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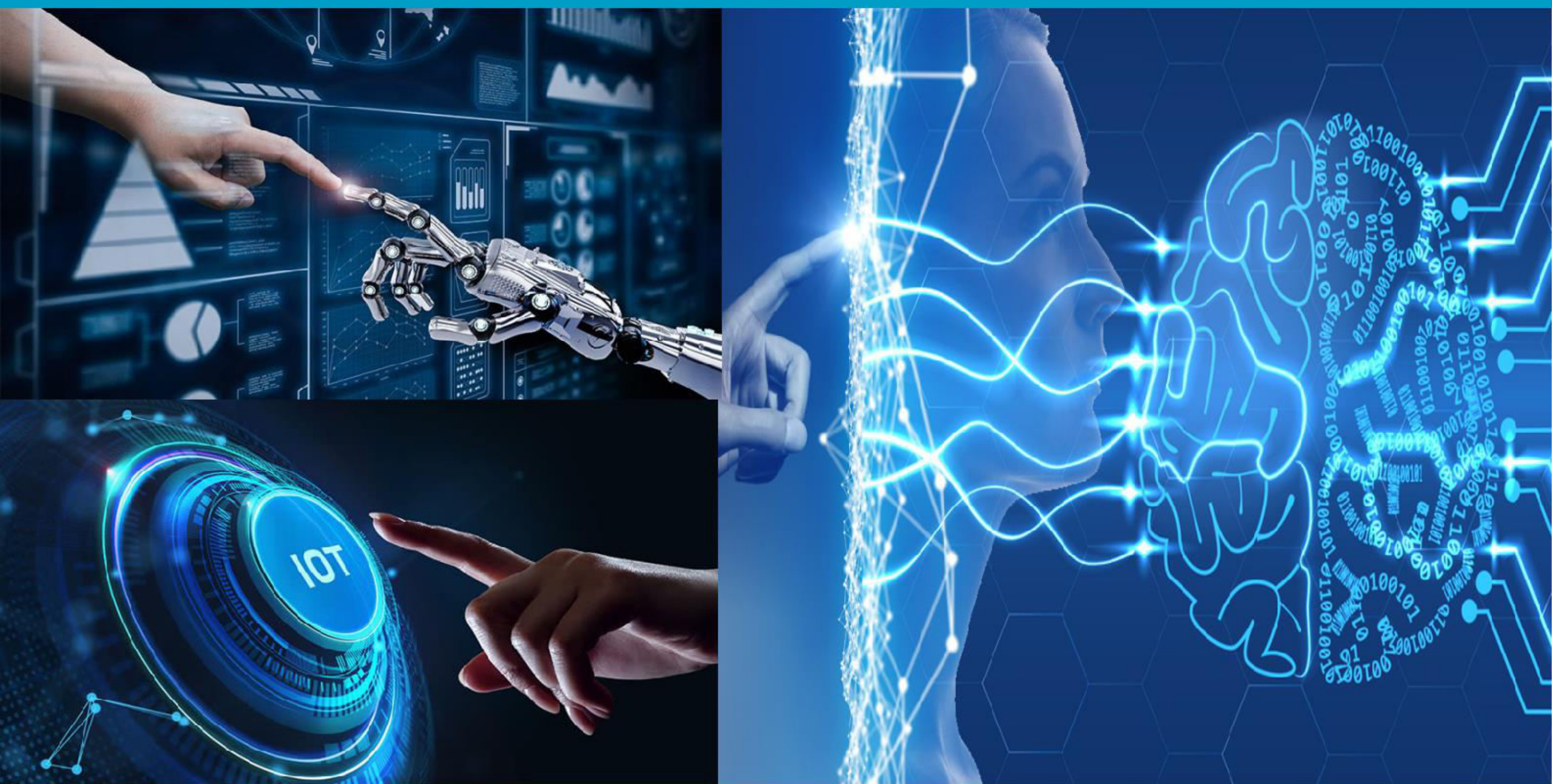

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Biogas Production, its Management and Utilization

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ABSTRACT: Biogas is widely available as a product of anaerobic digestion of urban, industrial, animal and agricultural wastes. Its indigenous local-base production offers the promise of a dispersed renewable energy source that can significantly contribute to regional economic growth. Biogas composition typically consists of 35–75% methane, 25–65% carbon dioxide, 1–5% hydrogen along with minor quantities of water vapor, ammonia, hydrogen sulfide and halides. Current utilization for heating and lighting is inefficient and polluting, and, in the case of poor quality biogas (CH4/CO2 < 1), exacerbated by detrimental venting to the atmosphere. Accordingly, innovative and efficient strategies for improving the management and utilization of biogas for the production of sustainable electrical power or high added-value chemicals are highly desirable. Utilization is the focus of the present review in which the scientific and technological basis underlying alternative routes to the efficient and eco-friendly exploitation of biogas are described and discussed. After concisely reviewing state-of-the-art purification and upgrading methods, in-depth consideration is given to the exploitation of biogas in the renewable energy, liquid fuels, transport and chemicals sectors along with an account of potential impediments to further progress.

KEYWORDS: biogas, production, renewable, utilization, management

I. INTRODUCTION

While most large farms use their biogas for heat and power, it is worthwhile to consider all the options before deciding which path to take, including direct sale of biogas to an off-farm buyer.

Raw animal manure biogas contains 55 to 65% methane (CH_4), 30 to 45% carbon dioxide (CO_2), traces of hydrogen sulfide (H_2S) and hydrogen (H_2), and fractions of water vapor. For the anaerobic digestion of sludge or landfill processes, traces of siloxanes may also be found in biogas. These siloxanes mainly originate from silicon-containing compounds widely used in various industrial material or frequently added to consumer products such as detergents and personal care products. [1,2,3]

Biogas is about 20% lighter than air and has an ignition temperature in the range of 650 to 750 degrees C. (1,200-1,380 degrees F.). It is an odorless and colorless gas that burns with a clear blue flame similar to that of natural gas. However, biogas has a calorific value of 20-26 MJ/m3 (537-700 Btu/ft3) compared to commercial quality natural gas' caloric value of 39 MJ/m3 (1,028 Btu/ft3).

Biogas can potentially be used in many types of equipment, including:

- Internal Combustion (Piston) Engine – Electrical Power Generation, Shaft Power
- Gas Turbine Engine (Large) – Electrical Power Generation, Shaft Power
- Microturbine Engine (Small) – Electrical Power Generation
- Stirling Heat Engine – Electrical Power Generation
- Boiler (Steam) Systems
- Hot Water Systems
- Process Heaters (Furnaces)

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- Space or Air Heaters
- Gas Fired Chiller – Refrigeration
- Absorption Chiller – Refrigeration
- Combined Heat and Power (CHP) – Large and Small Scale – Electrical Power and Heat
- Fuel Cells – Electrical Power, Some Heat

There are a variety of end uses for biogas. Except for the simplest thermal uses such as odor flaring or some types of heating, biogas needs to be cleaned or processed prior to use. With appropriate cleaning or upgrade, biogas can be used in all applications that were developed for natural gas.

The three basic end uses for biogas are:

- production of heat and steam
- electricity generation
- vehicle fuel

Production of heat or steam

The most straightforward use of biogas is for thermal (heat) energy. In areas where fuels are scarce, small biogas systems can provide the heat energy for basic cooking and water heating. Gas lighting systems can also use biogas for illumination.

Conventional gas burners are easily adjusted for biogas by simply changing the air-to-gas ratio. The demand for biogas quality in gas burners is low, only requiring a gas pressure of 8 to 25 mbar and maintaining H_2S levels to below 100 ppm to achieve a dew point of 150 degrees C.

Electricity Generation or Combined Heat and Power (CHP)

Combined heat and power systems use both the power producing ability of a fuel and the inevitable waste heat. Some CHP systems produce primarily heat, and electrical power is secondary (bottoming cycle). Other CHP systems produce primarily electrical power and the waste heat is used to heat process water (topping cycle). In either case, the overall (combined) efficiency of the power and heat produced and used gives a much higher efficiency than using the fuel (biogas) to produce only power or heat.

Other than high initial investments, gas turbines (micro-turbines, 25-100 kW; large turbines, >100 kW) with comparable efficiencies to spark-ignition engines and low maintenance can be used for production of both heat and power. However, internal combustion engines are most cmmonly used in CHP applications. The use of biogas in these systems requires removal of both H_2S (to below 100 ppm) and water vapor.

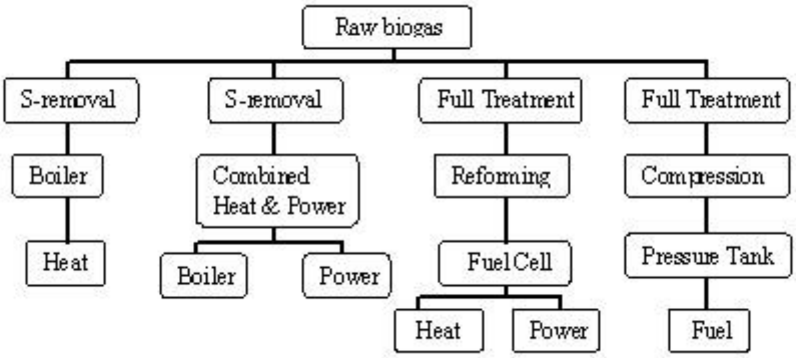
Fuel cells are considered the small-scale power plants of the future for production of power and heat with efficiencies exceeding 60% and low emissions. One of the largest digester/fuel cell units is located in Washington State. The fuel cell, located at the South Treatment Plant in Renton, WA, can consume about 154,000 ft^3 of biogas a day to produce up to 1 megawatt (1,000,000 watts) of electricity. That's enough to power 1,000 households, but it's being used instead for the operation of the plant.[5,7,8]

Vehicle fuel

Gasoline vehicles can use biogas as a fuel provided the biogas is upgraded to natural gas quality in vehicles that have been adjusted to using natural gas. Most vehicles in this category have been retro-fitted with a gas tank and a gas supply system in addition to the normal petrol fuel system. However, dedicated vehicles (using only biogas) are more efficient than these retro-fits.

Biogas Cleanup or Upgrading

Biogas cleaning is important for two reasons: (1) to increase the heating value of biogas, and (2) to meet requirements for some gas appliances (engines, boilers, fuel cells, vehicles, etc). Desired biogas cleaning or upgrading purposes are summarized in Figure 1. “Full treatment” implies that biogas is cleaned of CO_2, water vapor, and other trace gases, while “reforming” is conversion of methane to hydrogen.



Alternative biogas utilization and required cleanup
CO_2 Removal

For many of the simpler biogas applications such as heaters or internal combustion engines or generator systems, carbon dioxide (CO_2) removal from biogas is not necessary and CO_2 simply passes through the burner or engine. For more demanding biogas/engine applications, such as vehicles that require higher energy density fuels, CO_2 is routinely removed. Removing CO_2 increases the heating value and leads to a consistent gas quality similar to the natural gas. Carbon dioxide can be removed from biogas economically through absorption or adsorption. Membrane and cryogenic separations are other possible processes.

Pressurized counter-current scrubbing of CO_2 and H_2S from biogas can be accomplished in water. For removal of CO_2 in particular; pH, pressure, and temperatures are critical. High pressures, low temperature, and high pH increases CO_2 scrubbing from biogas. Use of $Ca(OH)_2$ solutions can completely remove both CO_2 and H_2S. Both CO_2 and H_2S are more soluble in some organic solvents such as polyethyleneglycol and alkanol amines that do not dissolve methane. These organic solvents can thus be used to scrub these gases from biogas even at low pressures. Systems using these kinds of organic solvents can remove CO_2 down to 0.5% from the biogas.

However, use of organic solvents is much more expensive than water systems. Adsorption of CO_2 on solids such as activated carbon or molecular sieves is possible although it requires high temperatures and pressures. These processes may not be cost-effective because of associated high temperature and pressure drops. Cryogenic separation is possible because at 1 atm, methane has a boiling point of -106^{o}C, whereas CO_2 has a boiling point of -78^{o}C. Fractional condensation and distillation at low temperatures can thus separate pure methane in liquid form, which is convenient for transportation. Up to 97% pure methane can be obtained, but the process requires high initial and operational investments. Membrane or molecular sieves depend on the differences in permeability of individual gas components through a thin membrane. Membrane separations are quickly gaining in popularity. Other chemical conversions are technically viable, but their economics are poor for practical biogas-cleaning.[9,10]

Water Vapor Removal

Straight from the digester, biogas will generally be saturated with vapor. Besides reducing the energy value of biogas, water can react with H_2S to create ionic hydrogen and/or sulfuric acid, which is corrosive to metals. Refrigeration or sensible pipe-work design can condense and remove the water. The biogas is normally compressed before cooling to achieve high dew points. Alternative water vapor removal mechanisms include adsorption on: (1) silica gel and Al_2O_3 at low dew points, (2) glycol and hygroscopic salts at elevated temperatures, and 3) molecular sieves.

Removal of Hydrogen Sulfide

Hydrogen sulfide in biogas needs to be removed for all but the most simple burner applications. Hydrogen sulfide in combination with the water vapor in raw biogas can form sulfuric acid (H_2SO_4), which is very corrosive to engines and components. At concentrations above 100 parts per million by volume (ppmv), H_2S is also very toxic. Activated carbon can be used to remove both H_2S and CO_2. Activated carbon catalytically converts H_2S to elemental sulfur. Hydrogen sulfide can also be scrubbed out from biogas in either: NaOH, water, or iron salt solutions. A simple and inexpensive process is dosing a stream of biogas with O_2, which oxidizes H_2S to elemental sulfur. Oxygen dosing can reduce H_2S to below 50ppm levels from biogas [Warning: IMPROPERLY DOSING A BIOGAS STREAM WITH O_2 CAN CREATE AN EXPLOSION HAZARD]. Iron oxide also removes H_2S as iron sulfide. This method can be sensitive to high water vapor content of the biogas. In addition to clean up of biogas of H_2S after it has been produced, available methods of reducing H_2S content from produced biogas include: co-digestions, multiphase digestion, reactor pH buffering, and removal of sulfur from feed substrates.

Biogas produced from animal waste can be a valuable energy resource. By combusting waste methane (biogas), a powerful greenhouse gas is eliminated that would otherwise be released. If used in simple burners for cooking or lighting the gas may not need to be treated prior to use. However, for uses that require the gas to be used in internal combustion engines, boilers or fuel cells, the biogas will probably need to be pretreated in order to remove corrosive or dangerous contaminants. The primary contaminant of biogas is hydrogen sulfide. This chemical will also react with water to form corrosive acids that can attack metals and plastics. Hydrogen sulfide is also toxic and sufficient quantities also present a possible health hazard if not treated.[11]

II. DISCUSSION

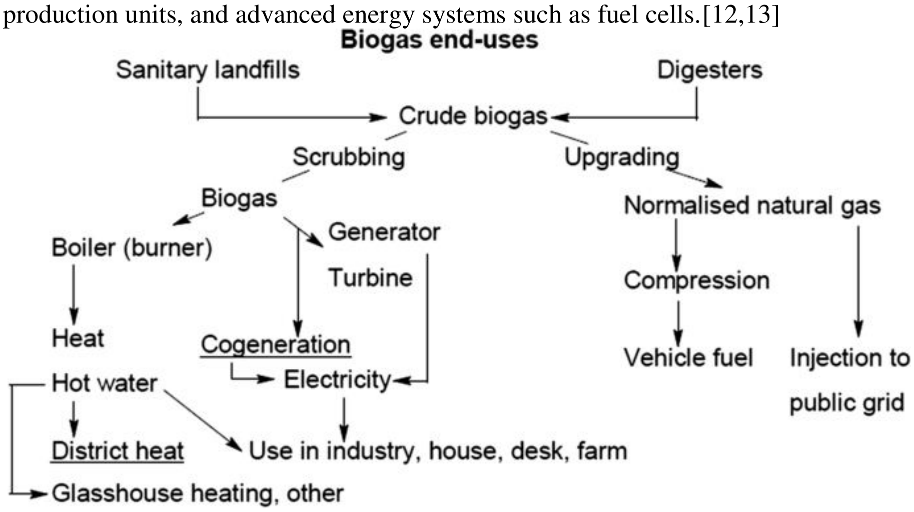
From the 1980s onward, the striking jump in global energy consumption has been largely driven through fossil energy resources. Generally, oil, coal, natural gas, electricity, nuclear energy, and renewable energies have shared 33, 27, 24, 7, 4, and 4% of total primary energy proportion in the whole world in 2018, respectively. Approximately, 85% of the world's primary energy consumption has been supplied by fossil fuels in 2018 (BP. 2019; Ghasemian et al.2020).
The conversion of biomass to energy has been promoting from 65 GW in 2010 to 120 GW in 2019 due to climate change, reasonable energy prices, distributed generation increase, and environmental aspects, in recent years. Wastes with high moisture content are more compatible with conversion by anaerobic digestion, landfill, and digestion technologies. The global amount of biogas plant capacity was about 19.5 GW at the end of 2019. Organic wastes are the most common feedstocks to produce biogas from wastes, including domestic wastes (food, fruits, and vegetables) or public moist wastes (cafes and restaurants, daily markets, and companies' biological wastes), due to significant moisture content and high degradability. These input materials are classified as OFMSW, which represents the organic fraction of municipal solid waste (Antoine Beylot et al. 2018; A. Luca C.R. 2015).
Biogas is inherently renewable, on the contrary to fossil fuels, because it is generated from biomass, and this source is practically a reserve of the solar energy via photosynthesis process. Anaerobic digestion (AD) biogas will not only enhance a country's energy basket status but also contribute significantly in conserving natural resources and protecting the environment (Teodorita Al Seadi DR 2008).
Biogas is naturally composed of biogenic material. This biogas, which occurs naturally, spreads into the ambient, and its major component, methane, plays a serious detrimental role in global warming (Bochmann and Montgomery 2013). Methane has been used as important fossil fuel and converted to generate power, transportation, and heating, over the past decades. Nowadays, the major portion of methane consumption and utilization comes from natural gas resources, but the production of bio-methane from waste recovery approaches has been meaningfully increased. Its production potential has been improved by 4% over 9 years (from 2010 to 2018). At present, about 3.5 Mtoe of biomethane is

produced around the world and the potential for biomethane production today is over 700 Mtoe (Edenhofer et al. 2011). Of course, this does not mean that methane conversion is feasible from all kinds of natural resources. In other words, infrastructures for biogas development extremely rely on specific equipment and the availability of control and management systems. Therefore, a sustainable industry can be installed and implemented to generate bio-energy from renewable and green natural resources (Bochmann and Montgomery 2013).

Developed countries use advanced large-scale plants for utilizing biogas. Biogas is regularly applied to generate heat, power, and electricity. Also, several industrial applications for its utilization in biogas plants as a substitute to natural gas are being progressed. Based on the analyzed data, a continuous increase in biogas production has been observed due to the global policies and programs. Since 0.5% proportion of renewable energies contribution that is about 12.8 GW (IRENA RES. 2015) is supposed to be achieved in 2020 for transportation sectors, bio-fuel production has been considered as the main source of this plan in different regions. It is noteworthy that biogas production should not be developed as a food production threat. For this reason, biofuels are mainly generated from cellulosic and lignin wastes (Nicolae Scarlat and Fahl 2018; Angelidaki et al. 2018).

A wide global market of biogas has been conspicuously promoted for the previous decades in various countries. Moreover, the advanced biogas production technologies have been supported by domestic or international supportive rules, such as research, design, and development (RD&D) financial funds, subsidization, and guaranteed electricity purchase contracts to make a competitive market against conventional energy suppliers (Teodorita Al Seadi DR 2008).

According to Fig. 1, the different utilizations of the biogas technology offer a multi-purpose solution to generate the required energy of the industrial or social sectors. Biogas is mainly consumed for combined heat and power (CHP) plants, hydrogen production units, and advanced energy systems such as fuel cells.[12,13]



Overview of biogas utilization

Generally, in the European Union (EU) and North America (NA), biogas plants came to be developed more than in other continents for the last 40 years. The main advantages of the units located in the mentioned regions are industrial scale, energy efficiency, and high complexity level. Biogas production was considered by academic centers and governments owing to its potential in response to different global challenges. It should also be pointed out that using biogas technologies allows industries to eliminate greenhouse gases (GHGs) emissions and waste disposal pollutions, while it provides a broad spectrum of energy utilization such as heat, electricity, and transportation purposes, based on its renewable nature.

There are various strategies around the world for producing biogas from agricultural products. In Germany, for example, the production of cheap agricultural products that require low processing (with no outcomes for consumers) provides feedstock for biogas plants. New policies recommend the use of crops and plant residents, life stocks remaining, and landfill use (IRENA RES. 2015).

This review focuses on proposing a comprehensive analysis of the recent biogas technologies progress, aiming advances toward wastes conversion to produce electricity, heat, and other forms of energy carriers. It reports the current and future AD conversion technologies, as well as examines accessible details in the literature about feedstock categories, pretreatment approaches, process development, and its yield to increase production efficiency. Furthermore, suggested future biogas application trends and directions for efficient ways of energy generation from wastes are other main outputs of this study. Also, the present review highlights the emerging biogas technologies which are promoted to distribute biomethane and biofuel production, especially the production of hydrogen from biogas is the innovative insight in the mentioned field.

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The structure of the present research is as follows: "Biogas Applications" reports extensive data on the up-to-date status of biogas consumption in energy generation, energy storage, and transportation. Biogas development levels around the world, regulations, and historical progress are expressed in "Biogas utilization in various parts of the world" section. Also, the characterization of the feedstocks and additives, pretreatment, process types, and related techniques are described in "Recent progress in biogas production" section. The novel technologies are indicated with their advantages and constraints for each section. Eventually, the conclusion and predictive tendencies for future research are explained in the last section.

Thus, this work represents a comprehensive review of the biogas in terms of a renewable energy source for both production and applications. The procedures for production and applications are up to date. Researchers' work in 2020 is presented where they used the most updated technologies which help other research agencies to continue from this end. The review of the development of the biogas industry and utilization covers 20 years of information. Moreover, a review of the international recent policies and regulations relevant to biogas management is provided. Based on that, a suggested policy based on international guidelines and international conventions is proposed.[15,17]

Published research papers and data on biogas sources, production, and applications are collected from the literature. These sources cover the years from 1997 till 2020 to summarize the current situation and development relevant to biogas. A review of policies and regulations on national and international levels is presented. Regulatory entities in the world that issue guidelines instruction to organize the biogas market are presented. This review showed the increase of world awareness regarding this source of energy by introducing the most updated policies in many countries. Based on all of the above, a proposed framework and policy is presented.

An introduction shows the necessity of biogas as a source of renewable energy is presented. The increasing demand for biogas in the energy section showed to be increased in the coming years. Biogas production process and the sources to get the biogas are presented. The sources vary from agricultural to animal wastes which are the richest biogas sources however, other sources such as wastewater treatment plants, and landfill disposal sites.

Applications of biogas and its contribution to the total national energy sector are presented. These applications range from energy conversion, producing alternative fuels, electricity generation, etc. Traditional methods of biogas production are presented with developments of such methods. New technologies and methods for production and purification of biogas are described.

Biogas applications

Biogas is globally considered as traditional off-grid energy. Biogas can also be utilized to generate electricity. The various applications of biogas are described below.

Electricity generation

Power generation from biomass is currently the most popular and growing market worldwide, due to technological improvements, decreasing reliance on fossil-based energy, and reduction of greenhouse gases (GHG) emissions. Biogas has the potential for electricity generation in power plants by internal combustion engines (ICEs) or gas turbines (GTs) as the two most commonly used power generation methods. Micro gas turbines are also an attractive method due to lower NOx emissions and flexibility to meet various load requirements. Multiple microturbines sizing from 70 kW to over 250 kW can be employed to meet low/medium power load demands. The electricity can provide the required power to the adjacent industries and companies. With the development of electric cars, another state-of-the-art application, especially in developed countries like Germany, is the utility of electricity for e-vehicles of a connected car-sharing association (Scarlat et al. 2018).
The major benefit of on-site electricity generation is to prevent transport losses and to increase reliability due to the independence from a centralized grid mostly run by traditional fossil fuels. It also brings extra economical profit by providing the required in-house power demand and selling the extra electricity (Scarlat et al. 2018).

Heat generation

Biogas can be directly combusted in boilers for heat generation only. It is feasible to slightly modify natural gas boilers to operate with biogas. As farm biomass is a major biogas production source, the generated heat can be used for heating the digesters, farm buildings like housing units for pigs/sties, greenhouses, as well as aquafarming, cooling/refrigeration of farm products, and drying purposes. The drying process in agricultural businesses, such as drying of digestate, woodchip, grain, herbs, and spices, is a remarkable added value to the farm economy (Herbes et al. 2018).

Available heat for external use, representing nearly 30–50% of generated heat, can be sold to a nearby district to be used for district heating/cooling like heating swimming pools. Also, an absorption chiller can be a potential candidate to better use heat through CHP, in addition to cooling power (tri-generation). It can convert heat into cooling power with high efficiencies of up to 70% (Rümmeli et al. 2010).[18,19,20]

Combined heat and power (CHP) generation

Concurrent generation of heat and electricity by CHP systems is an operational approach to upgrade the energy conversion efficiency of biogas. When only converting biogas to electricity or heat, just a minor fraction of energy contained in biogas is used. Characteristically, in these types of systems, associated power conversion productivity is somewhere in the region of 30 to 40%, while it is diminished by employing biogas as an alternative for refined and purely natural gas (Saadabadi et al. 2019).

CHP plants offer the advantage of high-temperature exhaust gas from the electricity generation subsystem (ICEs or GTs) as a source of valuable heat for many heating purposes already discussed before. Although the electricity generation efficiency of simple plants is only 20–45% (Muche et al. 2016), a larger portion of energy (around 60% of the utilized energy (Damyanova and Beschkov 2020)) is converted to heat that is reused by heat recovery systems; making it more attractive when there is a high heat demand. This considerably enhances the system efficiency and improves the payback period of plants, making the distributed generation the most common biogas application. The extra electricity could be supplied for the national grid and the extra heat can be sold to the local district utilization.

A CHP cycle has sufficient productivity that has an efficiency up to 90%, while it can produce 35% and 65% of the generated electricity and heat, respectively. In this case, some thermal energy is used to heat the process and about 2/3 is used for external uses. In some proposed models for biogas-based power plants, the use of generated heat is ignored and the focus is only on generating electricity. Without any doubt, this approach has no economic justification and must use all its thermal potential.

There are three common ways to produce heat and power from biogas including Gas-Otto engines, Pilot-injection gas motor, and Sterling motors (Teodorita Al Seadi DR 2008). In EU, four-stroke engines and ignition oil diesel engines contributed roughly the same in CHPs at somewhere in the vicinity of 50%, each (Dieter Deublein 2008). Biogas is also employed in gas turbines, microturbines, and fuel cells (discussed in detail in ``Fuel cells'' section) for CHP applications (Kaparaju and Rintala 2013; Nikpey Somehsaraei et al. 2014).

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Upgrading to biomethane

If biogas is upgraded and purified to biomethane, it can be fed into natural gas grid to be used for heating purposes, power generation, or to provide fuel for compressed natural gas (CNG) and even natural gas vehicles (NGV). A significant benefit of biomethane is that it can be stored to meet peak demands (Herbes et al. 2018). The two major steps to produce biomethane are upgrading methane content up to 95–97% followed by a cleaning process to eliminate water vapor, hydrogen sulfide, oxygen, ammonia, siloxanes, carbon dioxide, carbon monoxide, hydrocarbons, and nitrogen (Ryckebosch et al. 2011). Biogas upgrading is performed by physical and chemical technologies such as adsorption, absorption, cryogenic and membrane separations, and gas separation membranes as well as biological technologies (in situ and ex situ (Kapoor et al. 2019)). Although biological methods are emerging, suggesting an enormous technological potential, they are not widely used in industry since they are generally much slower, have low

rates of reaction/synthesis, and require long startup period that made them less economically feasible, while physicochemical methods are common due to technological advancements and implementations (Scarlat et al. 2018).
Upgrading biogas to biomethane or renewable natural gas (RNG) is on a hot trend in developed countries especially in North America among oil and gas companies for decreasing GHG emissions and using the carbon credit. There are also other environmental and economical benefits in smaller scale to farmers, municipalities, and counties for waste management and profitable contracts with gas utility companies. Biomethane market for transportation purposes equaled to 160 cubic meter per year in 2015 Eurostat.European Statistics (2019).

III. RESULTS

Transportation fuel

Biogas converted to biomethane (through upgrading and cleaning) can be readily used in natural gas-powered vehicles as another option for fossil natural gas. Using biomethane as transportation fuel results in remarkably low GHG emissions that make it a suitable source of renewable fuel. Biomethane turns out to be a great fit to replace fossil-based fuels in terms of environmental and economic considerations (Scarlat et al. 2018). However, the overall efficiency is extremely improved when biomethane is utilized in advanced hybrid or fuel cell vehicles (FCVs) in comparison to current biodiesel or ethanol-powered ICE vehicles (Faaij 2006).
Generally, biogas can be improved to transportation fuels (bio-CNG) that can be stored for future use, in the form of liquefied biogas (LBG), syngas/hydrogen, methanol for gasoline production, ethanol, and higher alcohols (Yang et al. 2014). Compression and liquefaction are common physical methods to convert biogas into bio-CNG and LBG, while the dominant chemical approach to obtain syngas is catalytic reforming. If Fischer–Tropsch synthesis (FTS) or fermentation is employed, syngas may be converted into a variety of alcohols like methanol, ethanol, and butanol (Yang et al. 2014). This fuel alternative has already been applied within the European Union and the USA. As an example, many vehicles run on biogas in the urban public transport (in Sweden and Germany) either as 100% methane (CBG100) or mixed with natural gas (e.g., CBG10 and CBG50) (Damyanova and Beschkov 2020; Yang et al. 2014).

Hydrogen production

Hydrogen displays many promising potentials for renewable energy and the chemical industry due to its high potential for energy production. Hydrogen offers the biggest share of energy per unit mass (121.000 kJ/kg). The hydrogen council suggests about 18% contribution of total final energy utilization by 2050. Hydrogen is best employed in fuel cells as an emerging energy application to produce electricity, heat, and possibly water. Furthermore, there are many applications in chemical industries for hydrogen, including food treatment, hydrogenation methods, production of ammonia and methanol, Fischer–Tropsch synthesis, pharmaceutical manufacturing, among others (Armor 1999).
Technically, hydrogen (H_2) can be released from the BSR (biogas steam reforming) process. This process has temperature flexibility in the range of 600 to 1000° C, which also includes catalytic techniques. (Holladay and J., King, D.L., Wang, Y. 2009; Alves and C.B., Niklevicz, R.R., Frigo, E.P., Frigo, M.S., Coimbra-Araújo, C.H. 2013). The main difference between BSR and SMR (steam methane reforming) is the presence of carbon dioxide in the feedstock. This factor increases the sensitivity to carbon production in the process. The produced carbon can deposit in the active phase of the catalyst to create deactivation.(Gioele Di Marcoberardino et al. 2018). Furthermore, fed gas can affect the hydrogen separation unit. In this case, PSA (pressure swing absorption) and VPSA (vacuum PSA) are the most common methods of purifying the system for hydrogen-rich reformate or syngas (Ugarte and P., Lasobras, J., Soler, J., Menéndez, M., Herguido, J. 2017; Ahn and Y.W., Lee, D.G., Kim, K.H., Oh, M., Lee, C.H. 2012). The potential of hydrogen production from all landfill sources in the USA is probably between the total potential of 16 million tons of methane from raw biogas and 4.2 million tons of hydrogen (Milbrandt GSaA. 2010). Biogas production systems have a capability for production from 100 Nm^3/h for small-scaled agricultural to a few 1000 Nm^3/h for large-scaled municipal waste landfills; furthermore, occasionally, not all biogas may be converted to the desired hydrogen and further biogas valorization can coexist in the system. Therefore, the capacity considered for BSR should be in the range of 50 and 1000 Nm^3 H_2/h (Doan Pham Minh et al. 2018).
Hydrogen is clean transportation fuel, while as discussed earlier syngas may be used as a feedstock for alcohol production. With new advancements in reforming procedures, biogas can now be directly improved to syngas by dry or steam reforming without the necessity to remove carbon dioxide (Yang et al. 2014).

Fuel cells

Fuel cells are probably the cutting-edge application of biogas. Recent advances in fuel cells resulting in low emissions (CO_2, NO_x) and high efficiency make them suitable for power generation and transportation purposes. Also, fuel cells

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can be utilized in large-scale power plants, power distribution generators, buildings, small-scaled and portable power supply apparatus for microelectronic equipment, and secondary power components in vehicles (Alves et al. 2013).

Fuel cells can use the chemical energy of hydrogen and oxygen without any intermediaries to deliver electricity and heat (A. Trendewicz R.B. 2013). In this case, there are only a small number of fuel cell-based power plants (most of which are pilots) that generate electrical power from biogas. (S. Ali Saadabadi ATT, Liyuan Fan, Ralph E.F. Lindeboom, Henri Spanjers, P.V. Aravind. 2019). Fuel cells exhibit high electrical efficiency of 60% (in power generation only mode) and thermal efficiency of up to 40% (in CHP applications) (Pöschl et al. 2010), but can easily be integrated with other power generation systems like gas turbines or microgas turbines to further improve their performance. Also, biogas fueled integrated solid oxide fuel cell (SOFC)-CHP offers a modern energy system that can address both heat and power generation demands for decentralized grids with drastically higher electrical efficiencies (Wongchanapai et al. 2013; Safari et al. 2020; Safari et al. 2020). Such high efficiency compared to other common combustion technologies is a result of not being limited by thermodynamic Carnot efficiency. SOFCs are more tolerant to fuel impurity and flexibility; hence offering better integration with biogas systems (Wasajja et al. 2020). This highlights their key role in enhancing the highly efficient generation of electricity from biogas, which demonstrates significant environmental and economic merits. However, for the use of biogas as fuel in fuel cells, a cleaning procedure seems essential to eliminate biogas impurities such as H_2S, siloxanes, and other volatile organic compounds (VOCs) that have harmful impacts on fuel cell operation.[23,25]

Furthermore, hydrogen produced from biogas can directly feed fuel cells. The reforming practice can be succeeded either internally employing fuel cells or externally by a catalytic pre-reformer. The three chief techniques for methane conversion are steam reforming, partial oxidation (POX), and dry reforming. Besides, mixed approaches like autothermal reforming (ATR) (mixed steam reforming and methane POX) are applicable. In a pilot plant constructed in Barcelona, Spain named “Biocell project”, biogas from a WWTP was employed in two categories of a fuel cell. The first was proton-exchange membrane fuel cell (PEMFC) that entailed exterior gas cleaning and reforming unit. Biogas has also been added into a SOFC after the cleaning process. This pilot plant is intended for 2.8 kWe. Electrical and thermal effectiveness for the SOFC pilot plant was 24.2 and 39.4%, respectively, which are considerably more than those for the PEMFC pilot plant (S. Ali Saadabadi ATT, Liyuan Fan, Ralph E.F. Lindeboom, Henri Spanjers, P.V. Aravind. 2019; Arespacochaga and CV, C. Peregrina, C. Mesa, L. Bouchy, J. Cortina 2015).

Biogas development in various parts of the world

The worldwide biogas industry has increased more than 90% between 2010 and 2018, while further growth is still expected. The International Renewable Energy Agency (IRENA) reported that the overall potential for the biogas industry in 2018 could provide 88 Tera Watt per hour (TWh) of biogas each year. Installed electricity generated from biogas reached 18.1 GW in 2018, against 8.2 GW in 2009 (Agency 2019). Over 20% of electricity produced in the entire biopowered production is generated from biogas, with a share of 4% of heat generation worldwide.

Among different countries throughout the world, Europe plays a pivotal role in biogas electricity generation. In 2017, Europe contributed to over 70% of the world biogas generation representing 64 TWh, followed by North America accounting for 15 TWh (in which the US participation was over 85% in entire North America). Asia produced 4 TWh followed by Eurasia with 1.7 TWh, South America with 953 GWh, and Africa biogas production accounted for 89 GWh (Scarlat et al. 2018; Agency 2019).

In terms of thermal energy production, biogas is turning to be a more significant source of heat, in which around 4% of the worldwide bioheat in 2015 was generated by biogas. In the EU, biogas produced 127 TJ of heat, which corresponds to almost 50% of entire biogas use in the EU (Scarlat et al. 2018). In Demark, the electrical power cost produced by biogas is 0.056 EUR/kWh in a CHP unit or injected into the grid (Seadi and J. 2019).

Biogas utilization differs significantly in various countries around the world. This varies from several small-scaled biogas plants providing heat in China and India to large-scale plants generating electricity as well as upgrading into biomethane as fuel, mostly in Sweden (McCabe et al. 2018).

Nanyang in China is one of the top biogas cities in the globe due to its location in the center of a rank soil zone. Since corn is abundant, other types of cereals can be employed for producing biogas (Dieter Deublein 2008; Lei Zheng 2020). In China, biogas plants are classified as medium scale with the volume of digester equaled to 300 cubic meters and large scale with a capacity of 500 cubic meters, with daily biogas production in the range of 150 to 500 cubic meters per day (Song and C., Yang, G., Feng, Y., Ren, G., Han, X. 2014). The governmental support for domestic digester has been stopped since 2015. More backing would make large-scale biogas plants and bionatural gas schemes (Ndrc 2015). Chinese biogas industry reported that 41.93 million biogas digesters were built (containing centralized biogas source for houses), for almost 200 million recipients, in which 14.5 billion m^3 biogas is produced per year (China Statistics Press 2018).

In India, around 2.5 Mio biogas plants are operating, with a medium digester volume of 3–10 m^3. Based on the circumstances, the plants produce 3–10 m^3 biogas daily, adequate to deliver a regular farmer family with energy for food preparation, heating, and lighting. Also, more than 1.2 million households employ small-scaled AD and 100,000

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family-sized AD units have been installed between 2016 and 2017. Over 35,000 biogas plants have been constructed with governmental investments (MNER 2016).

Japan is a pioneer in the use of biogas, with increasingly using AD to produce biogas and manage municipal waste in the last decade. The development is such that only Japan uses thermophilic AD (Abbasi et al. 2012).

Up to 2008, over 70 plants have been constructed in Russia, over 30 in Kazakhstan, and a single plant in Ukraine. In Ukraine, bioreactors with 162,000 m^3 volume have been previously installed in sewage treatment units (M. R. Atelge DK, Gopalakrishnan Kumar, Cigdem Eskicioglu, Dinh Duc Nguyen, Soon Woong Chang, A. E. Atabani, Alaa H. Al-Muhtaseb, S. Unalan. 2018).

It should be noted that some nations employed biogas as a practical tool for waste management, mostly to decrease the detrimental effects of municipal waste or wastewater. Likewise, a broad range of various technologies are employed from simple digesters to expanded granular sludge blanket (EGSB) digesters (McCabe et al. 2018).

Biogas technology and industry

The biogas industry varies significantly in the various parts of the world. Different countries have been advanced in several types of biogas systems mainly premised on different environment as well as energy demand and supply chain. The UK, Australia, and South Korea employed landfill sites to achieve a considerable portion of their produced biogas, while in Switzerland and Sweden, using decomposition of sewage to generate biogas is prevailing. Denmark utilizes mainly manure due to its abundance and availability. In Germany, UK and Sweden most of the biogas generation arises from food waste (McCabe et al. 2018; Union 2015; Association WB.Global Potential of Biogas 2019).

In farm-based biogas production, China and Germany are recognized as world leaders since about 24,000 small-scale plants exist in China and nearly 8000 agriculture plants in Germany. Similarly, France, Holland, Austria, and Italy employed considerable farm-based biogas plants (Union 2015). Moreover, the scale of plants ranges from small household units to larger plants using feedstocks such as household waste, industrial waste, and manure to generate both heat and electricity (Union 2015). Studies revealed that in Asia and Africa, most of the installed biogas plants were family-sized (Kemausuor et al. 2018). China and India have dominated the microscale biogas industry in the world. At this time, Thailand takes benefits from more than 1700 biogas plants and more than 150 plants of industrial waste. The Thai government has attempted to expand industrial wastewater technology that has the potential of 7800 TJ/y biogas production (Tonrangklang et al. 2017). The ministry of energy of Nepal (Government of Nepal Ministry of Energy WRaI.Biogas.20202020) has reported that most of the villages about 2800, out of the total 3915 in all 75 districts of Nepal, have small-scale or household biogas production systems. Primarily two categories of plants have been constructed in Nepal. These are the floating-drum plant based on the Indian style and fixed-dome plants with a flat floor, cylindrical digester, and a dome prepared by concrete. Among 50 million microscale digesters operating in various parts of the world, 42 million are installed in China and another 4.9 million in India. The statistics from the World Biogas Association (WBA) have shown that there are only 700,000 biogas plants installed in Asia, Africa, and South America (Association WB.Global Potential of Biogas.2019. 2019).

In terms of large-scale plants, about 7000 large-scale biogas systems are operating in China. Europe, in 2017, had a share of 17,783 plants, while Germany was dominating the European biogas industry with 10,971 plants followed by Italy with 1665 plants, France with 742, Switzerland, and the UK with 632 and 613 plants, respectively (Association 2018). The World Biogas Association data mentioned about 2200 anaerobic digesters large-scale plants in the USA, able to generate 977 MW (Association WB. International Market Report 2018).

Another application of biogas relies on upgrading to biomethane. Although being comparatively a novel technique, it achieves widespread utilization worldwide. Some biogas upgrade plants are employed to produce vehicle fuel, while others deliver it into the local or national grids Association WB.Global Potential of Biogas (2019).

Africa is a region with abundant and diverse resources for biogas production, though it has accomplished small progress in the sector. Although the continent has made considerable achievements in small-scale biogas plants, profitable biodigesters still require further development (Kemausuor et al. 2018). In Africa, harvest and livestock farmers, small to medium and large food treating businesses, wastewater, sanitation, and municipalities running institutes, as well as municipal waste management organizations, are considered as potential candidate employers of large-scale biogas technology. Moreover, schools, institutions of higher education, hospitals, and commercial buildings have the potential to benefit from biogas technologies and facilities (Parawira 2009). Excluding South Africa, insufficient scientific literature has reported technology development of the commercial biogas system in Africa. In the Southern parts of Africa, developed technologies are the lagoon, plug low, and up-flow sludge blanket (UASB) (Mutungwazi et al. 2018).

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Biogas production and utilization

In this section, biogas production from wastewater treatment plants (WWTP), biowaste digestion, agricultural products (largely manure and energy crops), waste stream from different industries, and landfill gas are considered. In Europe, Germany has dominated the industry by far in which its annual production is accounted for 120 TWh followed by the UK with 25 TWh and 9 TWh in France. Denmark and the Netherland's production capacity is around 4 TWh and the remaining countries share is less than 3 TWh (Bioenergy 2019a).

In Germany, the total gross electricity and heat production from biogas is about 33 TWh/year and 18.8 TWh/year, respectively. Based on statistics revealed by the Federal Ministry for Economic Affairs and Energy of Germany, a considerable amount of the biogas was utilized for electricity production (58%) and heat production (33%), and approximately only 1% was used as a vehicle fuel (Bioenergy 2019a).

In 2018, about 32% of entire renewable heat used in the UK was produced by anaerobic digestion technology, of which 9 TWh/year was produced by biomethane, 2 TWh/year by biogas and CHP accounted for 918 GWh/year, while 2681 GWh of electricity was generated by the sector (Association ADaB. ADBA annual report 2019.2018).

In France, total electricity production from biogas was about 1.8 TWh/year at the end of 2017, simultaneously total heat generated accounted for 1.7 TWh/year, which demonstrates nearly equal portion for both heat and electricity. Regarding heat production, the agriculture sector accounts for an indispensable portion, while in electricity production, the landfill has a pivotal role with 953 GWh/year followed by agriculture with 765 GWh/year (Bioenergy 2019a).

In Denmark, the biogas sector provides 5% of the entire energy consumption of which biogas plants contribution is 60% and the rest relies on wastewater treatment plants and landfill sites. The Danish Energy Agency states that due to several support schemes such as upgrading biogas to Natural gas, biogas employment for process purposes in the industrial sectors, etc. results in promoting biogas utilization through the country (Agency and Biogas in Denmark 2019). Total Danish biogas production at the end of 2018 was reported to be about 1763 GWh/year in which the agriculture sector (both centralized and farm plant types) showed the largest contribution with 1367 GWh/year. 66% of produced biogas energy (which corresponds to 1150 GWh) is used to provide electricity, followed by upgrading plants with 17% portion and heat generation with 16% Bioenergy IEAI.Denmark Country Report -2019 (2019). In the Netherlands, in 2017, two co-digestion and municipal waste plants had the largest share in production, and the final use of biogas (3034 TJ heat was produced solely with municipal waste, while co-digestion had a pivotal role in electricity production representing 1825 TJ) Bioenergy IEAI.The Netherlands Country Report -2019 (2019).

In Sweden, 48% of biogas production corresponds to co-digestion plants followed by WWTPs (37%), the remaining being produced by the other plant types such as landfills, industrial facilities, and farm-based. In terms of utilization, the upgrading or transport sector represented a considerable portion (65%) followed by heat (19%), while electricity production share was almost 3% (Bioenergy 2019b).

In Asia, China plays a significant role with 98.4% of biogas production between non-OECD countries. Primary infrastructures such as advanced industry and socioeconomic conditions have a profound impact on biogas generation and utilization growth. Small-scale and household biogas systems have been widely developed by countries like India and Bangladesh. Various researches prove that there are plenty of resources for producing biogas in developing countries when barriers such as socioeconomic, climate conditions, and appropriate technology have been addressed accurately. Several biogas plants in the range of medium to large scale have been launched in China and India (Mittal et al. 2019; Jiang et al. 2011; Gu et al. 2016).

In the USA, over 2200 biogas plants are operated, among which 250 AD on farms, 1269 wastewater recovery plants employing an AD, and 66 independent plants that use food waste as feed and 652 landfill gas projects. The America Biogas Council has revealed that there is still an enormous potential for developing the biogas industry in the USA where it is possible to achieve 103 trillion kWh/year (Council 2019a). California ranks first in biogas production potential among all the 50 states in the USA (Council 2019b), followed by Texas (Council 2019c).

The power generation from biogas is estimated to be 9731 million kWh and 6574 million kWh electricity for California and Texas states, respectively. In California, the manure system has the highest potential with about 900 biogas plants, while currently 38 manure plants are operated with 156 wastewater facilities in Texas. (Council 2019b,c).

In Canada, bioenergy currently provides approximately 26.7% of Canadian entire renewable energy market, the highest share is from burning solid biomass (23.1%), followed by the liquid biofuels (2.4%), and biogas (1.2%) (Canada 2019).

In Canada, total installed plants for biogas production are estimated to be around 150. Most production takes place in landfills with 45 plants (share of 30%), followed by the agriculture sector with 37 plants (share of 24.7%) and WWTPs with 31 plants (20.7% production portion) (Association WB.Canada Market Report.2019. 2019).

Based on the Canadian Biogas Association data, at the end of 2018, about 195 MW of electricity and 400,000 GJ of Renewable Natural Gas (RNG) were generated (Biogas and Potential.2019. 2019). Biogas is utilized for providing heat and electricity, delivering to a nearby user using a pipeline, converting into electricity and connecting to the grid, or refining to RNG based on circumstances such as the landfill site location, and the energy demand of plants. In this regard, approximately 50% of the produced biogas is converted into power, with the rest going to combined heat and power (CHP) application (about 25%), heat (only 10%) and RNG (about 4%), and electricity and RNG (about 1%) (Association WB.Canada Market Report.2019. 2019).

In Australia, at the end of 2017, generated electricity from biogas industry was approximately 1200 GWh, which is equivalent to almost 0.5% of the entire electricity generation of the country, while biogas potential electricity generation was estimated as 103 TWh, equal to almost 9% of Australia's entire energy consumption (Australia and Biogas opportunities for Australia. 2019).

The main use of biogas in Australia is for electricity with the greatest share for landfills (53.7%), followed by biowaste and WWTPs (40% and 33.3%, respectively). Heat is used in the industrial sector with a share of 30% and afterward the WWTPs with a share of 26.2%. In CHP applications, agriculture plants have the largest portion (50%), followed by the biowaste and the WWTPs (equal share of about 20% each). Between 40–50% of the excess biogas is flared at agriculture, industries, and landfills. Twenty percent of WWTPs and biowaste are no biogas upgrading plants in Australian's biogas industry (Bioenergy IEAI.Australia Country Report.2019. 2019).

In Africa, South Africa has the largest share of installed biogas plants with about 700 plants, while only 300 plants might have been in operation as of 2007, while it can generate 148 GWh electricity from estimated biogas potential by appropriate investment and implementation schemes (Kemausuor et al. 2018).

Various industrial trends in the biogas production have been introduced to improve quantitative and qualitative properties of the biogas. Yet, the accomplishments of AD intended for advanced investments will increase from the low charge of feedstock accessibility and the broad range of practical set ups of the biogas (i.e., heating, electricity power, and fuel form). The remained parts of slurry from biogas production procedure have the potentials to be improved to be used as fertilizer to enhance the sustainability. Produced biogas could be employed to generate power for integrated or isolated systems in the rural and urban regions and are deemed to be economical favorable. The employed processes of AD, modern trends accompanied by included advantages and disadvantages are also demonstrated more details and progress on the way to producing biogas in a sustainable approach. Obtained results from previous researches indicated that the present amount of biogas production confirms that regarded approaches would have main influence on the energy utilization in upcoming times. The impression contains diminished release of pollutants to the atmosphere guarantees that the global warming prevention. Nevertheless, the current trend of the biogas production varies in diverse countries, either in production or the sources (landfill, AD, sewage sludge, or thermochemical methods). The involvement of biogas to the domestic natural gas utilization varies differently, around 4% on standard values; however, it raised 12% in Germany. The major nations in the biogas production in the European Union are France, Italy, Germany, Czech, and UK. Germany stands as the European frontrunner with a biogas production of 329 PJ and a contribution of 50% of total in the EU. It's reasonable to surmise that, based on the provided data from various researches, it has been declared that given the growing need and available technology, European Union countries, and especially Germany and Sweden, will be pioneers in the development, operation, and production of biogas in the world. Table 1 indicates the biogas plants, upgrading units, and their upgrading capacities in certain EU countries (Lampinen 2015; Backman and Rogulska 2016; Esmaeilion et al. 2021).

Recent progress in biogas production

Producing biogas is a key option in the energy sector of various countries. There is a wide variety of raw materials for utilization in biogas plants. In this case, obtaining a stable state in plants is a crucial concern that influences the prices and additives. Another important issue in the biogas plants is that their products should be attractive in terms of value and efficiency (Chen et al. 2012). Recent progress in the field of biogas production can be divided into three categories: feedstock and additives, pretreatments, and processes.

Feedstock and additives

The organic matters are the main feedstocks in the biogas plant, which can fall into different categories. Evaluating the potential of biogas production based on organic matters from rural regions has been investigated. The highly fermentative wastes can decrease the quantity of feedstock in biogas plants (Pawlita-Posmyk and Wzorek 2018).

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Microalgae with satisfactory features is a potential option for feedstock in biogas systems. In comparison with other biomass resources, microalgae has better efficiency, more convenient production, and higher content of lipid and polysaccharide that make it a flexible choice in biogas plants (Wu et al. 2019). Kaparaju et al. (Kaparaju et al. 2009) explored the production of biogas from sugars released from wheat straw with the aid of hydrothermal pretreatment based on the biorefinery procedure. In this case, the pretreatment process increased the gas yield by 10%.
For achieving sustainable progress, the global trend of energy production is moving to the waste-to-energy (WTE) method which has multilateral benefits. Currently, biomass resources are being employed to generate energy. All around the world, biomass satisfies around 50 exajoule of the entire energy demand annually (Steubing et al. 2010; Ferreira et al. 2017; Ahmadi et al. 2020).

A broad spectrum of waste types can be consumed as a feedstock in biogas units by anaerobic digestion (AD) technology. Huge amounts of lignocellulosic waste could be collected from agricultural and municipal resources. The most common types of waste and residuals that can be used in the biogas sector are animal manures and dungs, muck and slurry, domestic/municipal wastewater (sewage), mud (sludge), urban garbage or municipal solid waste (MSW), and food substances loss. Table 2 indicates the power generation and associated yields of biogas production by accessible resources (Waste-to-energy 2015; Stucki et al. 2011).

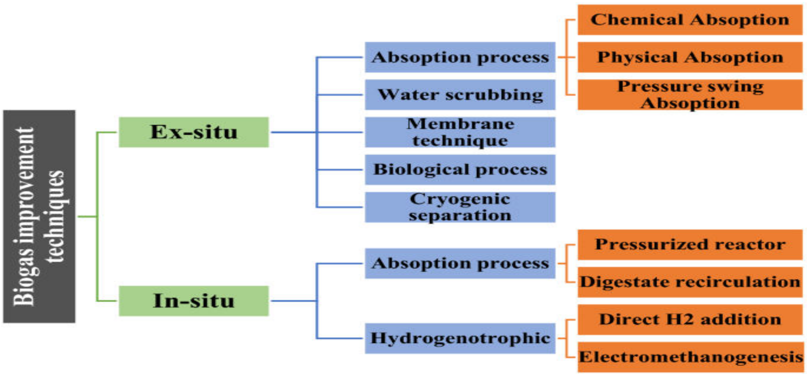
To enhance the yield of biogas production, utilization of additives is an acceptable method. Specifications of these components can be varied based on their biological or chemical properties under various conditions. With the aid of these materials, desirable conditions for bacteria could be provided. However, biocenosis features are vital for achieving the ideal concentration (Demirel and Scherer 2011).

Using salts with Mg and Ca improves methane production efficiency with low slurry foaming (Sreekrishnan et al. 2004). For stabilizing pH fluctuations and reducing the contents of NH_3 and H_2S, several types of additives have been studied (Kuttner et al. 2015). Furthermore, using zeolite compounds has the potential to intensify the quantity of biogas production by 15%, also the addition of $CaCO_3$ can improve this yield by 8%. Adding biological additives increased the production rate of biomethane and biogas by optimizing AD (Vervaeren et al. 2010). Using biological additives is a common way of increasing biogas production yield. Yi Zheng et al. (Zheng et al. 2014) stated that by adding enzymes to lignocellulosic biomass, biogas production was enhanced by 34%. Vervaeren et al. (Vervaeren et al. 2010) reported that by adding homo and hetero-fermentative bacteria to maize components, production yield increased by 22.5%. With the addition of fungi compounds (e.g., ceriporiopsis subvermispora ATCC 96,608) to the yard trimmings, methane production increased by 154% (Zhao 2013). The alternative options for biological additives are chemical compounds. Using a wide variety of chemical additives like NaOH, $Ca(OH)_2$, NH_4OH, H_3PO_4, etc., can improve the associated biogas production yield. Chandra et al. reported the effects of using NaOH as an additive to the wheat straw. Obtained results presented that yield of methane could be improved by up to 112% (Chandra et al. 2012). Badshah et al. investigated the diluted H_2SO_4 properties, added to the sugarcane bagasse, which could increase the production rate by up to 166% in comparison with pre-additive treatments (Badshah et al. 2012).

The impact of activator addition on the biogas quality slurry is investigated in Indonesia (Ginting 2020), the study started by adding new bioactivator prepared from agricultural wastes such as bananas, papayas, and pineapples waste with an additional of chicken intestines where the bacteria in the chicken intestine are effective at work. The addition of the activator resulted optimally in the work where stable gas production was achieved. The slurry at the end of the production process was a liquid fertilizer ready to use. The study showed the best concentration of the activator in the production process of both the slurry and the biogas.

Pretreatment

Predominantly, there are two wide-ranging classifications for biogas production upgradation, ex situ, and in situ techniques, while most of the methods focus on ex situ approaches. Some of the conventional ex situ treatments are adsorption, catalytic processes (e.g., biological or chemical), membrane gas permeation, desulfurization, scrubbing, and absorption. Sarker et al. (2018) overviewed the in situ biogas production upgrades.
With the help of the in situ method, the associated cost concerning cleaning techniques could be reduced and the quality of produced biogas improved in the same vein. Nevertheless, the in situ method is limited to the empirical state and prototype models. Figure 2 summarizes various types of biogas upgrading methods (Sarker et al. 2018; Bassani et al. 2016; Rachbauer et al. 2016; Lemmer et al. 2015).



Biogas improvement by ex situ and in situ techniques (Sarker et al. 2018; Bassani et al. 2016; Rachbauer et al. 2016; Lemmer et al. 2015)

The pretreatment productivity influences the associated bioprocess efficiency of lignocellulose. Pretreatment techniques are intended to make AD faster, enhancing the yield of the biogas, and producing a broad range of usable substrates.

V. CONCLUSIONS

With the new applications of biogas, the worldwide biogas industry has increased by more than 90% between the years 2010 and 2018, while further growth is still expected. However, the biogas industry varies significantly in different locations over all the world. Different countries have developed several types of biogas systems which are mainly dependent on different environments as well as on energy demand and supply chain. In this study, the production processes and specific applications of biogas in recent years were reviewed and discussed. In the lack of oxygen, the disintegration of organic material produces biogas that mostly consists of carbon dioxide and methane. In recent years, the exploitation of biogas and the expansion of its potential applications have gained popularity due to factors like climate change, reasonable energy prices, and an increase in distributed generation. Biogas also traditionally known as an off-grid energy resource and can be used in various applications consisting of electricity production and CHP systems.[25] The following key points are summarized from the study:

- It is envisioned that the extraction of intrinsic chemical energy of biomass with an efficient AD process can be achieved with proper microbial resource management. Further, advanced monitoring and control of the AD process are needed for the hour for decision making to improve the conversion productivity of the procedure by decreasing the loss of potential methane production due to imbalances of biomass charging rate.

- A sustainable circular economy can be created through biomass utilization by recycling organic residues including nutrients in order to bring it back to the society as energy and fuel.

- Upgradation of the existing technology for efficient conversion of biomass-based organic residues to biomethane and its utilization as a substitute natural gas or vehicle fuel is the trending research scope.

- Hydrogen production using a biogas reforming system with high efficiency is one of the recent applications of biogas. The progress in the application of hydrogen as a clean fuel especially for vehicles is very promising.

- Another cutting-edge application of biogas is fuel cells. Recent advances in fuel cells resulting in low emissions (CO_2, NO_x) and high efficiency make them suitable for power generation and transportation purposes.
- Even though the conversion of biomass to biogas through AD has already become a touchable reality in many countries, high financial risks linked to its establishment seek higher financial incentives from the policymakers for sustainable shifting of existing technologies.

Failure of the extraction/utilization of renewable energy sources does not sanction the researchers to explore further, but to transfer any sustainable technology from laboratory to the market seeks ground-breaking effort of the researchers and incentives from the policymakers to handle wisely the transition period of partial/full

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replacement(s)/modification(s) of the existing technologies/ infrastructures, and social acceptance of the simplified—and perhaps definitive—application of the renewables.[26]

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