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Biomass-fired combined cooling, heating and power for small scale applications – A review

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ABSTRACT

The growing demand for energy and the accelerating threats from climate change call for innovative and sustainable solutions to decrease dependency on fossil fuels. Biomass-based, small-scale Combined Cooling, Heating and Power (CCHP) systems are one of these solutions, because they can satisfy the energy demands of the consumer with enhanced flexibility, lower losses, less costs and less environmental pollution as compared to centralized facilities. Due to recent advances in several scientific subfields with relevance to small-scale CCHP, a rapidly increasing amount of literature is now available. Therefore, a structural overview is essential for engineers and researchers. This paper presents a review of the current investigations in small-scale CCHP systems covering biomass-fired concepts and solar extensions. To this end, critical system components are described and analysed according to their specific advantages and drawbacks. Recent case studies have been collected and key findings are highlighted according to each type of prime mover. The results indicate a scientific bias towards the economic viability of such systems and the need for real-life and experiment system data. However, the potential of biomass-fired CCHP systems and of such systems with solar extensions has clearly been recognised. Based on the results, future policy implementations should focus on fostering such systems in areas with high energy costs and to increase energy resilience in developed regions. Additionally research and industry applying novel prime mover technologies should be financially supported.

1. Introduction

To fuel the world's rising demand for energy while also to slow down emissions of greenhouse gases, more efficient and more sustainable energy systems are necessary [1]. Combined Cooling, Heating and Power (CCHP) is a technology that aims to raise the energy efficiency of an energy system by using the electric as well as the thermal output for practical applications. Most deployed CCHP systems involve centralized facilities with extensive heating and cooling networks supplying hundreds or thousands of industrial and residential consumers. However, the disadvantages of centralized energy systems are losses due to longer transfer distances, the inability to reply to the immediate demands of individual consumers and higher security risks should unexpected shutdowns occur [2,3]. Therefore smaller decentralized units, which serve the local demand for heat as well as for electricity, can be a more profitable and more efficient alternative to centralized facilities [4].

While small-scale systems providing cooling, heat and/or power driven by fossil fuels haven been successfully developed and constructed for decades, the implementation of renewable options is relatively new and successful mass-scale commercialization still has to be proven [5,6]. Amongst renewable energies, biomass seems to be the most promising energy source for CCHP systems as other renewable energies are either not generating enough heat in normal operation modes (wind, photovoltaic, hydro), are too locally limited (geothermal) or are too volatile (solar thermal) [7–10]. Hence, the development of small-scale, biomass-fired CCHP systems is becoming increasingly important for climate politics, economics and research. Such systems can be especially cost-efficient solutions in remote areas and islands with adequate sources of renewable energies [11,12]. Extensions involving solar electric energy can greatly augment the sustainability and viability of this approach, considering the vast solar potential and falling photovoltaic (PV) prices [13].

Historically CCHP is linked to the more well-known Combined Heat and Power (CHP) concept: a cooling unit is integrated to the CHP system, leading to more choices for energy outputs and higher operating times, especially in comparison to conventional power plants. Several synonyms of CCHP can be found in literature and the following list defines their meaning for this paper:

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Nomenclature

AC	Absorption Chiller
BCHP	Building cooling heating and power
CCHP	Combined Cooling, Heat and Power
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilization
CHP	Combined Heat and Power
COP	Coefficient of Performance
EES	Engineering Equation Solver
FC	Fuel Cell
GHG	Greenhouse Gases
ICE	Internal Combustion Engine
LiBr	Lithium-Bromide
LPG	Liquefied Petroleum Gas
MCCHP/μCCHP	Micro CCHP
ORC	Organic Rankine Cycle
PCM	Phase Change Materials
PESR	Primary Energy Saving Ratio
PV	Photovoltaic
PVT	Photovoltaic-Thermal
SE	Stirling Engine
SOFC	Solid Oxide Fuel Cell

- Trigeneration: essentially equivalent to CCHP [14]
- Polygeneration/Multigeneration: Any system which produces more than two energy services; this can be a CCHP system but may also be a system producing chemicals or other products [19,]
- MCCHP/ μCCHP: Micro CCHP (with less than 20 kW electric power) [15,16]
- CHP with Cooling or Cogeneration with Cooling: Essentially the same as CCHP [17]
- BCHP: Building Cooling Heating and Power [18]
- Biorefinery: Any system that produces chemical products out of biomass [14]

Several studies indicate significant potential for biomass-fired CCHP systems, but so far only medium-scale (1–10 MW) and large scale (> 10 MW) systems have been commercialised successfully, while micro-scale (< 20 kW) and small-scale (20 kW to 1 MW) systems are still in an experimental phase. To design a CCHP system for optimal environmental and economic performance, component type and size have to be evaluated and chosen carefully according to the electricity, heating and cooling demand [3,4]. For this, many authors argue that the prime mover is the heart of such systems with the biggest impact on system economics and environment [4,16,19]. Another possibility to optimize small-scale CCHP systems is to use operation strategies adjusted to the electric or the thermal load [15]. These loads depend heavily on the energy consumer, which can be a household, an office building, a hospital, or any similar buildings. Several studies investigate the optimal behaviour for CCHP systems and highlight the benefits of their flexibility for energy generation [14,20,21].

The previously mentioned studies review certain aspects of CCHP systems, but none of them focuses on the growing amount of literature on biomass-fired options. Hence, the aim of this paper is to summarize and structure the constantly increasing amount of scientific literature on small-scale (< 1 MW_{el}), biomass-fired CCHP systems. For this, currently used technologies are presented as shown in Fig. 1 and their specific benefits as well as drawbacks are identified. For each different prime mover technology, the key findings of the most recent case studies from 2010 to 2017 are highlighted and their key characteristics (maximal output, type of biomass, prime mover type, refrigeration technology, model software/experiment location) are assembled.

After this introduction, internal and external factors that affect the technological and economic development of CCHP systems will be listed in chapter 2. In chapter 3, the different ways to obtain biofuel for small-scale CCHP systems are presented. The studies investigating small-scale biomass-fired CCHP systems are summarized and listed according to their prime mover in chapter 4. Chapter 5 presents the most common cooling and storage technologies. The findings are discussed in chapter 6 and finally conclusions are drawn in chapter 7, where also future policy implementations are suggested.

2. Internal and external factors driving CCHP development

To seize the potential of small-scale CCHP systems internal as well as external factors will influence the development in the coming years. One external factor for the viability of small-scale CHP and CCHP systems is the adaption of government policies for support and subsidies. It was noted that governments from developed and developing countries like the USA, China, the EU, Brazil, Russia and Japan use different mechanisms to promote the use of CCHP systems [15,16]. This implies,

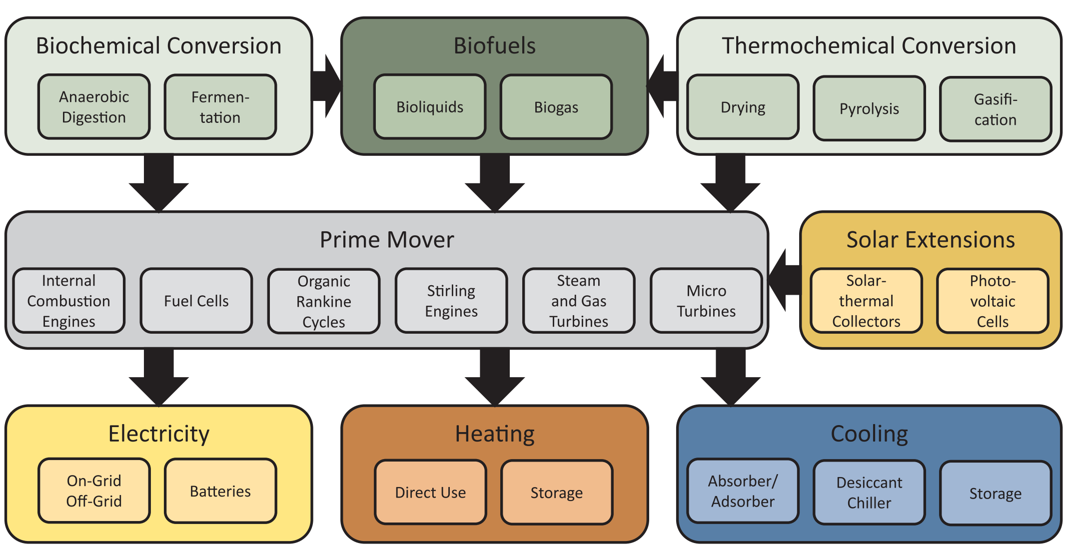

Fig. 1. Key components in biomass-fired and solar assisted small-scale CCHP systems.