Energy Conversion and Management 154 (2017) 262–285

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Review

Micro-combined heat and power systems (micro-CHP) based on renewable energy sources

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ARTICLE INFO

Keywords:
Micro-CHP
Combined heat and power
Small-scale
Renewable source
Distributed generation
Greenhouse gas emission reduction
Solar energy

ABSTRACT

This article presents a review of the available solutions of micro combined heat and power systems. First part focuses on existing energy conversion devices. If internal combustion engine technology seems to be the more mature and economically viable, several research and development works aim to develop other systems such as Stirling engine, organic Rankine cycle (ORC) and fuel cells. The second part deals with renewable energy fuelled micro combined heat and power systems with a focus on solar energy-based technologies.

1. Introduction

Worldwide, energy is consumed to produce heat and power in sectors such as industry, building, and agriculture. For a more sustainable future, due to global warming and the exhaustion of fossil resources, research and development works are conducted in order to create energy production systems more efficient and environmentally friendly [1].

In response to this issue, combined heat and power (CHP or cogeneration) can be a solution since it generally consists in generating simultaneously both useful heat and electricity in a single process and from a single energy source [2]. If natural gas remains the main resource used for cogeneration purposes, renewable sources such as biogas, biomass and solar can also be used.

1.1. Basics of CHP

A CHP system can be defined as the sum of individual components: conversion device (or heat engine), generator, heat recovery system and electrical converter [3]. CHP systems tend to improve the overall plant efficiency as it allows the heat recovery in an electricity production process [4]. Centralized electricity generation systems cause heat losses during production and transport. As an example, only one third of the primary energy is converted into electricity in a nuclear power plant. Therefore, the overall efficiency of classical energy production (electricity and heat) is around 60% when local CHP overall efficiency can reach 90% [5,6]. Thus, CHP systems improve usage of primary energy and, for this reason, the European Directive 2004/8 EC [7] encourages European countries to develop combined heat and power systems and to increase the use of cogeneration in order to save primary energy.

Additionally, CHP systems can contribute to diversifying the energy mix of a country with the local production of electricity and heat from installations well suited to the consumption location. According to the previously mentioned directive [7], CHP systems can be classified in three categories depending on their maximum electrical capacities, namely “micro-cogeneration” if fewer than 50 kW_e, “small scale (or mini) cogeneration” if ranging from 50 kW_e to 1 MW_e, and “cogeneration” if higher than 1 MW_e. Fig. 1 presents a classification of the main available CHP technologies and their main fields of applications. A particular attention has to be paid to the combustion process. For systems involving an external combustion process or no combustion process, the fuel adaptability is better. This is particularly interesting in the context of the wide spreading of renewable sources.

Micro combined heat and power (micro-CHP) is a decentralized heat and electricity production connected to low voltage grid, at the consumer level [8]. A distributed generation using renewable energy can be a solution in order to reduce greenhouse gas emissions and to increase the supply security [9]. Moreover, for rural regions in developing countries without power and electrical grid infrastructure, distributed energy generation based on renewable energies can provide access to a safe, reliable, affordable and sustainable clean energy [10]. Distributed micro-CHP units based on renewable energies and micro-grid dispatch technologies seem to be in conflict with fossil fuel based centralized technology for off-grid communities’ energy generation

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http://dx.doi.org/10.1016/j.enconman.2017.10.035
Received 29 June 2017; Received in revised form 28 September 2017; Accepted 14 October 2017

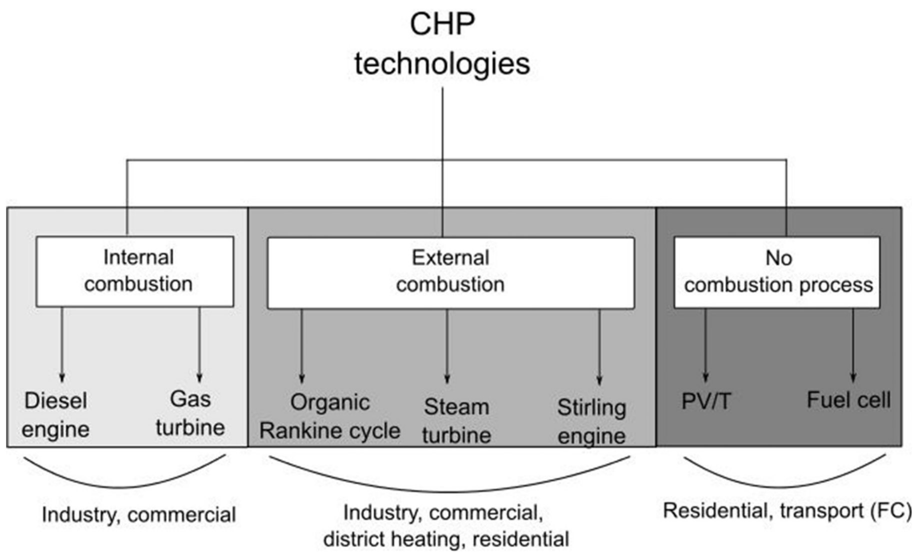

Fig. 1. Main CHP technologies and their fields of applications.

[11].

Regarding available technologies for micro-CHP, one can distinguish two main categories, namely: (i) technologies based on thermodynamic cycles used to generate electricity; and (ii) technologies not based on thermodynamic cycle. The first category concerns both internal and external combustion technology. Rankine cycle is the most common way to generate electricity from a heat source (external combustion process or no combustion process). Two working fluids are mainly used in Rankine cycles: water (steam Rankine cycle) and organic fluids (organic Rankine cycle (ORC)) [12]. Organic fluids are considered as promising solution for low-medium temperature and small-scale applications [13,14]. Several expansion devices are available to generate electricity with thermodynamic cycles in small-scale applications. The main devices currently used are ICE (Internal Combustion Engine), microturbine and Stirling engine. Nevertheless, the integration of new expander technologies for micro-CHP applications, such as Wankel-type expanders [15], are investigated. The second category, not based on thermodynamic cycles to generate electricity and heat, mainly concerns fuel cells and solar thermal photovoltaic hybrid technologies (PV/T).

Recently, attention has been paid to micro-CHP in the building field to increase the efficiency of distributed power generation systems by a local production of power and heat [16]. As an example, in the MICROSOL project, a solar distributed technology has been investigated for developing countries. The micro-CHP unit includes a heat storage module, an ORC for electricity production and a water purification process [17]. An interesting approach to the micro-CHP issue in the residential sector has been presented by Bianchi et al. [18]. The micro-CHP unit under study is composed by a CHP prime mover, an auxiliary boiler and a thermal storage unit. Electricity produced can be either consumed on site or injected into the electricity grid. Fig. 2 presents a typical integration of a micro-CHP unit in a building. Usually, an auxiliary boiler and a thermal storage enable the system to properly cover thermal needs.

Historically, cogeneration is as old as the generation of electricity. The concept of centralized power plant was born when electrification replaced gas and kerosene lighting in buildings. District heating systems were popular during the late 1800s, while district electrification began with Thomas Edison's plants in New York, the two were quickly combined. With the development of large centralized power units, it started to be cheaper to buy electricity from a central utility. The end of cogeneration in industrial plants has come at this time but, since the energy crisis of 1973, CHP and micro-CHP have gained interest again [19].

1.2. Development of the technology

In 2008, IEA sums up several country policies in order to promote CHP [20]. Feedback from several test countries pointed out that incentive policies can have important effects on the development of CHP. Countries first set targets and created dedicated government departments in charge of identifying CHP potentials. These departments, then promote policy tools and solutions to develop CHP. Fig. 3 presents the CHP share of national power production for several industrialized countries. The main conclusions are that CHP contributes to around 10% of the electricity production in the world, and that only four countries (Denmark, Finland, Russia and Latvia) have successfully implemented CHP in their electricity production (more than 30%). These countries have obtained successful CHP markets due to favourable government policies.

In Europe, CHP development incitation has been done with success in Denmark with the "integrated approach to heat and electricity planning", which has immediately decreased its energy consumption and achieved energy self-sufficiency. Denmark also became the first European user of CHP and a world CHP leader. Common measures mainly deal with economic, regulatory and social issues. Modest and targeted policies seem efficient to improve the realization of the CHP potential. Fig. 4 presents the percentage of power generated from CHP in several countries around the world. If Denmark and other north European countries clearly appear as leaders in this domain usually, CHP remains marginal in the other national power productions. The previous study and figures tend to show that incentive policies are vital for the development of CHP technology and can be extended for the development of micro-CHP.

Fig. 5 focus on the CHP fuel mix repartition in European countries. It clearly appears that non-renewable energy sources are mainly used for CHP. In 2013, natural gas represented 45% of the CHP fuel mix. This can be explained by the maturity of the technologies using this energy source. Renewable sources accounted for 18% of this fuel mix. However, this value has continuously increased from 9% in 2005 [22].

The variability of the European energy mix is highlighted in Fig. 6 in terms of total energy produced. In 2013, Germany, Italy, and the Netherlands were quantitatively the three major users of CHP. Category "Other fuels" includes industrial wastes and coal gases. Among the main European CHP users, Finland and Sweden appear as the major users of renewable sources, while the biggest European producer (Germany) mainly used natural gas. One can also note in Fig. 6 that the CHP fuel mix deeply varied between countries. As an example, in 2013, it was composed by 74.8% of renewable sources in Sweden, and by