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Combined bioheat and biopower: A technology review and an assessment for Turkey

Guner Eksi*, Filiz Karaosmanoglu

Chemical Engineering Department, Istanbul Technical University, Maslak, Istanbul 34469, Turkey

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ABSTRACT

Combined bioheat and biopower (CBHBP) is named to emphasize that a biomass source is used as the feedstock for the production of combined heat and power (CHP). Turkey is a country with rich biomass potential; however, traditional utilization is predominant. The purpose of this paper is to describe the entire value chain of biomass-to-biopower by focusing on the current commercial technologies in the world and to provide an alternative solution for modern utilization of solid biomass sources in Turkey, while being a reference for other countries interested in biopower. The first aim is to explore the major conversion technologies for CBHBP production considering the entire value chain of biomass-to-biopower, with a focus on the most established path applied to solid biomass sources worldwide. The next aim is to examine the status of biomass energy in Turkey, concentrating on current biopower applications.

This review shows that combustion coupled with steam turbine technology is the primary approach to produce biopower and/or bioheat from solid biomass sources worldwide. In different countries, CBHBP production through distributed generation (DG) is seen as a viable way of taking advantage of local biomass sources. In Turkey, biopower production through thermochemical conversion technologies that require solid biomass sources is still at an early stage. A challenging increase in biopower development is needed. In conclusion, modern utilization of solid biomass sources through distributed CBHBP production based on combustion and steam turbine technology, in line with worldwide biopower developments, is a solution to utilize the existing potential efficiently that can be implemented in the short term. Distributed CBHBP should be implemented as soon as possible and become widespread in the country, especially in rural areas near forest villages and in agricultural regions where solid biomass sources are locally available and where there is a constant heat/cold and power demand.

1. Introduction

Energy production [1,2] has many challenges associated with sustainability. Above all, the energy sector is responsible for roughly two-thirds of all anthropogenic greenhouse gas (GHG) emissions globally. The scientific community accepts that GHG emissions, primarily from fossil fuels, are perturbing the Earth's climate, causing climate change [3,4].

If they can be sustained, renewable-based energy sources offer numerous advantages over conventional energy sources that are nonrenewable (fossil and nuclear energy sources). To maintain a clean environment, renewable-based energy sources are considered as a promising alternative globally. In 2015, renewable sources represented more than 60% of net additions to global power capacity. By the end of 2015, renewables supplied an estimated 23.7% of global electricity [5]. Today, renewable-based energy sources are playing a major role in the fuel mix in many countries around the world.

Among renewable-based energy sources, biomass is a strategic energy source because it is renewable, environmentally friendly, favorable to socio-economic development, and suitable for producing

Abbreviations: BFB, bubbling fluidized bed; BIGCC, biomass integrated gasification combined cycle; CBHBP, combined bioheat and biopower; CFB, circulating fluidized bed; CHP, combined heat and power; CH_4, methane; CO, carbon monoxide; CO_2, carbon dioxide; DG, distributed generation; ESP, electrostatic precipitator; EU, European Union; FB, fluidized bed; GHG, greenhouse gas; HRSG, heat recovery steam generator; ICE, internal combustion engine; INDC, intended nationally determined contributions; kW, kilowatt; kW_e, kilowatt electrical; kWh, kilowatt-hour; LCA, life cycle assessment; LHV, low heating value; MENR, ministry of energy and natural resources; Mt, million tons; Mtoe, million tons of oil equivalent; MW, megawatt; MW_e, megawatt electrical; MW_{th}, megawatt thermal; NREAP, national renewable energy action plan; N_2O, nitrous oxide; NO_x, nitrogen oxides; ORC, organic Rankine cycle; SO_2, sulfur dioxide; SO_x, sulfur oxides; t, ton; TPES, total primary energy supply; UNFCCC, United Nations framework convention on climate change; λ, excess air ratio

* Corresponding author.
E-mail address: geksi@itu.edu.tr (G. Eksi).

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solid, liquid, and gaseous fuels, in addition to power, heat, and cold [6]. Biomass, which is a readily available energy source, is a general term used to describe all biologically produced carbonaceous materials on Earth [6–9]. Biomass materials either are available from natural processes or can be made available through various human activities [9]. Briefly, they are directly or indirectly a result of plant growth [10,11]. Plant biomass (phytomass) [12] is formed through photosynthesis. Animal biomass (zoomass) [12] is formed when plant biomass is used as food by animals and converted into manure. The major anthropogenically modified [8] biomass materials used for energy production include organic residues and wastes from forests, agriculture, industry, and municipalities. Although there is a large number of different biomass materials that can be used to produce energy, the majority comes from three sources: forests, agriculture, and wastes/residues.

For energy purposes, biomass has been used since man discovered fire. Today, use of biomass for energy is multi-faceted so that many different biomass sources can be transformed via various conversion technologies for use in the energy sector [5]. Climate change mitigation and energy independence are major drivers for biomass energy developments around the world. Energy from biomass plays a dominant role among renewable-based energy options. Biomass is the largest renewable-based energy source and supplies 10.3% of the global energy supply [2]. The third largest source for renewable electricity generation is biomass, and biomass constitutes the largest source for renewable heat generation and for contributing to the transportation sector [2,5,13,14].

A key advantage of biomass energy is its capability to provide base load electricity generation without any supplementary energy storage facilities. Moreover, among all the renewable-based energy sources, biomass is unique since it is the only natural carbon-rich material source available on Earth besides fossil fuels. Consequently, while electricity and heat can be produced by a variety of renewable-based sources other than biomass such as wind, solar, and hydro energy, the only alternative to fossil sources for producing fuels, chemicals, and materials is biomass. In this context, the biorefinery concept has arisen to convert biomass into energy carriers (biofuels, biopower, bioheat, and biocold) and a range of useful products (biochemicals and biomaterials) including food and feed [15,16]. Many believe that building a bio-based economy using the biorefinery concept will result in an environmentally benign global industry [15,17]. Today, biomass utilization for energy purposes is classified into two broad categories, namely traditional (classic) and modern. While modern biomass utilization includes biomass energy technologies to convert biomass into useful forms of energy, traditional biomass utilization includes direct combustion for heating and cooking purposes, a practice widely used in many parts of the world, especially in rural areas. To apply the biorefinery concept, considerable research efforts have been devoted worldwide to devise biomass conversion technologies, hence enabling modern biomass utilization.

Turkey is an energy importer country. In 2015, the country depended on imports for 76% of its total primary energy supply (TPES) [18]. Therefore, biomass as an indigenous energy source has strategic importance for Turkey [19]. Moreover, Turkey is a country with rich biomass potential [10,19,20]. Biomass energy accounted for about 20% of the renewable-based energy supply in 2015 [18]. However, traditional utilization predominates. In rural areas like forest villages and agricultural zones, biomass is often the only readily available and affordable energy source [21], and has great potential to provide improved rural energy services in Turkey [22,23]. In forest villages, where 10% of the total population in Turkey lives, wood is often used as a source of energy for heating and cooking needs, resulting in a serious threat to forest sustainability. In rural areas where agricultural activities take place, the main energy sources consumed are fossil-based. In Turkey, agriculture plays a significant role in sustainability since almost 30% of the total population is engaged in agricultural activities [24–26]. Although agricultural and forest residues/wastes are among Turkey's major biomass energy sources, they are not efficiently used to meet the needs of the country. Modern utilization of solid biomass sources is still at an early stage. In Turkey, solutions are being investigated and discussed for modern utilization of these sources.

The first aim of this paper is to explore the major conversion technologies for CBHBP production considering the entire value chain of biomass-to-biopower, with a focus on the most established path that has been applied to solid biomass sources globally. The next aim is to examine the status of biomass energy in Turkey, concentrating on current biopower applications.

The first objective is to carry out a comprehensive technology review on biomass conversion technologies starting from biomass sources to produce CBHBP. The conversion paths that are currently commercial or have high commercialization potential are discussed, and then the focus shifts to CBHBP production and commercial CBHBP plants based on combustion and steam turbine technology, which is the primary approach applied to solid biomass sources in the world. The second objective is to first evaluate Turkey's current energy outlook and the status of biomass energy, and then to present a detailed assessment of current biopower applications, together with commercial examples in Turkey.

This study should be helpful to investors, policymakers, and academicians dealing with biomass energy applications by presenting the major alternatives for implementing CBHBP technologies. The review will contribute to the literature by showing in one place the entire value chain of biomass-to-biopower commercial technologies.

The remainder of the article is organized as follows. First, an overview of CHP is given and its current status in Turkey is detailed. Then, a comprehensive technology review of CBHBP production is provided. Next, for combustion and steam turbine technology, a schematic flow diagram of a typical CBHBP plant is presented along with a technical review. Later, commercial CBHBP plants worldwide are described with a table listing their basic technical features. After the distinctive characteristics of biopower production are examined, Turkey's detailed energy outlook is presented, focusing on biomass energy utilization in the country. Finally, a detailed assessment of biopower applications in Turkey is provided.

2. CHP overview

CHP or cogeneration (abbreviated to cogen) is the simultaneous generation of two or more secondary energy carriers such as useful heat and electricity using a single fuel in one conversion process.

The thermodynamics of electricity generation require that a large quantity of heat is rejected to a lower temperature sink. CHP is essentially implemented by the addition of a heat exchanger to capture a significant proportion of the rejected heat, i.e., the heat created as a byproduct in electricity generation [27]. While the electricity produced can be used onsite or distributed through the utility grid, the thermal energy recovered is usually used on-site for district heating, cooling networks, hot water, industrial process heat, or for steam generation [28]. In a cogeneration system, it is essential that a significant portion of the recovered heat must be used in a thermal process. Therefore, the main precondition for an effective cogeneration operation is a stable thermal energy demand [29]. CHP is actually an integrated energy system that can be modified depending on the needs of the energy end user, i.e., to satisfy an existing heat demand at the regional or local level. Hence, the design of CHP systems depends on the relevant site-specific conditions. For example, it is important for CHP technologies that the rejected heat is provided at a sufficiently high temperature in a useful form for space or hot water requirements (CHP for district heating), or alternatively for steam to meet industrial process needs (CHP for industry) [27].

A cogeneration unit consists of the following three main compo-