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Overview and evaluation of Biogas, Biomethane, and Purification Methods

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ABSTRACT. Biogas and biomethane are renewable gases that should be strongly considered to accelerate decarbonization and reduce greenhouse gas emissions in many sectors. In addition, biomethane is important to provide renewable and more economical energy to consumers using the existing gas infrastructure. Moreover, biomethane can be easily stored and can be used as a balancer for intermittent renewable energy sources such as solar and wind. The EU considers bio-CNG (compressed), bio-LNG (liquefied) fuels to be an effective method in reducing emissions. Therefore, Europe leads the world in biogas and biomethane production. In this study, evaluations and general views were made about the definition of biogas and biomethane, production amounts in the world and purification methods (treatment) of biogas. The main purpose of the current study is to emphasize that biogas provides an important solution for decarbonization and that its usage areas can be expanded by purifying it as biomethane.

Keywords: Biogas, Bomethane, Purilification, Decarbonization

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1. INTRODUCTION

Increasing global energy demand and the rise of global warming have increased the importance of renewable energy sources. According to the “BP World Energy Statistical Review 2022, 71st edition” report, while total world energy consumption was 587 EJ in 2019, it decreased to 564 EJ in 2020 due to the COVID-19 pandemic, which had a global impact. However, with the global recovery from the pandemic, total world energy consumption increased to 595 EJ in 2021, exceeding the consumption of 2019 [1]. According to the "Energy Institute Statistical Review of World Energy 2024, 73rd edition" report, total world energy consumption continued to rise. According to this report, total world energy consumption was 607 and 620 EJ in 2022 and 2023, respectively [2]. In these reports, the sources that meet the world's energy needs in all years are oil, coal and natural gas, respectively. On the other hand, when comparing the data of 2019 and 2023, the change in the resources that meet the world's energy needs is seen as nuclear energy, hydroelectricity, oil, natural gas, coal, renewables energy -3.5, -1.2, 2.2, 2.7% 4.3% 59.4%, respectively. Despite the decrease in hydroelectricity and nuclear energy, the rates of hydroelectricity, oil, natural gas, coal, and renewable energy resources in meeting the world's energy needs have increased. The increase rate of renewable energy sources is striking (Table 1 and Figure 1.a) [1].

Table 1. Primary energy consumption

Exajoules (10^{18} Joule)	**2019**	**2020**	**2021**	**2022**	**2023**	**Energy consumption growth rate between 2019-2023**
Nuclear Energy	25.5	24.4	25.3	24.1	24.6	**-3.5%**
Hydro Electricity	40.2	41.1	40.3	40.6	39.7	**-1.2%**
Oil	192.1	174.2	184.2	191.6	196.4	**2.2%**
Natural Gas	140.6	138.4	145.4	144.3	144.4	**2.7%**
Coal	157.3	151.1	160.1	161.5	164.0	**4.3%**
Renewables	31.7	34.8	39.9	45.2	50.6	**59.4%**
Total	**587.43**	**564.01**	**595.14**	**607.35**	**619.63**	**5.48%**

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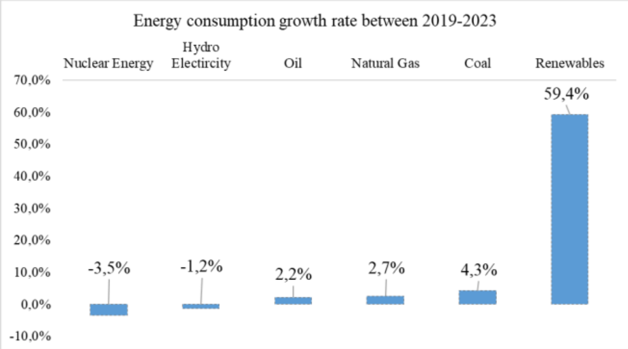

Fig. 1.a. Energy consumption growth rate between 2019-2023

The percentage change of the resources that meet the annual energy consumption by years is presented in Fig1b. According to this figure, it is clearly seen that while the rates of other energy resources other than renewable energy resources fluctuate over the years and can be considered relatively constant, renewable energy resources increase their place in annual energy consumption linearly.

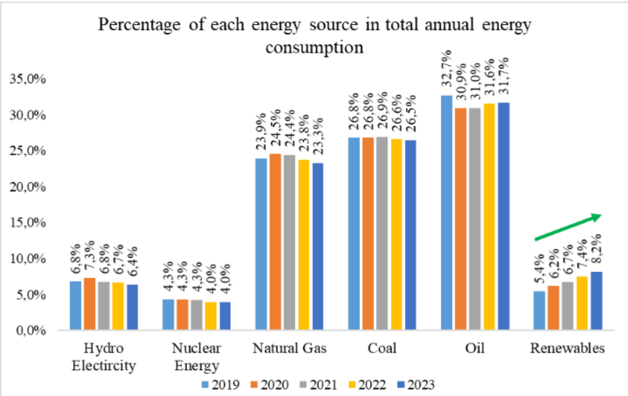

Fig. 1.b. Energy consumption growth rate between 2019-2023

Another report supporting these results, “U.S. According to the Energy Information Administration (EIA), the International Energy Outlook 2019 report, it is predicted that the world energy need will increase by 50% in 2050, and the Asian continent will have the largest share in this increase. According to the same report, it is emphasized that renewable energy sources will be the primary energy source in 2050 [3] (Fig.2).

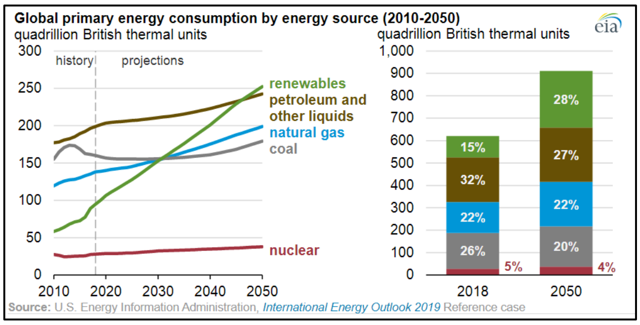

Fig. 2. Global primary energy consumption by energy source 2010-2050 (Source: U.S. Energy Information Administration, International Energy Outlook 2019 Reference case) [3]

Solar and wind energy are the leading sources of renewable energy. However, the production of biofuels as another renewable energy source is increasing rapidly. While the total production of bio gasoline and bio diesel was 1174 tboe/d in 2011, it increased to 1747 tboe/d (Thousand barrels of oil equivalent per day) in 2021 [1]. The amount of energy produced from biogas in the world (electricity production capacity) increased from 9.3 GW in 2010 to 17.7 GW in 2018. According to the IEA (2018) report, biogas production today is approximately 35 Mtoe. 3.5 Mtoe of the biogas production amount is converted into biomethane (Mtoe=11.63 TWh) [4].

As can be understood from the reports, the world attaches great importance to renewable energy sources. In addition, in 2015, in the Paris Agreement at COP21, it was decided to reduce greenhouse gas emissions and keep global warming below 1.5 degrees Celsius compared to pre-industrial levels. This decision increases the importance of renewable energy sources [5].

In this report, Biogas and Biomethane, one of the renewable energy sources whose importance is increasing rapidly, will be discussed. Biogas is the first product of an anaerobic digestion plant. It consists primarily of methane and can be used to generate heat or electricity. Biogas generally contains 45% - 85% methane (CH4) and 25% - 50% carbon dioxide (CO2). After biogas is purified (explained in detail in section 4) from other compounds such as nitrogen dioxide (CO2), oxygen dioxide (O2), hydrogen sulfide (H2S) or water vapour (H2O), it turns into biomethane, which consists almost entirely of methane, between 95% - 99%. As mentioned above, the main difference between biogas and biomethane is related to the amount of methane it contains. The main purpose of the current study is to emphasize that biogas provides an important solution for decarbonization and that its usage areas can be expanded by purifying it as biomethane.

2. BIOGAS AND BIOMETHANE

Biogas is formed by the biodegradation of organic wastes in an oxygen-free environment. Potential feedstocks to produce biogas are biological waste materials, agricultural residues from some plants, grains and crops, animal manure, algae biomass, food waste, municipal waste, fruit and vegetable waste, and raw materials such as cellulose-containing substrates (Fig. 3) [6].

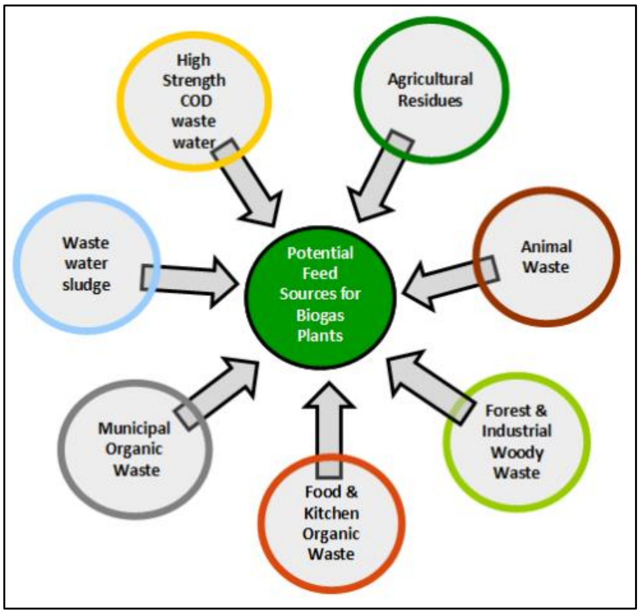

Fig. 3. Biogas raw materials [6]

The feedstock types actually used for biogas production in the worldwide are shown in Fig. 4. According to the IEA's report (2018), biogas currently production is about 35 Mtoe (Mtoe=11,63 TWh). Europe takes the first place in biogas production and the most frequently used feedstocks are Crops, Animal manure and municipal waste [4].

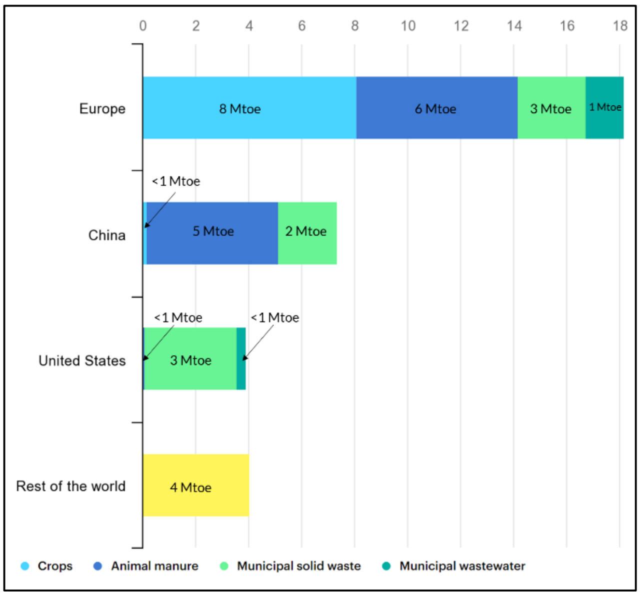

Fig. 4. Biogas production by region and by feedstock type, 2018 [4]

The substances in the biogas may differ according to the raw material used during anaerobic digestion. The main components of biogas are 55-70% methane and 30-40% carbon dioxide. In addition, biogas contains pollutants such as moisture (H2O), siloxanes, VOC (volatile organic compounds), NH3, O2, N2, and CO. The ratio of these ingredients may vary depending on the type of raw material. For example, while the ratio of H2S and NH3 is high in biogas produced from farm waste, siloxanes are high in biogas produced from sewage waste [7,8]. The lower heat value of methane gas (LHVmethane) is 49.93 kJ/kg. The biogas lower heat value can be calculated according to this equation 1, [9]. The LHV value of biogas with 70% methane content can be calculated as 34.95 kJ/kg.

$$LHV_{biogas}=LHV_{methane}\ x\%CH_4 \qquad (1)$$

Biomethane can be obtained by applying various purification and upgrading techniques to Biogas. After these processes, Biomethane containing 95-97% methane can be obtained [8, 10]. Fig. 5 shows the usage areas of biogas and Biomethane. While biogas generally can be used for heating and electricity generation without enrichment, for vehicles and natural gas pipelines have to be use Biomethane.

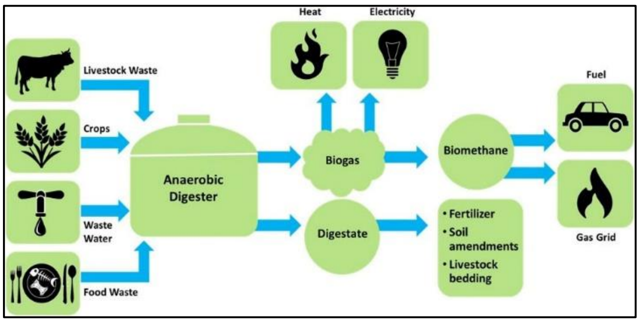

Fig. 5. Biogas and Biomethane usage areas [11]

3. FORMATION OF BIOGAS

Anaerobic digestion consists of three main processes (Fig. 6). These are Hydrolysis, Acidification and methanogenic processes. These three processes occur simultaneously in the digestion reactor. But these biochemical processes develop in conjunction with each other. Because the substrate of one process is the food of another process. Methane is produced in large quantities in the last phase. The first process of anaerobic digestion is hydrolysis. In this process, carbohydrates, fats, and proteins are converted into long-chain sugars, fatty acids, and amino acids. The second process, the acidification phase, can be examined in two separate groups as acidogenesis and acetogenesis. Acidogenesis bacteria convert the long sugar chains, amino acids and fatty acids formed in the hydrolysis process into alcohols, CO2, H2, VFA (Volatile Fatty Acid), Propionic, acetic and butyric acids. Acetogenesis bacteria convert acetogenesis products to acetates, CO2 and H2. In the last process, methanogenesis, methanogenic bacteria produce 70% of methane from acetate and the rest from H2- CO2 conversion. The most sensitive process is methanogenesis because methanogenic bacteria are very sensitive to parameters such as temperature, pH value and feeding rate. In this way, biogas is produced, all these processes take place at the same time during biogas production, so process monitoring should be done very well in the facilities [12, 13, 14].

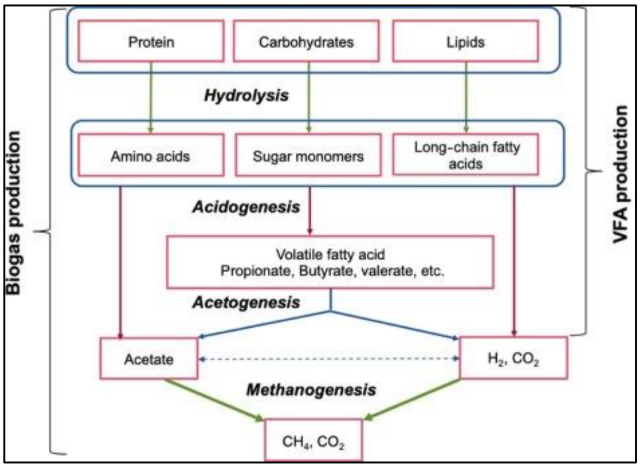

Fig. 6. Formation of Biogas [12]

4. Biogas Purification and Upgrading Methods to Convert to Biomethane

There are basically two ways to produce Biomethane, upgrading biogas and Biomass gasification [15]. Biomass gasification is a process applied to produce Biomethane from dry woody biomass. It consists of stages such as drying, pyrolysis and gasification. There are two equal gasification management. High temperature gasification is done above 1300 degrees Celsius, while low temperature gasification is not done at 800 - 1000 degrees Celsius. Low-temperature gasification is more efficient [16, 17]. Upgrading biogas is the process of removing carbon dioxide and other pollutants from biogas containing around 60% methane and bringing the methane ratio to 95% and above [18]. Currently, 3.5 Mtoe (Mtoe=11.63 TWh) Biomethane is produced worldwide. 90% of this Biomethane produced was obtained by upgrading Biogas [4] (Fig. 7).

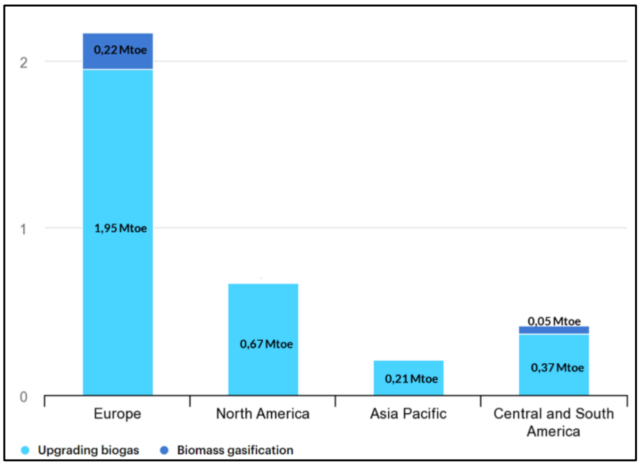

Fig. 7. Biomethane production that is upgraded in selected regions, 2018 [4]

Before biogas can be used, it must be cleaned to protect equipment such as engines, storage tanks and pipelines. We can divide this cleaning process into two main groups as purification and upgrading. Purification is done to remove various pollutants such as Sulphur, while upgrading is done to increase methane content. After upgrading, the biogas converts to Biomethane. Since Biomethane is rich in methane content, it is a gas that can be used in natural gas pipeline [19].

According to the IEA Bioenergy Technology Collaboration Program - Upgrading Plant List 2019 report, there are 673 upgrading plants that produce biomethane by increasing the methane concentration of the biogas to 96% by using various upgrading methods (Fig. 8). Germany ranks first in the world in terms of the number of plants that produce biomethane by upgrading biogas [20].

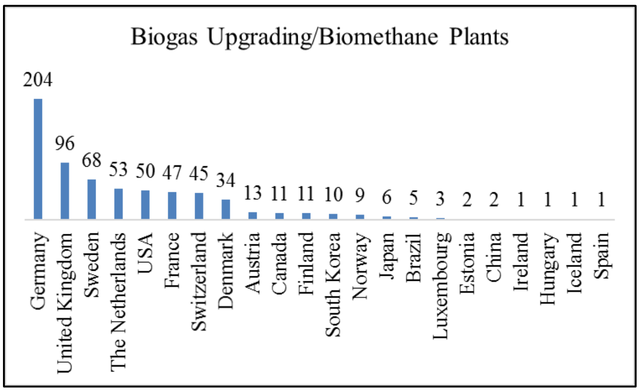

Fig. 8. Biogas Upgrading/Biomethane Plants

Of the 673 plants cited in the report, the upgrading methods 601 used to produce biomethane were cited. Considering these 601 facilities, it is seen that the most used upgrading methods to produce biomethane are water scrubbing (32%), membrane separation (30%), chemical/amine scrubbing (18%), pressure swing adsorption (PSA, 14%), organic physical scrubbing (3%) and cryogenic upgrading (2%), (Fig. 9). Most of the biomethane produced by different upgrading methods is used in natural gas grid. In addition, 11% of the biomethane produced is used as vehicle fuel (Fig. 10), [20].

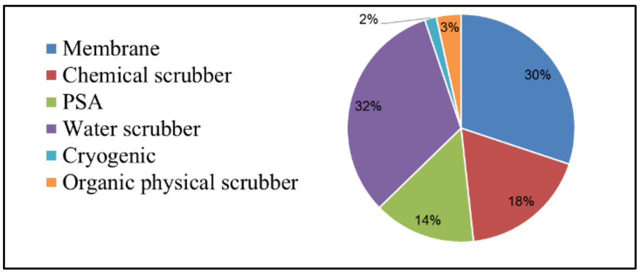

Fig. 9. Upgrading methods used in the world

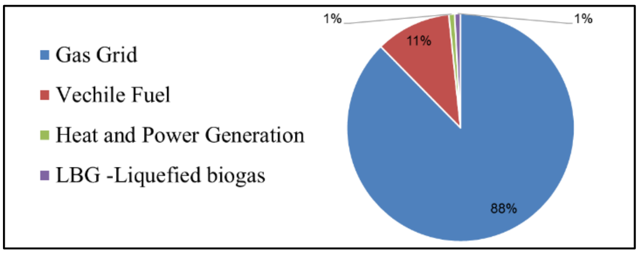

Fig. 10. Utilizations of Biomethane

4.1. Biogas Purification

4.1.1 Desulphurization (Removal of H_2S)

H2S is a very harmful and toxic gas for human health. May cause damage to the blood, nervous and respiratory systems. It is colorless and has a rotten egg odor. It is explosive when reacted with oxygen. When burned, it produces corrosive and environmentally harmful emissions [21]. According to EN 16723-1:2016 and EN16723-2:2017 standards, a maximum of 20 and 5 mg/m3 of sulfur is allowed in the biogas content, respectively. Techniques such as microaeration, adsorption, absorption and biofiltration are used to purify H2S.

I. Microaeration

The purification of H2S is an effective and simple method in the production of biogas by anaerobic digestion. In this method, it is aimed to oxidize sulfur and turn it into elemental base by giving oxygen to the digester in a controlled manner. Elemental sulfur can then be taken from the digester along with the sludge [22].

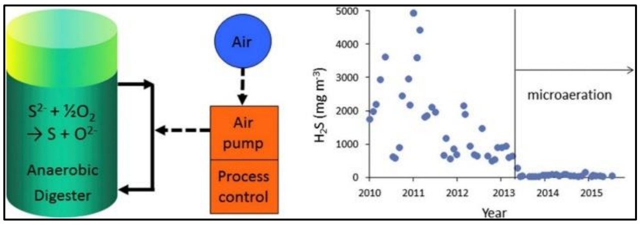

Fig. 11. Microaeration, 2018 [22]

II. Adsorption Method for Removal H2S

It is the collection of one or more substances on a surface to form a film layer and bonding with van der Waals forces. It can occur at gas/solid, liquid/solid, or immiscible liquid/liquid interfaces. The presence of any substance on a liquid or solid surface in a higher concentration than the main phase is called adsorption. The substance whose concentration increases on the liquid or solid surface is called adsorbate, and the substance that adsorbs is called adsorbent [23]. Activated carbon and sodium hydroxide washing are the methods used for adsorption [18]. Fig. 12 shows the application of microaeration and adsorption methods together.

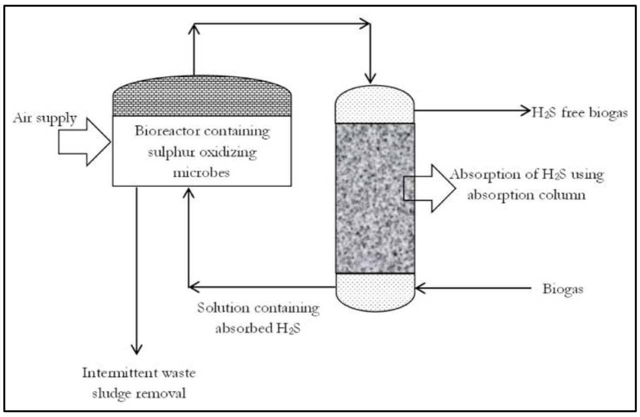

Fig. 12. Application of microaeration and adsorption methods together [24]

III. Absorption Method for Removal H_2S

Removal of H_2S with this method is based on the direct washing of biogas with water or its interaction with suitable organic solvents. H_2S is absorbed by water and converted to elemental sulfur. This method is also called the water scrubbing method [24].

IV. Bio filters

The biofilter consists of filtered microorganisms in the form of a film. Mixtures of substances such as soil, peat and manure form the content of the biofilter. By biofiltration, H_2S in biogas is converted into oxygen and biomass, carbon dioxide, metabolic by-products and sulfur monoxide with the help of microbes in the biofilter [25].
It is very important to remove H_2S from Biogas. However, other pollutants that must be removed from biogas include halogens, oxygen, nitrogen and siloxanes.

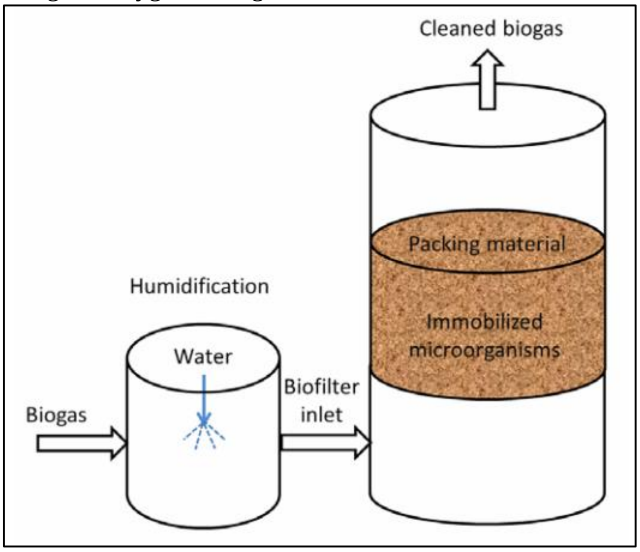

Fig. 13. Representation of a biofilter [26]

4.1.2 Water Removal

The removal of water is important in terms of preventing corrosion at the gas usage points. The water removal method can be considered in two ways as physical and chemical drying. The physical drying method is based on the logic of cooling and condensation. Condensed water droplets are collected and removed. It can be used in cyclone separators by making use of centrifugal force. In addition, the condensed water from the taps in the biogas pipes can be collected and removed. Chemically drying is done by adsorption and absorption methods. Silica, activated carbon, aluminum oxide or magnesium oxide can be used for drying in the absorption method. In the absorption method, water is removed by using triethylene glycol and hygroscopic salts [8]. Biogas purification methods are shown in Table 2 comparatively.

Table 2. Comparison of biogas purification methods [19]

Method	H_2S removal efficiency	Approximate annual operating cost (€/ [1000 Nm³/h])	Advantages	Disadvantages
In-situ microaeration	90 – 99 %	20 300	• No additional costs for separate unit • No addition	• Elemental sulphur can be oxidized to sulphates which limits CH_4 content •Suphuric acid can form causing corrosion in the digester
Impregnated activated carbon	95 – 99 %	% (overall adsorption cost) 60 000	• 40 – 60 times more efficient than activated carbon • Can remove multiple contaminants (H_2S, siloxanes, water)	• Decreases ignition temperature of carbon which can cause it to self-ignite • Difficult to regenerate
Iron oxide	99.98 %		• Highly effective and efficient method	• High operation costs • Highly chemical intensive
In-situ chemical precipitation (iron salts)	N.A	70 000	• Easy to monitor, handle and implement	• Difficult to control degree of H_2S removal • Can impede formation of CH_4
Bio scrubber	98%	130 000	• Can be used for biogas with up to 30 000 mg/m³ H_2S • Highly efficient with little clogging issue	• High operation costs • Difficult to achieve efficiencies >98 % • Can wash off slow growing microorganisms
Biofilter	90 – 99 %	560 000	• Low energy and equipment requirements • No additional chemicals	• Accumulation of biomass on surface • Large carbon footprint
Bio-trickling filter	100 – 200 ppm	100 000	• No CH_4 depletion • No additional chemicals • Methane enrichment (conversion of CO_2 to CH_4)	• High amount of air bubbles in the biogas

4.2. Biogas Upgrading

4.2.1. Water Scrubbing

This method takes advantage of the solubility difference of methane and carbon dioxide in water. According to Henry's law, the solubility of carbon dioxide in water at 25 degrees Celsius is 0.034 M/atm, while the solubility of methane is 0.0013 M/atm. In other words, carbon dioxide is much more water-soluble than methane. Since this solubility difference will be better at low temperature and high pressure, this environment should be tried to be provided in the water scrubbing method. In this method, biogas is compressed around 6 bars after H2S removal. While the biogas is supplied to the absorption tank from the bottom side, the water is sprayed from the top side. Thus, while carbon dioxide dissolves in water, methane can be taken from the top of the tank. The methane from the top of the tank can be compressed into gas line pressure with a methane ratio of around 98% after drying and purification from Volatile Organic Compounds. During washing, about 5% methane and carbon dioxide can be dissolved in water. For this reason, this water is taken into a flash tank with 2-4 bar pressure. In this flash tank, methane is separated and circulated. The water saturated with the remaining carbon dioxide is taken into a desorption tank. Here, carbon dioxide is separated from the water and the water is sent back to reuse. About 3% of methane may be lost in the result of this method [27-29].

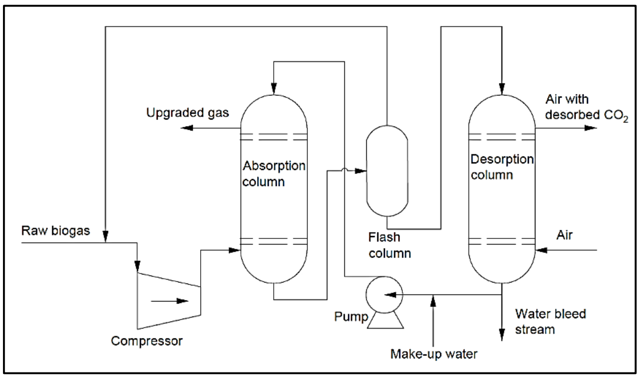

Fig. 14. Water Scrubbing [30]

4.2.2. Organic Physical Scrubbing

Organic physical scrubbing method is very similar to water scrubbing method. Organic solvents such as polyethylene glycol are used in this method. Because carbon dioxide is more soluble in these solvents than water. In this method, the flash tank used in the water scrubbing method is not used. Commercial liquids with names such as Selexol and Gensorb are used in biogas upgrading plants [18, 29].

4.2.3. Chemical/Amine Scrubbing

The amine scrubbing method is similar to the water scrubbing method in terms of operation. However, in this method, organic amines such as diethanolamine, diglycolamine, monoethanolamine and ethyldiethanolamine are used as solvents instead of water. These amines absorb more carbon dioxide than water and can work efficiently even at atmospheric pressure. Therefore, in this method, the biogas may not be compressed before scrubbing [27, 29].

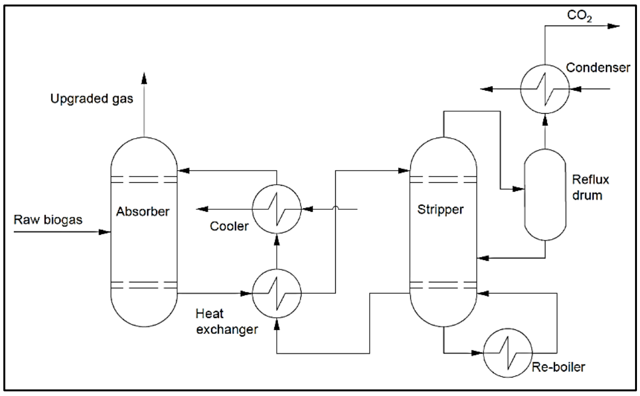

Fig. 15. Chemical/Amine Scrubbing [30]

4.2.4. Pressure Swing Adsorption (PSA)

In this method, adsorbing materials such as silica gels, activated carbon and zeolites are used at high pressure. When the adsorbing material becomes saturated in a tank, the raw gas is sequentially taken to another tank where the adsorber is regenerated, and the pressure is sequentially reduced. In this way, carbon dioxide is removal from the biogas [18, 31, 32].

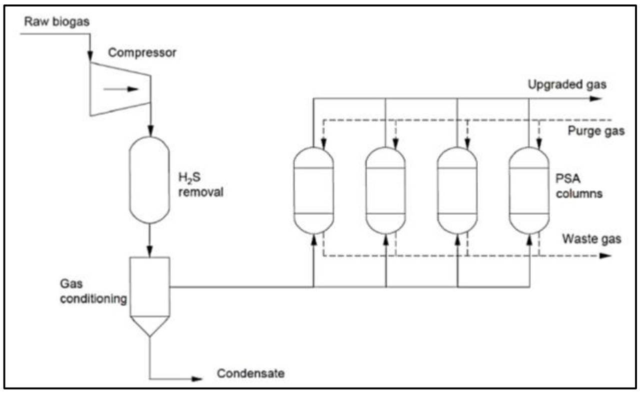

Fig. 16. Pressure Swing Adsorption [29]

4.2.5. Membrane Separation

In this method, different chemical structures are separated along a membrane according to their velocity. Before the raw biogas enters the membrane, the water and H2S in it are removed. Carbon dioxide separation is made in the membrane to a large extent. Unlike other upgrading methods, higher pressure is used in the membrane method. The pressure used is at the level of 9-19 bars [29].

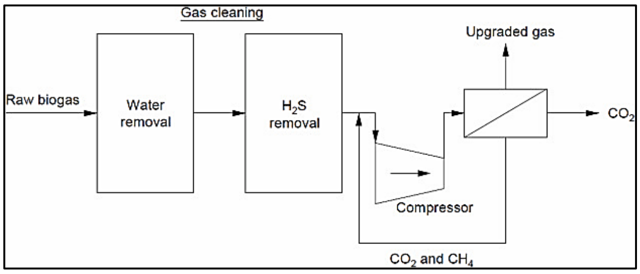

Fig. 17. The Membrane Separation [29]

4.2.6. Cryogenic Upgrading

Cryogenic upgrading is the separation process by utilizing different liquefaction temperatures of the components in the biogas. There are two different application methods. The first is based on a gradual reduction in temperature, keeping the pressure constant at 10 bars. First, the biogas is cooled to -25 degrees Celsius. At this temperature, water, H2S and siloxanes are separated. Afterwards, it is cooled to -55 degrees Celsius and carbon dioxide decomposition begins. By reaching -85 degrees, almost all of the carbon dioxide is decomposed [33]. The second method is again based on the liquefaction of gases at different pressures and temperatures. With this method, in order to remove carbon dioxide from the biogas, the gas is cooled down to -75, -85 degrees Celsius and compressed to a pressure of 80, 110 bar at the same time. Since this process is done gradually, carbon dioxide and methane can be easily separated from each other because they have different liquefaction conditions. Biomethane containing 99% pure methane can be produced by cryogenic upgrading method. Methane loss during upgrading is less than other methods, but requires more equipment [33-35].

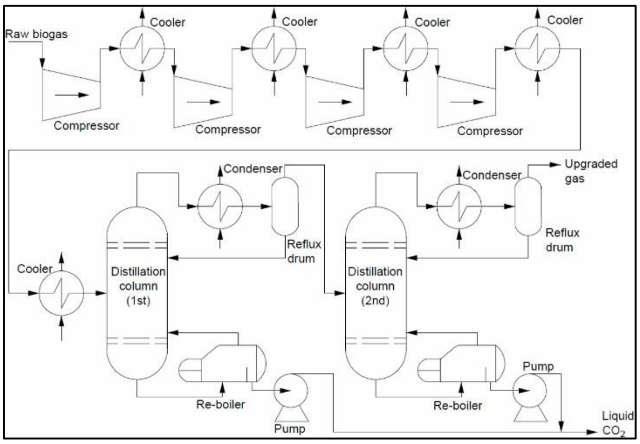

Fig. 18. Cryogenic Upgrading [29]

Table 3 shows the parameters of biogas upgrading methods comparatively. This table also indicates the requirements, efficiency and operating conditions of the upgrading methods.

Table 3. Comparison of biogas upgrading methods [18, 19]

Parameters	PSA	Water Scrubbing	Organic Physical Scrubbing	Chemical/ Amine Scrubbing	Membrane Separation	Cryogenic Upgrading
Pre-cleaning /H_2S removal	Yes	No	No	Yes	Possible	No
Working pressure (bar)	4 - 7	4 - 7	4 - 7	No pressure	9 - 19	80 - 110
Methane loss	<3%	<2%	<4%	<0.5%	<5%	<0.1%
Heat requirement (°C)	No	No	55 - 80	160		(-75) / (-80)
Methane content in upgraded gas	96 - 98%	95 - 98%	93 - 98%	99%	90 - 99%	99%
Electricity consumption (kWh/Nm^3)	0.25	<0.25	0.24 - 0.33	<0.15	0.18- 0.35	0.18 - 0.25

5. CONCLUSION

In this study, the change in world energy consumption, the place of renewable energy in world annual energy consumption and biogas and biomethane, which are increasingly important renewable energy sources, were examined.

1- While the world's annual energy consumption was 587.43 EJ in 2019 (before the Covid 19 pandemic), it increased by 5.48% and reached 619.63 EJ in 2023.

2- The amount of renewable energy resources in the world's annual energy consumption increased from 31.7 EJ in 2019 to 50.6 EJ in 2023, an increase of 59.4%.

3- The electricity generation capacity from biogas, which is among the renewable energy sources, was increased from 9.3 GW in 2010 to 17.7 GW in 2018.

4- Approximately 35 Mtoe of Biogas was produced in the world in 2018. Some of this amount was upgraded to 3.5 Mtoe of biomethane (1 Mtoe = 11.63 Twh).

5- Biogas is mostly produced in Europe. Following Europe, China and the USA come respectively. Germany has the most facilities in the world that upgrade and convert biogas into biomethane.

6- The methods used in the world to upgrade biogas to biomethane are water scrubber, membrane, chemical scrubber, PSA, organic physical scrubber and cryogenic, respectively.

7- Biogas and biomethane production, which are among the renewable energy sources, are promising for the future according to published international reports.

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