.g-tet.com	Turbo-alternator	25-100

4. Conclusions

In this paper, working fluid selection criteria, heat source type and field of application for ORC systems has been presented. Indications have been provided for the degree of maturity for different ORC technologies as in table 1, for systems within 100kW plant sizes. Literature suggests the use of positive displacement type machines like the scroll as the expansion device for very small (<10kWe) applications while the screw and vane types expanders for very small-medium size (10-100kW) ORC applications. Furthermore, no single fluid has been identified as optimal for ORC as the choice depends on the specific application and the working conditions. A simulation model has been developed computing 6 different working fluids; the results obtained with the code show a good match between simulated and experimental results for R245fa, thus the code can be used for future studies on ORC system parameter analyses and different working fluids comparison. To conclude this review a list of manufacturers' website has been provided in table 2, while table 3 provides indications related to: plant size, working fluid type, heat source type, expander type, system thermal efficiency and system architecture for existing commercial installations as well as experimental prototypes.

Table 3 References installations for micro ORC

Architecture	Expander	Application	Degree of Maturity	Working fluid	T_{cond} [°C]	T_{evap} [°C]	η_exp [%]	η_th [%]	Size [kW]
SORC	Vane	Power	Mature	R11	20	99[34]	30	n/a	1.4
RORC	Turbine	Biomass CHP	Mature	Decane	100	345 [35]	70	86	0.76
RORC	Turbine	Biomass CHP	Mature	Decane	100	337 [36]	70	86	5.02
SORC	Scroll	WHR	V Promising	R123	10	180[37]	70	n/a	1.98
SORC	Scroll	WHR	V Promising	R245fa	10	180 [37]	70	n/a	2
TORC	Piston	ICE-WHR	V Promising	Steam	100	450 [38]	78	44.9	24
SORC	Vane	CHP	Mature	Steam	n/a	n/a [39]	75	n/a	20
SORC	Scroll	Solar	Developing	R245fa	n/a	150 [40]	70	75	3
SORC	Scroll	Power	Mature	R245fa	n/a	120 [41]	70	n/a	1.5
n/a	Screw	Solar	Developing	R245fa	n/a	121 [42]	n/a	80	50
SORC	Scroll	WHR	V Promising	R245fa	30	85 [9]	70	n/a	1.7
SORC	Scroll	CHP	Mature	R245	26.6	97.5 [43]	75	n/a	2.1
n/a	Vane	Solar	Developing	R11	n/a	n/a [39]	55	n/a	5
SORC	Wankel	CHP	Mature	Steam	n/a	170 [44]	65	n/a	20
SORC	Scroll	Power	Mature	R134a	n/a	80 [45]	65	n/a	1.5
SORC	Scroll	n/a	n/a	Helium/R123	n/a	165 [46]	68	n/a	1.82
SORC	Scroll	Solar	Developing	R123/R134a	n/a	150 [28]	68	56	7.3
n/a	Scroll	n/a	n/a	Ammonia	n/a	n/a [47]	60	7.2	5
n/a	Scroll	WHR	V Promising	Air	n/a	n/a [48]	69	n/a	3.5
RORC	Scroll	Power	Mature	R123	37	160 [49]	49.9	92.3	0.3
SORC	Scroll	Power	Mature	Steam	n/a	n/a [50]	34	n/a	11.5
SORC	Scroll	Solar	Developing	R113	35	136 [51]	65	42	0.45
SORC	Scroll	WHR	V Promising	R123	n/a	n/a [52]	83	n/a	2.96
SORC	Gerotor	WHR	V Promising	R123	n/a	n/a [52]	85	n/a	2.07
n/a	Scroll	n/a	n/a	R245fa	n/a	100 [53]	71.03	71.9	2.5
n/a	Scroll	Power	Mature	R134a	n/a	n/a [54]	77	n/a	1
n/a	Scroll	Desalination	Promising	R134a	n/a	60 [55]	50	35	1
SORC	Scroll	HVAC	Promising	R245fa	n/a	n/a [56]	87.2	n/a	1
SORC	Turbine	WHR	V Promising	R245fa	n/a	137 [57]	n/a	60	100
RORC	Vane	CHP	Mature	HFE7000	46.2	123.[58]	53.92	61.1	0.861
n/a	Scroll	CHP	Mature	R245fa	26.6	97.5 [43]	75.7	n/a	2.1
RORC	Turbine	Solar	Developing	R245fa	30	137 [59]	75	n/a	100

References

[1] M. J. Moran, *Engineering Thermodynamics*, vol. 181. 1958.

[2] H. Chen, D. Y. Goswami, and E. K. Stefanakos, "A review of thermodynamic cycles and working fluids for the conversion of low-grade heat," *Renew. Sustain. Energy Rev.*, vol. 14, no. 9, pp. 3059–3067, 2010.

[3] B. F. Tchanche, G. Lambrinos, a. Frangoudakis, and G. Papadakis, "Low-grade heat conversion into power using organic Rankine cycles - A review of various applications," *Renew. Sustain. Energy Rev.*, vol. 15, no. 8, pp. 3963–3979, 2011.

[4] O. Badr, P. W. O'Callaghan, M. Hussein, and S. D. Probert, "Multi-vane expanders as prime movers for low-grade energy organic Rankine-cycle engines," *Appl. Energy*, vol. 16, pp. 129–146, 1984.

[5] K. K. Srinivasan, P. J. Mago, and S. R. Krishnan, "Analysis of exhaust waste heat recovery from a dual fuel low temperature combustion engine using an Organic Rankine Cycle," *Energy*, vol. 35, no. 6, pp. 2387–2399, Jun. 2010.

[6]H.H. Dow, "Diphenyl Oxide Bi-Fluid power plants," *J. Am. Soc. Nav. Eng.*, vol. 38, pp. 940–950, 1926.

[7]S. Lecompte, H. Huisseune, M. van den Broek, S. De Schampheleire, and M. De Paepe, "Part load based thermo-economic optimization of the ORC applied to a combined heat and power (CHP) system," *Appl. Energy*, vol. 111, pp. 871–881, Nov. 2013.

[8]S. Lecompte, H. Huisseune, M. van den Broek, B. Vanslambrouck, and M. De Paepe, "Review of organic Rankine cycle (ORC) architectures for waste heat recovery," *Renew. Sustain. Energy Rev.*, vol. 47, pp. 448–461, 2015.

[9]J. Chang, C. Chang, T. Hung, and J. Lin, "Experimental study and CFD approach for scroll type expander used in low-temperature organic Rankine cycle," *Appl. Therm. Eng.*, pp. 1–9, 2014.

[10] S. Quoilin, R. Aumann, A. Grill, A. Schuster, V. Lemort, and H. Spliethoff, "Dynamic modeling and optimal control strategy of waste heat recovery Organic Rankine Cycles," *Appl. Energy*, vol. 88, no. 6, pp. 2183–2190, 2011.

[11] I. Vaja and A. Gambarotta, "Dynamic model of an organic rankine cycle system. part I - mathematical description of main components," *Proc. 23rd Int. Conf. ECOS 2010*, vol. 3, no. june, pp. 35–42, 2010.

[12] Gary Zyhowski and Andrew Brown, "Low Global Warming Fluids for Replacement of HFC-245fa and HFC-134a in ORC Applications Honeywell – A History of Innovation CFCs HCFCs HFCs HFOs," 2014.

[13] Q. Chen, J. Xu, and H. Chen, "A new design method for Organic Rankine Cycles with constraint of inlet and outlet heat carrier fluid temperatures coupling with the heat source," *Appl. Energy*, vol. 98, pp. 562–573, Oct. 2012.

[14] C. Guo, X. Du, L. Yang, and Y. Yang, "Organic Rankine cycle for power recovery of exhaust flue gas," *Appl. Therm. Eng.*, vol. 75, pp. 135–144, Jan. 2015.

[15] K. Yang, H. Zhang, Z. Wang, J. Zhang, F. Yang, E. Wang, and B. Yao, "Study of zeotropic mixtures of ORC (organic Rankine cycle) under engine various operating conditions," *Energy*, vol. 58, pp. 494–510, Sep. 2013.

[16] P. Garg, P. Kumar, K. Srinivasan, and P. Dutta, "Evaluation of isopentane, R-245fa and their mixtures as working fluids for organic Rankine cycles," *Appl. Therm. Eng.*, vol. 51, no. 1–2, pp. 292–300, Mar. 2013.

[17] X. D. Wang and L. Zhao, "Analysis of zeotropic mixtures used in low-temperature solar Rankine cycles for power generation," *Sol. Energy*, vol. 83, no. 5, pp. 605–613, May 2009.

[18] J. Xu and C. Yu, "Critical temperature criterion for selection of working fl uids for subcritical pressure Organic Rankine cycles," *Energy*, vol. 74, pp. 719–733, 2014.

[19] S. Quoilin, M. Van Den Broek, S. Declaye, P. Dewallef, and V. Lemort, "Techno-economic survey of Organic Rankine Cycle (ORC) systems," *Renew. Sustain. Energy Rev.*, vol. 22, pp. 168–186, Jun. 2013.

[20] E. Barbier, "Geothermal energy technology and current status: an overview," *Renew. Sustain. Energy Rev.*, vol. 6, no. 1–2, pp. 3–65, Jan. 2002.

[21] A. Franco and M. Villani, "Optimal design of binary cycle power plants for water-dominated, medium-temperature geothermal fields," *Geothermics*, vol. 38, no. 4, pp. 379–391, Dec. 2009.

[22] S. Clemente, D. Micheli, M. Reini, and R. Taccani, "Energy efficiency analysis of Organic Rankine Cycles with scroll expanders for cogenerative applications," *Appl. Energy*, vol. 97, pp. 792–801, Sep. 2012.

[23] W. W. Husband and A. Beyene, "Low-grade heat-driven Rankine cycle, a feasibility study," *Int. J. Energy Res.*, vol. 32, no. 15, pp. 1373–1382, Dec. 2008.

[24] A. M. Delgado-Torres and L. García-Rodríguez, "Analysis and optimization of the low-temperature solar organic Rankine cycle (ORC)," *Energy Convers. Manag.*, vol. 51, no. 12, pp. 2846–2856, Dec. 2010.

[25] X. D. Wang, L. Zhao, J. L. Wang, W. Z. Zhang, X. Z. Zhao, and W. Wu, "Performance evaluation of a low-temperature solar Rankine cycle system utilizing R245fa," *Sol. Energy*, vol. 84, pp. 353–364, 2010.

[26] J. L. Wang, L. Zhao, and X. D. Wang, "A comparative study of pure and zeotropic mixtures in low-temperature solar Rankine cycle," *Appl. Energy*, vol. 87, no. 11, pp. 3366–3373, Nov. 2010.

[27] L. Jing, P. Gang, and J. Jie, "Optimization of low temperature solar thermal electric generation with Organic Rankine Cycle in different areas," *Appl. Energy*, vol. 87, no. 11, pp. 3355–3365, Nov. 2010.

[28] Y. A. M. Kane, D. Larrain, D. Favrat, "Small hybrid solar power system," *Energy*, vol. 28, 14, 1427–1443, Nov. 2003.

[29] L. Dong, H. Liu, and S. Riffat, "Development of small-scale and micro-scale biomass-fuelled CHP systems – A literature review," *Appl. Therm. Eng.*, vol. 29, no. 11–12, pp. 2119–2126, Aug. 2009.

[30] U. Drescher and D. Brüggemann, "Fluid selection for the Organic Rankine Cycle (ORC) in biomass power and heat plants," *Appl. Therm. Eng.*, vol. 27, no. 1, pp. 223–228, Jan. 2007.

[31] G. Yu, G. Shu, H. Tian, H. Wei, and L. Liu, "Simulation and thermodynamic analysis of a bottoming Organic Rankine Cycle (ORC) of diesel engine (DE)," *Energy*, vol. 51, pp. 281–290, Mar. 2013.

[32] H. G. Zhang, E. H. Wang, and B. Y. Fan, "A performance analysis of a novel system of a dual loop bottoming organic Rankine cycle (ORC) with a light-duty diesel engine," *Appl. Energy*, vol. 102, pp. 1504–1513, 2013.

[33] B. F. Tchanche, M. Pétrissans, and G. Papadakis, "Heat resources and organic Rankine cycle machines," *Renew. Sustain. Energy Rev.*, vol. 39, pp. 1185–1199, Nov. 2014.

[34] T. A. Davidson, "Design And Analysis Of A 1 kW Power Cycle Employing A Multi-Vane Expander, For Use With A Low Temperature Solar Collector."

[35] A. Algieri and P. Morrone, "Techno-economic Analysis of Biomass-fired ORC Systems for Single-family Combined Heat and Power (CHP) Applications," *Energy Procedia*, vol. 45, pp. 1285–1294, 2014.

[36] A. Algieri and P. Morrone, "Energetic analysis of biomass-fired ORC systems for micro-scale combined heat and power (CHP) generation. A possible application to the Italian residential sector," *Appl. Therm. Eng.*, vol. 71, no. 2, pp. 751–759, 2014.

[37] B. F. Tchanche, S. Quoilin, S. Declaye, G. Papadakis, and V. Lemort, "Economic optimization of small scale organic

rankine cycles," *Proc. 23rd Int. Conf. ECOS 2010*, vol. 3, no. june, pp. 379–388, 2010.

[38] M. Badami, M. Mura, P. Campanile, and F. Anzioso, "Design and performance evaluation of an innovative small scale combined cycle cogeneration system," *Energy*, vol. 33, pp. 1264–1276, 2008.

[39] O. Badr, S. Naik, P. W. O'Callaghan, and S. D. Probert, "Expansion machine for a low power-output steam Rankine-cycle engine," *Appl. Energy*, vol. 39, pp. 93–116, 1991.

[40] E. Bocci, M. Villarini, L. Bove, S. Esposto, and V. Gasperini, "Modeling small scale solar powered ORC unit for standalone application," *Math. Probl. Eng.*, vol. 2012, p. 10, 2012.

[41] R. Bracco, S. Clemente, D. Micheli, and M. Reini, "Experimental tests and modelization of a domestic-scale ORC (Organic Rankine Cycle)," *Energy*, vol. 58, pp. 107–116, 2013.

[42] T. Chambers, J. Raush, and B. Russo, "Installation and Operation of Parabolic Trough Organic Rankine Cycle Solar Thermal Power Plant in South Louisiana," *Energy Procedia*, vol. 49, pp. 1107–1116, 2014.

[43] S. Declaye, S. Quoilin, L. Guillaume, and V. Lemort, "Experimental study on an open-drive scroll expander integrated into an ORC (Organic Rankine Cycle) system with R245fa as working fluid," *Energy*, vol. 55, pp. 173–183, 2013.

[44] R. Zanelli, "Experimental Investigation of a Hermetic Scroll Expander-Generator," 1994.

[45] T. H. T. Yanagisawa.M. Fukuta, Y. Ogi, "Performance of an oilfree scroll-type air expander," in *International Conference on Compressors and their Systems*, 2001.

[46] V. Lemort, S. Quoilin, C. Cuevas, and J. Lebrun, "Testing and modeling a scroll expander integrated into an Organic Rankine Cycle," *Appl. Therm. Eng.*, vol. 29, no. 14–15, pp. 3094–3102, Oct. 2009.

[47] H. A. Ingley, R. Reed, and D. Y. Goswami, "Optimization of a Scroll Expander Applied to an Ammonia/Water Combined Cycle System for Hydrogen Production," *Proc. Sol. World Congr.*, no. 1645, p. Paper No. 1645, 2005.

[48] G. Xiaojun, L. Liansheng, Z. Yuanyang, S. Pengcheng, and S. Jiang, "Research on a scroll expander used for recovering work in a fuel cell," *Int. J. Thermodyn.*, vol. 7, no. 1, pp. 1–8, 2004.

[49] T. H. R.B Peterson, H. Wang, "Performance of a small scale regenerative power cycle employing a scroll expander," *J. Power Eng.*, 2008.

[50] H. J. Kim, J. M. Ahn, I. Park, and P. C. Rha, "Scroll expander for power generation from a low-grade steam source," *Proc. Inst. Mech. Eng. Part A J. Power Energy*, vol. 221, no. 5, pp. 705–711, Jan. 2007.

[51] T. Saitoh, N. Yamada, and S. Wakashima, "Solar Rankine Cycle System Using Scroll Expander," *J. Environ. Eng.*, vol. 2, no. 4, pp. 708–719, 2007.

[52] J. A. Mathias, J. R. Johnston, J. Cao, D. K. Priedeman, and R. N. Christensen, "Experimental Testing of Gerotor and Scroll Expanders Used in, and Energetic and Exergetic Modeling of, an Organic Rankine Cycle," *J. Energy Resour. Technol.*, vol. 131, no. 1, p. 012201, 2009.

[53] V. Lemort, S. Declaye, and S. Quoilin, "Experimental characterization of a hermetic scroll expander for use in a micro-scale Rankine cycle," *Proc. Inst. Mech. Eng. Part A J. Power Energy*, vol. 226, no. 1, pp. 126–136, Nov. 2011.

[54] H. Wang, R. B. Peterson, and T. Herron, "Experimental performance of a compliant scroll expander for an organic Rankine cycle," *Proc. Inst. Mech. Eng. Part A J. Power Energy*, vol. 223, no. 7, pp. 863–872, Nov. 2009.

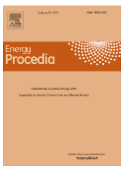
[55] D. Manolakos, G. Kosmadakis, S. Kyritsis, and G. Papadakis, "Identification of behaviour and evaluation of performance of small scale, low-temperature ORC system coupled with a RO desalination unit," *Energy*, vol. 34, no. 6, pp. 767–774, Jun. 2009.

[56] K. J. Harada, "Development of a small scale scroll expander," Oregon State University, 2010.

[57] D. Wei, X. Lu, Z. Lu, and J. Gu, "Dynamic modeling and simulation of an Organic Rankine Cycle (ORC) system for waste heat recovery," *Appl. Therm. Eng.*, vol. 28, pp. 1216–1224, 2008.

[58] G. Qiu, Y. Shao, J. Li, H. Liu, and S. . B. Riffat, "Experimental investigation of a biomass-fired ORC-based micro-CHP for domestic applications," *Fuel*, vol. 96, pp. 374–382, Jun. 2012.

[59] A. M. Delgado-Torres and L. García-Rodríguez, "Preliminary design of seawater and brackish water reverse osmosis desalination systems driven by low-temperature solar organic Rankine cycles (ORC)," *Energy Convers. Manag.*, vol. 51, no. 12,. 2913–2920, 2010.



Biography

John Besong OBI is holder of a B.Sc as well as an M.Sc in Mechanical Engineering at the university of Trieste where he is currently doing a PhD in distributed and micro-generation systems (ORC for Waste heat recovery systems) with some previous industrial experience in the HVAC field.