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BIOGAS UTILIZATION IN THE BUILDING SECTOR: APPLICABILITY AND FUTURE PERSPECTIVES

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Abstract: Global climate change is one of the greatest challenges of our time for the European Union and its member states. Several attempts are underway to control and reduce global greenhouse gas emissions. Demand for electricity has increased in recent years, leading to an increased need for more diversified sources of energy supply. In this context, the construction sector has a significant impact on energy consumption and environmental concerns. In fact, buildings contribute significantly to greenhouse gas emissions because of their energy consumption for heating, cooling, lighting and other operational needs. Biogas produced from industrial, municipal, organic and agro-industrial waste is an alternative renewable energy source that can be used for bioenergy generation. Efficient management of such waste promotes the use of biogas by reducing the environmental problems associated with it. The problem can be examined both from an energy perspective, considering the use of renewable fuels, and from an environmental perspective, such as a decrease in emissions of a greenhouse gas. Biogas can be used for the cogeneration of electricity and heat in combined heat and power stations, potentially reducing the fuel consumption, compared to the conventional heat and power generation in separate plants. It is an innovative solution for obtaining electricity and heat simultaneously through a highly efficient process. By using cogeneration plants, energy efficiency can be maximised, as electricity and useful heat are produced simultaneously. Cogeneration systems play an important role in reducing greenhouse gas emissions, reducing costs and reducing environmental pollution while increasing system reliability and energy quality, reducing network overload and avoiding distribution losses. Net-zero energy buildings are one of the promising decarbonization attempts due to their potential of decreasing the use of energy and increasing the total share of renewable energy. This study provides valuable tips and practical advice to encourage sustainability in buildings and facilitate the transition to a low-carbon built environment.

Keywords: Energy transition, Renewable energy, Biogas, Heating buildings, Net-zero energy buildings

1. Introduction

Our lifestyles are based on energy, which is a source of economic progress, development, human well-being and improvement of living standards. The mitigation of CO_2 emissions and related global warming requires the exploration of alternative energies to reduce dependence on fossil fuels [1]. The current inclination is towards the development of innovative approaches for the production of bioenergy, biomaterials and chemicals that use biomass in order to replace fossil fuels and address future environmental, climate and energy challenges in a sustainable manner. Attention to energy sustainability is definitely focusing on energy conservation. Among the various energy-intensive sectors, construction is confirmed as one of the main users. Buildings account for 30 % - 40 % of total annual primary energy consumption in advanced countries and about 15 % - 25 % in developing countries [2]. Recent years have seen an evolution in building regulations and practices, which promote the use of sustainable materials, innovative construction techniques and renewable energy technologies. The energy industry is therefore currently the largest contributor to greenhouse gas emissions and, by extension, holds the key to reducing the most severe effects of climate change [3]. By focusing on sustainable energy resources, the use of limited fuel reserves can be reduced and greenhouse gas emissions curbed. This involves the use of renewable energy sources. Much research is focused on the development of different sustainable energy technologies, the combinations of which aim to optimise the energy efficiency of buildings and reduce carbon emissions. Among the available solutions for bioenergy production, biogas is rapidly emerging as a viable energy alternative due to its low initial investment and low operating costs, as well as its ability to utilize various types of organic biomass waste as feedstock [4]. The valorisation of resources that would otherwise remain unused and contribute to greenhouse gas emissions not only reduces the environmental impact of waste disposal, but also promotes the transition to a circular and low-carbon economy. Biogas is a gaseous biofuel obtained from the fermentation of biomass, in the absence of oxygen and at a controlled temperature, by microorganisms [5]. Biogas can be produced from various biodegradable materials such as the organic fraction of municipal solid waste, animal manure, energy crops, agro-food waste and agricultural products. Biomass is converted into energy during biogas production, through Anaerobic Digestion (AD) [6]. The evolution of biogas through AD takes place in four stages: hydrolysis, acidogenesis, acetogenesis and methanogenesis. The complexity of anaerobic digestion means that the entire process is particularly sensitive to several parameters, which must be constantly monitored to avoid possible inhibition of microorganisms, leading to lower biogas yields. A biogas plant is in fact capable of transforming different raw materials into biogas, through anaerobic transformations due to the activity of micro-organisms present in nature, but replicated on an industrial scale. The activity of microbial communities, together with factors such as pH, temperature and substrate type, are crucial for biogas production. This process is an efficient technology for handling organic materials and is expected to play a key role in renewable energy generation in the future. The energy generated by the process can be used as fuel in households, to produce heat and heat buildings, in vehicle power systems, and as a source of electricity. The main biogas utilization pathways are shown in Figure 1. The main applications of biogas include electricity generation, thermal applications such as cooking, heating and lighting, and the production of biofuels. In addition, its use helps reduce harmful emissions into the atmosphere [7]. Biogas also has the advantage of generating different types of fertilizers with high quality by-products [8]. Biogas shows considerable potential as a renewable energy source for both industrial and domestic applications, as well as being an efficient solution to the global energy crisis.

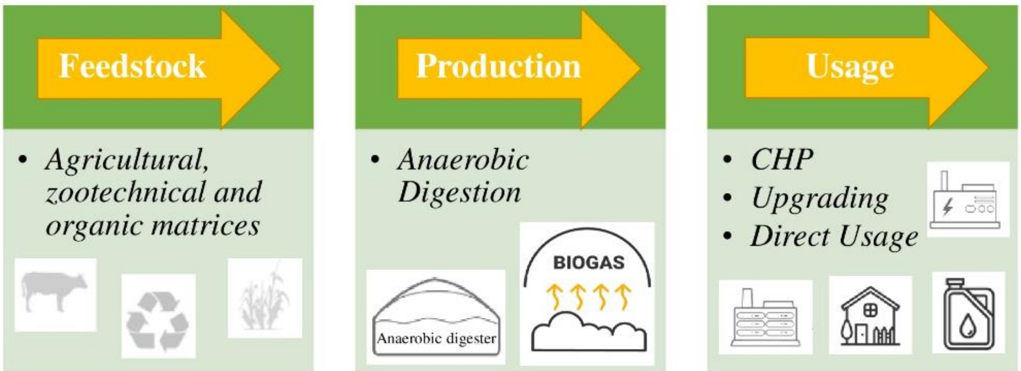

Figure 1. Potential utilization pathways for biogas.

Biogas is colourless and odourless and in addition to methane also contains carbon dioxide (CO_2) and a variety of other compounds depending on the source material used. Furthermore, the concentrations of the components also vary greatly depending on the biogas source. The gas mixture generally consists of 60 % methane and 40 % carbon dioxide, along with other secondary pollutants such as, nitrogen (N), oxygen (O), water vapor (HO), hydrogen sulfide (H_2S) and ammonia (NH_3) [9]. The typical composition of biogas is reported in Table 1. The elimination of various impurities and carbon dioxide is essential to generate better quality biogas with a higher calorific value [11]. The calorific value of biogas is determined by its CH_4 content, while the presence of impurities (CO, CO_2, N_2, H_2O, H_2S, NH_3), even in traces, determines its quality and possible utilization.

Table 1. Biogas constituents [10].

Mixture Components	Percentage %
Methane (CH_4)	40-80
Carbon dioxide (CO_2)	30-50
Hydrogen sulfide (H_2S)	1-4
Nitrogen (N_2)	0-1
Oxigen (O_2)	0-1
Water vapor	0-1
Iron (Fe)	Trace
Nichel (Ni)	Trace
Cobalt (Co)	Trace
Selenium (Se)	Trace
Molybdenum (Mo)	Trace
Tungsten (W)	Trace

Only clean and improved biogas is suitable for use in sensitive applications such as injection into the gas grid or use as vehicle fuel. Gas removal is used to increase the methane concentration in the biogas (reaching levels of over 90 %), otherwise the residue would release heat as flue gas. Upgrading processes involve the application of process techniques to remove impurities from biogas, mainly CO_2. According to Dalpaz et. al, as the concentration of methane in biogas increases, the resulting generated energy also increases, leading to a better use of fuel [12]. Purified biomethane can be used for various purposes, such as heating and electricity production, transport or injection into the natural gas grid after removal of contaminants, and it can also be stored for later use. This offers the advantage that it can be used spatially and temporally independently of its production. Feeding biomethane into the grid is already a common practice in countries such as Germany, Sweden, the Netherlands, Switzerland and Austria [13]. In Europe, biogas is mainly used to generate electricity and heat through cogeneration processes, as well as for the production of biomethane [14]. Taking these characteristics into account, biogas and its upgrade are considered a significant source of energy supply. Besides the obvious environmental aspect, these processes are fundamentally associated with biomass utilization. Thanks to the variety in the choice of organic materials that can be used as biomass, biogas can be used in plants of different sizes, both large-scale and domestic. This flexibility allows renewable energy production to be adapted to different contexts, contributing significantly to the reduction of CO_2 emissions. The growing interest in these renewable solutions is also evidenced by the increasing number of research studies conducted in recent years. The European Green New Deal emphasised the urgency of supporting climate-neutral solutions, promoting the adoption of renewable energies, improving energy efficiency and fostering the decarbonisation of the industrial and transport sectors [15]. In this context, biogas will play a crucial role in the decarbonisation process of the European energy system.

2. Biogas as an energy resource for sustainable and zero-emission buildings

In order to achieve sustainable development, the production and supply of clean energy has become a critical global issue. In this context, the building sector plays a vital role due to its high portion in energy consumption. The creation of innovative, environmentally friendly and efficient means of supplying the energy required by the building sector is currently one of the most important challenges. Biogas is recognised by the European Commission as one of the key solutions for both existing buildings and various industrial applications [16].

Biogas produced from industrial, municipal, organic and agro-industrial waste is a renewable alternative energy source increasingly appreciated for its versatility and sustainability. This is due to the significant availability of cheap raw materials and the variety of applications offered by biogas. Over 7000 MW of electricity is generated annually from biogas [17].

Biogas can be used directly for domestic purposes, as well as to generate energy and produce Fischer-Tropsch (FT) fuels. Biogas can also be used as fuel in combined heat and power (CHP) systems, powering engines or turbines for the combined production of electricity and heat, further increasing the overall efficiency of the system. The electricity generated can be fed into the grid to meet local demand and the heat can be used for district heating or integrated into the hot water system [18]. The CHP unit can be located close to the biogas source, or the biogas can be transported or piped to the CHP plant.

The use of biogas in cogeneration systems has great potential for both energy and heating. This approach meets energy demand through the use of local renewable resources. In almost every country in the world, the energy structure is in transition to integrate the use of renewable energies as far as possible into existing networks and offer systems that meet the needs of different sectors. Precisely for this reason, the sustainable future prospects of the building energy sector will have promising roles [19]. The connection of biogas plants to local energy networks has synergy effects with energy generation from other renewable sources and distributed cogeneration.

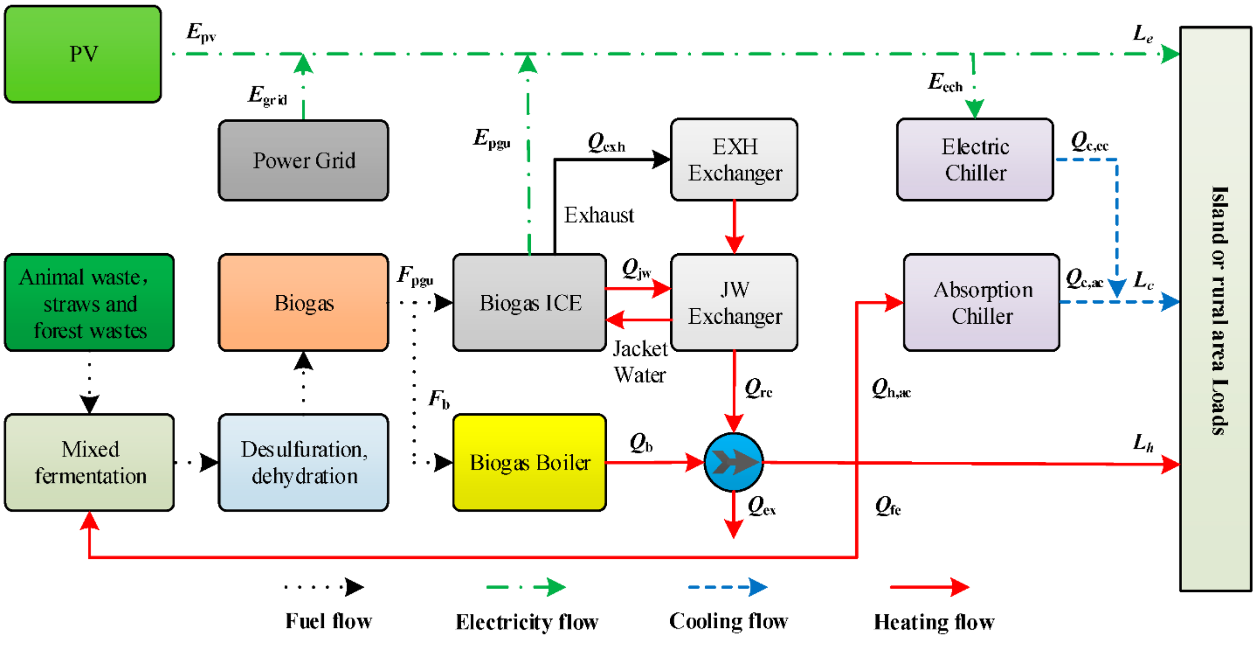

Figure 2. Energy flows of RES–CCHP system (source [20])

Building energy consumption for heating, domestic hot water, cooling and electricity needs constitutes more than 40 % of the total primary energy used globally [20]. Reducing energy use in homes would substantially reduce energy consumption and greenhouse gas (GHG) emissions. There have been many district heating and cooling systems installed worldwide, particularly in the countries like United States, Europe, China and Japan [21]. In order to realise a future perspective of energy sustainability of buildings, the NZEB (Nearly Zero Energy Building) concept offers a promising contribution. This concept is based on the general principle that a building meets most of its energy needs through on-site or nearby renewable energy sources [22]. The generation and use of renewable energy (e.g. wind, solar, geothermal and bioenergy) play a central role in the realisation of NZEBs [23]. Advancements in residential net-zero energy buildings could significantly reduce energy consumption and greenhouse gas emissions. There are many approaches to realising residential NZEBs, either by reducing the building's energy demand (through better building design and/or occupant behaviour) or by increasing renewable energy production [24]. However, the concrete implementation of NZEBs is still at a preliminary stage, especially those supported by distributed renewable energy sources. NZEB projects should consider available infrastructure connections, available energy sources, climatic conditions and economic factors.

The integration of biogas-powered cogeneration systems in net zero energy buildings can further improve the sustainability of these buildings. The use of biogas for the production of electricity and heat reduces external energy consumption and lowers energy costs, facilitating the transition to a decentralised and more resilient energy network. By simultaneously generating electrical and thermal energy, it utilizes the low-grade waste heat from the power generation cycle for subsequent heating applications, using a unified energy source [25]. The heat obtained from the cogeneration installation of the biogas plant is used to maintain the process temperature of the fermenter, but its excess can be used for other processes, such as heating buildings. Another method is to transmit or store heat and produce cold [26]. When the recovered low-grade heat is used not only for heating but also for cooling, the system is considered a trigeneration system, also known as a combined cooling, heating and power (CCHP) system, as illustrated in Figure 2. Research has shown that the use of biomass in the CCHP system offers advantages in terms of flexibility, conversion efficiency and commercial possibilities [27]. In light of this, the on-site use of biogas energy for heating/cooling can be an economically and environmentally attractive solution to meet both the growing demand for energy and the environmental challenges of waste management. Cogeneration systems mainly consist of an internal combustion engine connected to a generator and a heat recovery system, which uses heat exchangers to collect thermal energy from the waste system. The combination of electricity and heat generation optimises the potential of biogas. It is now known that, at higher levels of methane concentration, higher efficiency in combined heat and power generation is achieved [11]. The use of biogas in combination with combined heat and power systems and zero net energy building technologies optimises the use of local resources, reducing dependence on external energy sources and helping to reduce CO_2 emissions.

The applicability of biogas in building heating may depend on several factors, including the availability of organic material for biogas production, the presence of anaerobic digestion plants nearby and the presence of biogas distribution networks. It is also important to emphasise that biogas could be an excellent alternative as an energy source for GEHP (Gas Engine Heat Pump) systems. The feasibility of implementing GEHP systems makes biogas a globally replicable solution to be used for heating and cooling. The use of GEHP with biogas contributes to the achievement of European energy strategies and promotes the widespread use of biogas [28]. The prospects for the use of biogas in building heating thus look promising, thanks in part to the increasing global production of biogas and ongoing efforts to develop more efficient and economical technologies for its production. The practical aspects of large-scale renewable heating systems offer tangible evidence of the economic and environmental benefits of using biogas, making it an increasingly advantageous solution for the design of near-zero energy buildings. Therefore, improving the energy performance of residential buildings will reduce energy consumption (approaching net zero energy) and minimise electricity consumption. These concepts will be fundamental in defining energy saving and climate change targets in the building sector.

3. Conclusion

It is now well known that energy sustainability has become increasingly important for the conservation of energy resources. The need to increase energy production from renewable sources leads to the development of innovative ‘green’ technologies. The construction industry is one of the main energy-consuming sectors. Today, building industries are moving towards near-zero energy buildings to ensure energy sustainability. Extensive studies have been carried out on the development of NZEBs with different types of renewable energy. However, practical implementation is still at an early stage, especially for those based on distributed renewable energy sources. The potential of biogas in the transition to net-zero emissions is a topic of growing interest and importance, especially in the context of sustainability and reduction of greenhouse gas emissions. With its application in power generation and fuel production, biogas serves as a substitute for fossil fuels in electricity generation and thermal applications. Biogas is also an excellent resource in terms of energy storage and integration. Its ease of storage and production independent of environmental conditions makes it a perfect complement to other renewable sources, enabling effective integration between different microgeneration systems.

The prospects for the use of biogas in building heating systems are considered promising applications, due to the ever-increasing production of biogas and ongoing efforts to develop more efficient and economical technologies for its production. These characteristics make biogas a strategic choice for communities and industries aiming to transition to more sustainable, low-emission energy models. Biogas finds wide application in CHP and CCHP systems, which are designed to convert the chemical energy contained in biogas into electrical and thermal energy simultaneously and highly efficiently. The integration of CHP systems, zero net energy buildings and biogas is an effective solution for reducing greenhouse gas emissions, improving energy efficiency and promoting sustainability. By combining these approaches, a synergy can be achieved that not only leads to improved energy efficiency, but also supports the goal of transition to a decarbonised and sustainable energy system. Cogeneration systems play an important role in reducing greenhouse gas emissions, reducing costs and reducing environmental pollution while increasing system reliability and energy quality, reducing network overload and avoiding distribution losses. NZEBs decrease energy consumption by reducing the energy needs of buildings through energy efficiency solutions and by using renewable energy technologies to cover the remaining needs. Reducing greenhouse gas emissions, together with the use of local renewable resources such as biogas and optimising building efficiency, is an important step towards a low-carbon future. The combination of these solutions is key to promoting and building a green, resilient and more equitable energy future for future generations. As technology continues to evolve, the successful integration of renewable energy systems will play a key role in the future of building design that is not only highly energy efficient, but also meets environmental sustainability goals, reducing ecological impact and optimising the use of natural resources. Future research should focus on how to improve the integration of renewable energy generation technologies in the design and analysis of NZEBs. At the same time, it is essential to promote incentive policies, foster collaboration between the public and private sectors, remove economic barriers and enhance sustainability education. These aspects are crucial for achieving the EU's energy goals and accelerating the transition to a low-carbon environment.

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