Biomass-Based Gas Turbine Systems for Power Generation: Sustainable Feedstocks and Environmental Benefits

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Abstract. This paper explores the significance and operational mechanisms of biomass-based gas turbine systems, which present a renewable and sustainable substitute for conventional fossil fuel-based electricity production methods. These systems utilize biomass as a source of fuel to produce heat, which is then converted into power through a gas turbine. The process involves the combustion of biomass fuel to heat a working fluid, such as air, which subsequently drives the turbine to produce electricity. Biomass can be derived from various organic materials, encompassing urban solid trash, forest residues, and agricultural residues, making it a versatile and sustainable fuel option. The paper also includes a practical case study, highlighting the system's advantages and disadvantages. Additionally, it identifies future trends, emphasizing the importance of efficiency enhancement. To achieve this, scientists are increasingly proposing hybrid systems that combine biomass-based gas turbines with other technologies. This approach aims to optimize performance, reduce emissions, and contribute to guaranteeing a future with more sustainable energy. The study underscores the potential of biomass-based gas turbine systems to play a crucial part in the shift to renewable energy sources.

Keywords: Biomass, gas turbine, sustainable feedstocks, environment.

1. Introduction

Given the growing need for global energy and severe environmental pollution, renewable energies have become crucial methods to tackle these problems. The European Union's gross final power consumption is 1147 Mtoe (million tons of oil equivalent), as shown in Fig. 1. Of this energy, renewables accounted for 17%, or 195 Mtoe [1]. With a 116 Mtoe contribution, bioenergy made up 59% of renewable energies, indicating that biomass energy was becoming more and more popular.

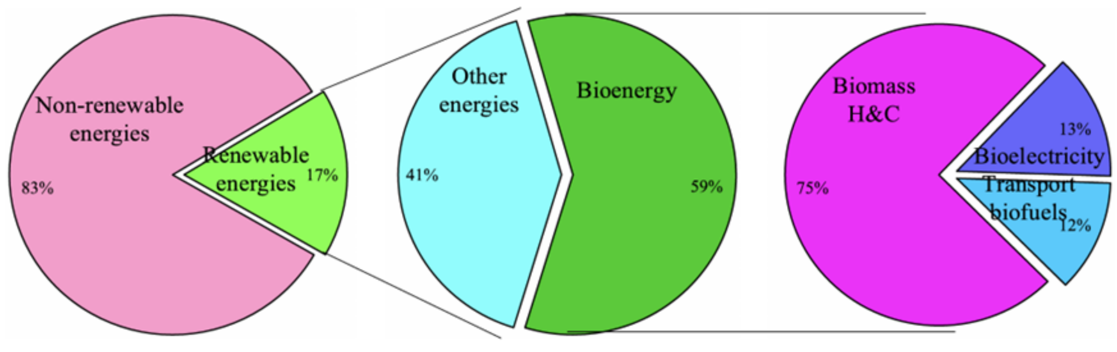

Figure 1. The EU's contribution of bioenergy to total final energy consumption [1]

Biomass, which refers to material derived from organic substances that are utilized for bioenergy production, is emerging as a rapidly developing clean energy with vast potential. Biodegradable product components, waste and residues from biological materials like forestry, agriculture, and associated industries, as well as biodegradable waste components, are all included in biomass [2, 3]. As it has a wide range of sources and various forms, the role of biomass energy is significant in reducing traditional fossil consumption and carbon dioxide emissions.

The utilization of biomass as an energy source for gas turbines began to develop in the 1990s. The technological and financial viability of using biomass gasification to generate electricity is covered by Bridgwater (1995), specifically focusing on wood [4]. Buhre et al. (2000) explore the adoption of a tiny gas turbine with a solid oxide fuel cell (SOFC) using a biomass gasifier, emphasizing the possibility of minimal emissions and high efficiency in electricity and heat generation [5]. Similarly, Hosseini et al. (2014) investigate a hybrid photovoltaic-biomass system with a gas turbine powered by biomass, noting the impact of the energy and energy efficiency of gas turbine inlet temperature [6]. Gholamian et al. (2016) conducted a parametric study on a biomass-based cogeneration system, highlighting the significance of pressure ratios for gas turbines and S-CO_2 turbines in system performance [7]. According to the study, burning biomass made of wood can result in lower CO_2 emissions and a maximum energy efficiency of 40.11%.

Additionally, Habibollahzade et al. (2019) suggest a novel setup for the production of energy and H_2 using a SOFC powered by biomass using a solid oxide electrolyzer and a gas turbine [8]. Some work also presents multi-criteria planning studies on hybrid biomass-derived systems employing SOFCs, gas turbines, and other components for energy generation, cooling and the creation of freshwater [9, 10]. Last but not least, Cao et al. (2021) provide a novel triple combined power cycle powered by solar and biomass that is connected with hydrogen generation, highlighting optimization with various goals depending on CO_2 emissions and electricity cost [11]. This work showcases the ongoing research and development in utilizing biomass-based gas turbine systems for producing power in an economical and sustainable manner.

The biomass-based gas turbine has great potential for its abundant raw materials and environmental friendliness. In this article, it will focus on biomass-based gas turbine systems for power generation. Different from traditional gas turbines, the system based on biomass can make a significant step toward replacing traditional fossil fuels.

2. Basic Principles of Biomass-based Gas Turbine System

2.1. Working Mechanism of Gas Turbine

The gas turbine was used for practical application and developed rapidly in 1939. The gas turbine is composed of three parts: compressor, combustion and turbine. The mechanism is that gas compressed in a compressor is fired in the combustor and after that, expands inside the turbine to begin working, causing the turbine to spin rapidly, transforming some of the chemical energy in the gas or liquid fuel into mechanical work and producing electrical power. Compared with steam turbines, gas turbines do not have a temperature difference between flue gas and working fluid, so the efficiency is enhanced significantly. Besides, the structure of a gas turbine is compact, quite smaller than the steam turbine. However, fuels used in gas turbines are always flammable gases and oils. If biomass gas is used as a fuel that can be acquired easily, it will reduce not only fossil energy consumption but also environmental pollution. So, biomass-based gas turbine is invented.

2.2. Gasification

Gasification is a method for converting carbon-based materials, such as biomass, into a gaseous product of H_2, CH_4, CO, and CO_2 through an array of chemical processes. Examples include wood and crop stalks, which turn into gaseous fuels under high-temperature conditions. Specific examples could be using wood chips and crop stalks. The gasification process that occurs in the gasifier has been modeled using the equations of thermodynamic equilibrium [12]. It is believed that the chemical reaction in the gas producer takes the typical form of

$$CH_XO_YN_Z + \omega H_2O + m(O_2 + 3.76N_2) \rightarrow x_1H_2 + x_2CO + x_3H_2O + x_4CO_2 + x_5CH_4 + x_6N_2 \quad (1)$$

Biomass materials react using gasifying agents such as supercritical water (SCW), oxygen, air, or steam in a gasifier at elevated temperatures. Fixed or fluidized beds, and entrained flow gasifiers are the most often utilized kinds of gasifiers [13].

2.3. Cleaning Process of Biomass Gas

Biomass gasification is a strong contender to replace traditional waste treatment methods like landfill incineration because it accepts ample feedstock and requires greater reaction conditions than pyrolysis and hydrothermal liquefaction technology. Gasification reactions involve a complicated procedure that includes gasification, pyrolysis, drying the feedstock, and partial combustion of intermediates to produce the desired products [13]. The cleaning process is a crucial step for synthesized natural gas produced through gasification (SNG). During the gasification process, it inevitably generates contaminants like tar, particle matter, and toxic gasses like sulfur, ammonia, and hydrochloric acid, which can cause serious issues for applications farther down the line [14]. For example, reducing tar content in the SNG lower 100mg/N·m^3 can achieve great success in commercial power generation as it can significantly reduce biomass consumption and logistics issues. Besides, environmental and energetic evaluations have been conducted to assess the production of hydrogen's effectiveness via lignocellulosic gasification process of biomass, highlighting the importance of gas cleaning and purification processes in achieving outstanding efficacy and minimal influence on the environment.

After extensive deliberation, the most practical choice for the vast manufacture of pure generating gas was found to be cleaning using catalytic hot gas. In addition to producing clean gas by destroying or adsorbing toxic gases and particles, the catalyst bed can also reconstruct tar molecules into gas [14]. Overall, advancements in biomass gas cleaning technologies exert crucial impacts on optimizing the efficiency and sustainability of biomass-to-energy conversion processes.

3. Recent Advances

3.1. A Geothermal Power Plant Enhanced by Biomass Integration for Freshwater Production

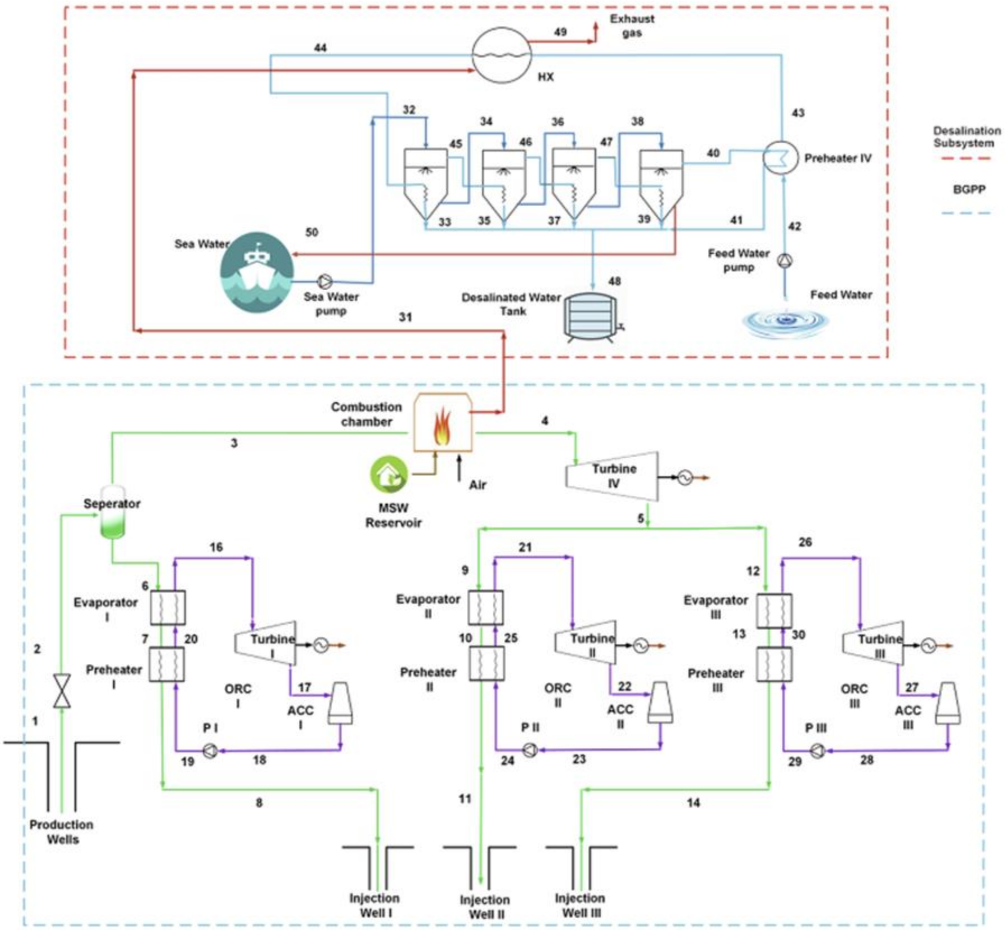

Figure 2. Diagram showing the suggested BGPP in conjunction with the desalination system [15]

It is highly practical that this system is intended to be situated in Aydın City, Turkey. As shown in Fig. 2, it is divided into 2 subsystems: BGPP and desalination subsystem. It utilizes geothermal energy and the combustion of municipal solid waste to generate electricity and desalinate seawater. The heat generated from geothermal energy and burning municipal solid waste is used for power generation as well as heating seawater for desalination, ultimately providing desalinated water for consumption [15].

3.2. Analysis

This system combines with geographical advantages ingeniously, which can enhance efficiencies to a great extent. The efficiencies are 13.86% of energy and 19.39% of exergy, respectively. Besides, costs according to the thermoformed analyses for power and freshwater exergy units are computed at 23.17 $/GJ and 16.97 $/GJ, respectively.

However, the clever combination of geology can also cause a severe problem. The application of this kind of system has extremely high requirements for the topography, which means it cannot be used on a large scale.

4. Future Trend of Biomass-based Gas Turbine System

The future trend is to be as efficient as possible and reduce fuel consumption. In order to reach this goal, a method easy to think of is to combine biomass-based gas turbine systems with other systems. In recent years, more and more scientists have raised novel combined systems. Two innovative solar-biomass hybrid power generating systems are proposed. They are modeled and contrasted with one another in addition to with the conventional system based on biomass that does not use solar energy. In both of the above systems, A gas turbine facility uses syngas together with a cycle of Rankine after biomass is first gasified in the gasifier process. The result is that the performances of combined systems are better than the standard system.

There are many innovative systems, such as a biomass-powered gas turbine by incorporating wind energy and injecting hydrogen, an SOFC with an integrated combustion engine and solid oxide electrolyzer that recycles anode and cathode using biomass, a three-generation combined solar-driven power cycle along with biomass energy coupled, etc. In the future, there will be more and more novel systems proposed.

5. Conclusion

Biomass-based gas turbines holds great potential in future power system, unlocking a green and renewable energy technology. It has great potential to apply to practical. Research indicates that biomass gas turbines can effectively utilize biomass resources, reduce carbon emissions, and improve energy efficiency. Therefore, biomass-based gas turbines have high environmental and economic benefits, with broad market prospects in replacing traditional fossil fuels. However, the limitations of the system are obvious, too. Many biomass-based gas turbine systems are limited by geological facts, especially for some combined systems. They can only be applied in specific situations, such as remote areas far away from people. Besides, how to use the electricity produced by the system in real life is also an unsolved problem because it is quite hard to integrate electricity into the grid.

Future research work can focus on the following directions: firstly, to further improve the efficiency and stability of biomass gas turbines to enhance their competitiveness in the energy system. One of the main methods to improve efficiency is to make use of the exhaust or reduce exhaust emissions. Besides, to expand the application range of biomass gas turbines and increase research on the utilization of different types of biomass resources to enhance their applicability and flexibility. In addition, efforts can be made to strengthen the integration research of biomass gas turbines with other energy technologies, promote the diversification and coordination of energy systems, and achieve the goals of efficient energy utilization and reduced carbon emissions.

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