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ORC based micro-cogeneration systems for residential application – A state of the art review and current challenges

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ABSTRACT

The environmental awareness and sustainability concerns have reached an unprecedented level of importance that is leading to, among other things, constant improvements in the traditional methods of energy conversion. One of those improvements involves the use of micro-CHP (combined heat and power production) systems for residential applications since the potential in terms of primary energy savings and GHG (greenhouse gases) reductions is considered to be enormous. Among the different technologies available for micro-CHP systems, ORC based ones seem the most suitable and promising option due to its simplicity and its ability to retrofit current heating systems used in residential dwellings.

This work reviews the use of ORC for micro-CHP applications taking into account the intrinsic requirements of the residential sector. One of those requirements is the ability to face highly variable thermal demand loads for which a short response time is necessary to ensure. The present research analyzes how manufacturers and the researcher centers are dealing with this key requirement. One of the findings of this work is that the referred requirement is essentially dependent on the ORC-evaporator design and how the primary energy reaches the power cycle, while the remaining ORC main components (expander, pump and condenser) play a minor role on that ability. Additionally, this research also offers an analysis of the micro-CHP potential and of the ORC market evolution, presenting a historical perspective of the technology, current main manufacturers, main application areas and a comparison between the use of an organic fluid and water/steam as working fluid for Rankine cycles.

1. Introduction

The last decades of worldwide social, economic and technological developments have led to an increase in the number of people requesting for energy-consuming living amenities. This results in an increase rate of primary energy use much higher from what could be justified by the population growth (Table 1) [1,2]. Alongside with the energy use increase rate, there has been a gradual rise of the average prices of conventional fossil fuels such as gas, oil or coal. Nowadays, these conventional fuels cover a large share of the primary energy needs (see Fig. 1) and are, by far, the biggest contributors to the world's greenhouse gas (GHG) emissions that lead, among other consequences, to climate changes and health problems [3,4]. The need to question the use of these traditional fuels, of traditional energy conversion methods and of current consumption patterns, has reached an unprecedented level of importance and there is an imperative necessity to change them into low environmental impact, secure and cost-effective alternative approaches based on renewable or highly efficient energy systems [5,6].

The mentioned facts enlighten all applications or technologies that, somehow, work against these major issues. One of those technologies, receiving increasingly attention from industries and research centers, is the Organic Rankine Cycle (ORC) [7]. According to Vélez et al. [8] and Tchanche et al. [9] this technology presents some specific characteristics that makes it suitable to be part of the solution for the aforementioned issues. Those characteristics are: i) adaptability to various heat sources, ii) proven and mature technology in the medium-to-large scales, iii) simpler and more reliable when compared to other technologies, iv) the possibility to be built in a wide range of scales sizes, v) low investment and maintenance costs and vi) good market availability with well-known suppliers.

Often used together with ORC technology is the well-known technique of simultaneous production of heat and power, also known as CHP (Combined Heat and Power). The combined production of heat and power not only reduces the losses of the energy conversion process but also avoids the losses associated with its transportation and distribution, improving the sustainability of the whole process and contributing to the increase of grid reliability and to the reduction of grid

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Nomenclature

CEN	European Committee for Standardization
CHP	Combined Heat and Power
CODE	Cogeneration Observatory and Dissemination Europe
DHW	Domestic hot water
EU	European Union
Geo	Geothermal
GHG	Greenhouse gas
ICE	Internal Combustion Engine
ORC	Organic Rankine Cycle
R&D	Research and Development
RC	Rankine Cycle
SME	Small and medium-sized enterprises
TPES	Total primary energy supply
UK	United Kingdom
USA	United States of America
WHR	Waste heat recovery

dependence [10,11]. Moreover, CHP systems not only provide significant savings over individual heating and power systems in terms of operational costs and of primary energy consumptions but also in terms of GHG emissions [12–14]. Dentice d'Accadia et al. [15], refers that the CHP has been considered, worldwide, as the major alternative to traditional systems in terms of significant energy savings and environmental conservation.

Both technologies (ORC and CHP) have been widely studied in the last years. Studies regarding ORC systems normally range from the development of more or less sophisticated models used to: i) estimate the economic benefits from the system operation, ii) support the system working fluid and components selection, iii) evaluate the system design, and off-design, key operation conditions or iv) develop the system control strategies; to the realization of more or less extended experimental tests. These are generally used to characterize a specific component or to validate the different options taken regarding, for example, system design configurations, component selection and control strategies [16–24]. The expander is the only ORC system's component that is frequently addressed in an isolated manner [25–30]. Usually, studies concerning CHP systems report the analysis of alternative configurations, or the comparison of different usable technologies, regarding the energy and economic benefits [31–36]. Given its technological maturity and the individual magnitude of the energy and economic savings, the great majority of the CHP projects are generally done for steady-state operation regimes, in a medium-to-large scale. However, the potential for savings associated with micro-to-small scale and non-steady-state CHP systems (e.g. systems suitable to retrofit domestic combi-boilers) is believed to be enormous [37–41]. At this scale – micro-scale – the Rankine technology is being widely considered for CHP systems [42–44] and either due to restrictions related with dimension or with the system's response time, direct vaporization of the working fluid becomes more than an option, a demand. In those situations, to avoid high pressures and high superheating degrees that are typical of water/steam Rankine Cycles, the use of an organic fluid seems to be the reasonable option. In such circumstances, to prevent the degradation of the organic fluid in the thermal boundary layer, the evaporator needs to be carefully engineered and, together with the expander, becomes a key component of the ORC based micro-CHP system.

The major objective of this paper is to contribute to the widespread use of the ORC technology in micro-CHP systems for domestic applications. To achieve that purpose this paper not only attempts to identify the specificities of the operating conditions requested by this particular application, and the technological gaps arising from them, but also provides an overview of the way how manufacturers and research centers are trying to overcome the problems opposing its practical implementation. The paper also includes a general analysis of micro-CHP specificities and its potential in terms of energy savings and GHG emission reductions. Since ORC is considered one of the most suitable technology for this specific application, an analysis regarding its state of maturity, through its whole power range, is made in which its main manufacturers are referenced and a trend regarding the average system size is presented.

Table 1
World energy and economic key indicators for the years 1993, 2011 and a projection for 2020 (data from [4]).

	1993	2011	2020	% growth (1993–2011)
Population [billion]	5,5	7	8,1	27%
Gross domestic product [trillion USD]	25	70	65	180%
Total primary energy supply (TPES) [Mtoe[a]]	9.532	14.092	17.208	48%
Coal [Mt[a]]	4.474	7.520	10.108	68%
Oil [Mt[a]]	3.179	3.973	4.594	25%
Natural gas [bcm[a]]	2.176	3.518	4.049	62%
Nuclear [TWh[a]]	2.106	2.386	3.761	13%
Hydro power [TWh[a]]	2.286	2.767	3.826	21%
Biomass [Mtoe[a]]	1.036	1.277	1.323	23%
Other renewables [TWh[a]]	44	515	1.999	1170%
Electricity production/year				
Total [TWh[a]]	12.607	22.202	23.000	76%
Per capita [MWh[a]]	2	3	3	52%
CO_2 emissions/year				
Total CO_2 [Gt[a]]	21	30	42	44%
Per capita [tonne CO_2]	4	4	n/a	11%

[a] **Mtoe** Million tonnes of oil equivalent; **Mt** Mega tonne; **Gt** Giga tonne; **bcm** Billion of cubic meters; **TWh** Tera Watt hour; **MWh** Mega Watt hour.

2. Micro-cogeneration potential and technologies

Micro-CHP is the designation given to the cogeneration systems that are able to fulfill thermal loads that range from those typical public/commercial buildings such as health centers, office blocks, schools, small and medium-sized enterprises (SME) and others, down to the needs of individual household or residential dwellings. In terms of nominal electrical power, these systems range from bellow 1 kW_e to 50 kW_e. At medium-to-large scale (electrical power above 50 kW_e), CHP systems are a mature technology with a fairly widespread use, while the micro-scale systems are still limited by several problems [45]. Nevertheless, the potential market for systems of this scale is huge [46] since one of their possible applications is the domestic hot water generation (for sanitary and space heating purposes). In fact, the Cogeneration Observatory and Dissemination Europe (CODE) performed a comparative analysis between different heating technologies currently used in buildings, specially addressing micro-CHP in order to understand its versatility and retrofitting (or add-on) ability [40]. The results of that analysis are shown in Table 2. CODE is a European project focused on the analysis and dissemination of the potential benefits and of the applicable legislation of CHP systems. This analysis was done having in mind the Energy Efficiency Directive (2012/27/EU) [47].

As stated by Alane and Saari [39] the most promising market for the micro-CHP systems lies in the residential sector (according to Kuhn et al. [48], in Europe this is especially true for countries like United Kingdom, The Netherlands, Germany, France, Italy, Belgium, Denmark and Ireland). In fact, the annual dimension, in sales and stocks, of the European residential boiler market is around 8 and 100 million of units, respectively; while the sales and stocks of all other sectors is around 1 and 20 million of units, respectively, as shown in Fig. 2.

The enormous dimension of the European potential market of