Chapter 14
An Overview About of Limitations and Avenues to Improve Biogas Production

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Abstract Worldwide, biogas production has been successfully happening in rural and urban areas, catering to livestock and industry. However, there are great obstacles to be overcome and public policies to be developed aiming at the materialization of biogas plants for green energy purposes and recycling of nutrients. In this context, this chapter will discuss the main challenges encountered worldwide in the biogas chain, highlighting the scenario and innovations on biogas chain and the legal and administrative framework/incentives for biogas production and uses.

Keywords Innovations · Bioenergy · Biotechnology · Green energy Administrative framework

14.1 Scenario and Innovations on Biogas Chain

The need to mitigate greenhouse gas (GHS) emissions to climate change control and global energy demands has boosted and stimulated production and biogas. The Paris Agreement, signed at the 21st Conference of the Parties (COP-21) in December 2015, continued the global actions to mitigate GHS emissions, where

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countries signatories of the agreement have entered into national commitments called the National Contribution, to reduce its GHG emissions and prevent of climate change (UNFCCC 2017).

In this context, the biogas is a clean and green source of energy that can contribute to the reduction of carbon footprints. However, small part of the biogas production potential is used in the world, and the usual energy from biogas will depend of composition and properties of biogas, according to feedstock types and their pretreatment and digestion systems model, considering temperature, pH and retention time as main components. Policies for regulation and encouragement of biogas production and use are essential to foster this green energy chain.

This chapter discusses trends and challenges in the chain of biogas, with a view of perspectives (pretreatment, new systems and methods) on the production and yield of biogas, as shown in Fig. 14.1, which outlines key points in this chain.

Biogas production can be carried out from a wide diversity of raw materials, combined or not. The choice for feedstock or substrate should take into account regional availability and potential. This leads to several forms of process optimization for the various substrates (Sun et al. 2015). In addition, the conduction forms are also variable, including different metabolic profiles from the employed microorganisms. Such differences range from the way of obtaining energy and carbon (since the production of methane can occur by secondary fermentation of acetate in chemoorganotrophs or by consumption of H_2 and CO_2 in chemolitotrophs) to the optimum temperature for microbial metabolism.

Regarding the efficiency and yield gain in the biogas production, the concentration of methane has a prominent place, given the extreme importance of CH_4 for the potential of biogas application and valorization. In addition, some impurities can have significant negative impacts on the utilization system, such as corrosion,

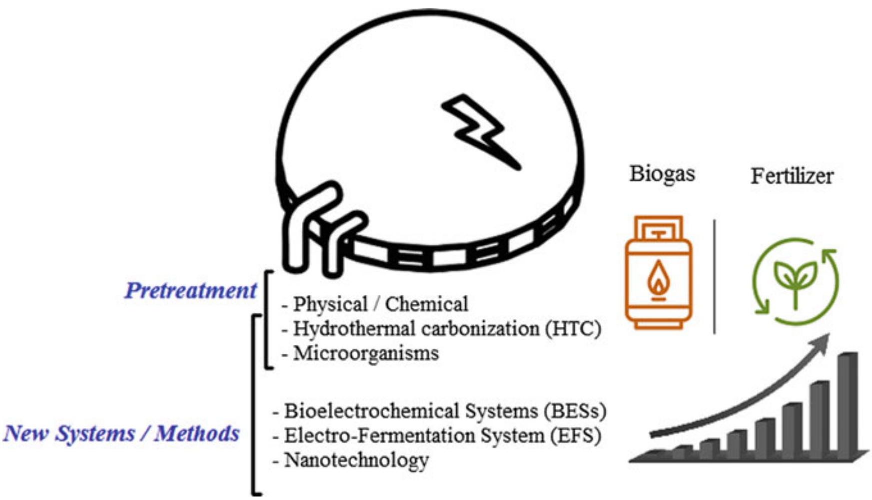

Fig. 14.1 Key points in the biogas chain described in this chapter

uncontrolled emissions and increased risk to human health. In this sense, different biogas cleaning and upgrading technologies have shown to be very promising and have attracted great interest from the bioenergy industry (Sun et al. 2015). Using thermophilic upflow reactors, Bassani et al. (2017) obtained an upgrade from 23 to 96% in the methane content, with the totality of H_2 and CO_2 externally provided being converted to CH_4. With two upflow reactors in series or with bubble column reactors, and with recirculation of the gas produced (for reuse of H_2 and CO_2 by hydrogenotrophic methanogenesis metabolism), Kougias et al. (2017) upgraded the methane content to 98%. More recently, Bu et al. (2018), using a biogas bio-upgrading technique with coke oven gas injection under thermophilic and extreme-thermophilic conditions, verified not only gain in methane yield, but also reduction of lag phase by one-fifty. However, there must be considered the financial, energy and environmental costs for biogas upgrading, in order to verify the feasibility of each strategy employed. More than simply choosing the cheapest technology, it is necessary to select the most appropriate for each circumstance, since the greatest advances are obtained when the technology employed is site-specific and case-sensitive (Sun et al. 2015).

14.1.1 Co-digestion and Pretreatment

Recent studies describe several kinds of co-digestion as alternative technologies for increasing biogas yield in biodigesters (Adelard et al. 2015). In addition to the use of municipal waste, food and animal waste, co-digestion can be performed using crops and animal manure, which is one of the major stakes in increasing biogas production (Wangliang et al. 2016). On the other hand, this strategy is not just a simple mixture; it is necessary to measure the capacity of biogas production and it is imperative to analyze the proportions of each substrate added in order to ensure the highest biomethane potential possible. Valenti et al. (2018), for example, tested six different feedstock mixtures and, when they evaluated their biomethane potential, technical feasibility and economic feasibility, authors verified a difference of up to 100% between the potential of the different tests performed.

Taking into account the co-digestion with lignocellulosic biomass, the pretreatment of the feedstock can contribute greatly with the optimization of the process, in such a way that different research groups have looked for economically viable alternatives to reach this purpose (Paudel et al. 2017). Recently, Thomas et al. (2018) observed an increase of up to 37% on the biochemical methane potential (BMP) using lime (CaO) as a pretreatment of *Miscanthus* biomass. On the same track, Venturin et al. (2018), using swine manure and corn stalk as substrate, detected a 22% increase in the final volume of biogas and a reduction of more than 60% in the time required for digestion, when the lignocellulosic biomass was pretreated with hydrogen peroxide.

The hydrothermal carbonization (HTC) is also an important low-cost alternative for pretreatment of raw materials. It has recently been found that the addition of hydrochar on food waste was able to promote a 2.5-fold increase in methane specific yield (Zhao et al. 2018). In the same line, Gómez et al. (2018), using swine manure as feedstock, obtained a 39% increase in methane production when digestions were supplemented with biochar. It is worth noting that this same benefit was observed, by the same authors, when the raw material employed was pretreated with microwaves. The latter strategy, however, may instill higher production costs.

Still keeping the pretreatment of raw materials as a central point, there are studies focused on the availability of carbohydrates (for conversion to biogas) through swelling agents that facilitate the digestion process of polymers such as cellulose (Hewetson et al. 2016; Shiga et al. 2017). The crystallinity of this polysaccharide is one of the main limiting factors for an efficient hydrolysis of the lignocellulosic biomass and its consequent conversion to biogas. Thus, crystal disruption and the breakdown of hydrogen bonds are necessary to allow the access of enzymes or other catalysts to the cellulose structure, facilitating the hydrolysis of the glycosidic bonds between the glucose monomers. Zhang et al. (2018) have shown that the use of moderate acids such as phosphoric acid and trifluoroacetic acid can promote a more than twofold increase in glucose yield during cellulose hydrolysis with a commercial enzyme.

There are also examples of pretreatments employed in processes that use only one substrate. Lu et al. (2018) employed EDTA to remove organic-bonding metals from sewage sludge and, through this pretreatment, obtained an expressive decrease of these metals in the substrate (from 5.1 to 1.4%). Besides, this assured a 48% increase in methane generation.

The feedstocks for biogas production are so variable that even wool and feather can be used. And even in this context, despite the few studies on the literature, there are already strategies to increase the methane yield through alkaline, thermal, enzymatic and biological pretreatments of these raw materials, which, if combined, can increase up to 20 times the yield of CH_4 (Forgács et al. 2013; Kabir et al. 2013; Patinvoh et al. 2016). In addition to these methods, Kuzmanova et al. (2018) have shown that, by reducing the size of the particles and consequently increasing their solubility and bioavailability, the use of liquid nitrogen (LN_2) can increase the methane yield from wool by more than 80%.

Pretreatments, however, can be economically, energetically and environmentally onerous. Although they may be used to increase biogas yield, the use of some pretreatment technologies can increase energy consumption (with uninteresting unbalance), cost (with the use of hydrolytic enzymes, for example) and even the carbon footprint in the process (Fan et al. 2018). In this sense, researchers have shown that the use of inoculums containing a consortium of interdependent microorganisms previously adapted and selected (as it is carried out in several other bioprocesses that rely on microorganisms) can be beneficial to the production of biogas and may be less expensive and more friendly environment.

14.1.2 Use of Inoculums Consortium—Microorganisms

The prevalence of some anaerobic microorganisms can affect hydrolytic and methanogenic activities, which provides different yield degrees to the process. It has already been verified that the inoculum performed with a selection of high hydrolysis efficiency bacteria and with methanogenic archaea increases the methane yield in biodigesters using seaweed biomass as substrate (Sutherland and Varela 2014), and that the inoculation reduced by half the lag phase of processes carried out with swine wastewater (Córdoba et al. 2016). Indeed, the selection and adaptation of microorganisms at the same time decreases diversity and increases specificity, which directly affects yield (De Francisci et al. 2015). Given the low cost of selection and maintenance of microorganisms and the non-energetic and environmental burden, this can be an interesting technology. In this sense, Gonzalez-Fernandez et al. (2018) have shown that in microalgae biomass, the use of previously adapted anaerobic microorganisms may prevent the application of pretreatments which, although may slightly increase the yield, can be costly.

Moreover, in the field of microorganism selection, the so-called bioaugmentation appears to be promising among low-cost technologies to increase the yield of biogas, opening up even the possibility of using genetically modified organisms (Nzila 2017). The literature presents several very recent works, with different microorganisms used, both fungi and bacteria, under different conditions of temperature and substrates. In biodigesters with cow manure, the bioaugmentation with an enriched cow rumen culture promoted a nearly sixfold increase in methane production (Ozbayram et al. 2018). In another work, the combination of pretreatment by steam explosion with the bioaugmentation by a cellulolytic bacterium (*Caldicellulosiruptor bescii*) increased in 140% the methane yield compared to the untreated birch in processes with lignocellulosic biomass (Mulat et al. 2018). Ferraro et al. (2018) found that a combination of anaerobic ruminal fungi and a pool of hydrogen-producing fermentation bacteria allowed an increase of up to 330% in wheat straw and mushroom spent straw when compared to the unaugmented condition.

14.1.3 Innovative Systems

Another innovative and very promising technology for the production of biogas with high yield is the Bioelectrochemical Systems (BESs). These low-cost systems are based on biological and electrochemical processes, which can be used to exploit waste to increase the generation of different products of interest, including biogas (Sasaki et al. 2010, 2018a; Schievano et al. 2016). In the last ten years, different BESs have been developed and, more recently, it has been verified that the presence of an anode and a cathode can control microbial fermentations by overcoming the thermodynamic limits of some metabolic pathways. In BESs, called

Electro-Fermentation System (EFS), the electrodes function as a supplementary electron source or sink, affecting both extracellular and intracellular oxidation-reduction potential. Thus, in addition to exerting significant effects on microbial metabolism and cellular regulation, an EFS also influences the interspecific interactions and the selection of bacteria in the processes (Moscoviz et al. 2016). Recently, Sasaki et al. (2018b) have demonstrated an increase in the proportion of methane in the biogas produced even in two-stage processes from these systems.

Nanotechnology also deserves notoriety among the strategies that promote high productivity and yield increase in biogas production. Quan et al. (2017) reported a molecular basket sorbent, based on tertiary amine supported over mesoporous silica, with high selectivity for removal of H_2S from the biogas, which ends up increasing the desired proportion of CH_4. In another recent study, Anjum et al. (2018) have synthesized nanotubes composed of carbon nitride and titania (C_3N_4/TiO_2) aiming to improve the increase visible light-mediated photocatalytic degradation of wastewater sludge. In this approach, they verified an increase of up to 60% in methane generation. From brewery wastewater, Carpenter et al. (2015) demonstrated that the addition of 0.25% nanoscale zerovalent iron (NZVI) to the bioreactors promoted a 28% increase in methane production and a 58% decrease in CO_2 release. It has also been verified that the addition of nanoparticles of trace metals to livestock manures biodigesters can increase the yield of biogas by 80% and by more than 100% the methane yield in this biogas (Abdelsalam et al. 2016).

14.1.4 Post-digestion

Finally, in addition to the concern with the yield gain in biogas production, there is also concern about the use and stability of the digestates. Although they are often used in agriculture (Tambone et al. 2010), unstable digestate may still have potential for extra biogas production, and thus, post-digestion may contribute not only to increased biogas production, but also with the reduction of environmental and health impacts, since these digestates may even promote higher proliferation of pathogens (Abdullahi et al. 2008).

Wojnowska-Baryła et al. (2018) point out the possibility of using the digestate for a psychrophilic post-digestion, which allows, in addition to an increase in methane production, a reduction of uncontrolled emission of this gas into the atmosphere—which would occur if unstable digestate were employed in agriculture without a post-digestion (thereby increasing the release of greenhouse gas into the atmosphere). In this work, the authors demonstrated the possibility of an additional of up to 27% in biogas productivity, using the same raw materials through post-digestion. Thus, post-digestions can generate not only a production gain, but also provide mitigation of process impacts.

14.2 Legal and Administrative Framework/Incentives for Biogas Production and Use

The main discussions on renewable energy production took place in the 1970s due to concerns about high GHG emissions, discussed at the Stockholm Conference in 1972, and the intense oscillation in the fossil fuels price during the oil crises of 1973 and 1979. Since then, discussions have been held with the aim of establishing government policies to stimulate the production and use of renewable energy throughout the world.

In the last four decades, Europe has emerged in production accounting for 72.3% of the total biogas produced in the world in 2016. Among the main biogas producers are Germany as the world leader (33,803 GWh), followed by the USA (13,466 GWh), Italy (8259 GWh), UK (7706 GWh) and Czech Republic (2590 GWh) (IRENA 2018b). High production in the Europe countries is due to biogas being considered one of the key technologies both to reach RED (Renewable Energy Directive) targets for renewable energies in 2020—renewable energy as 20% share of total energy consumption (Directive 2009/28/CE; EU 2009)—and to meet their requirements within the European organic waste management directive as energy source (Directive 2006/12/CE; EU 2006). In 2014, European Parliament also establishes regulations for the implementation of an infrastructure for alternative fuels (Directive 2014/94/UE; EU 2014). However, the incentives have been different for each country, since the final product should consider local needs and feedstock materials (Pfau et al. 2017), as will be summarized below.

Germany stands out not only because of the greater biofuel volume, but also because it started production more than four decades ago. A great example of biogas incentive policies has been observed in this country, where the first projects were operated in the 1970s by farmers mainly to use liquid and solid manure and feed leftovers in a useful way, to protecting the climate and avoid GHG emissions and to generate electricity and heat for its own operation ($\sim$70 kW; Markard et al. 2016). In 1991, the country adopted the feed-in tariff system (StrEG), which guaranteed the incentive of 6.5 eurocents/kWh for electricity generated (<500 kW) from landfill gas and sewage gas and 7.1 eurocents/kWh for biomass-based energy (<150 kW) (Wütenhagen and Bilharz 2006). In 2000, the StrEG system was updated within the Energy Renewable Sources Act (Erneuerbare-Energien-Gesetz—EEG), revised in 2004, which was mainly based on: (i) the right of grid connection for renewable energy facilities, (ii) the obligation for grid operators to preferentially purchase electricity based on renewables, and (iii) a minimum feed-in tariff to be paid for the generated electricity (Daniel-Gromke et al. 2018). This update marked a strong development of biogas through different rules for each renewable energy technology, as well as stimulating the use of energy crops, an important fact when the country was experiencing a reduction in agricultural production, closure of farms and availability of agricultural areas (Markard et al. 2016). Thus, Germany increased from approximately 100 to 4000 biogas plants between

1990 and 2008 (Koçar and Civaş 2013), and a new generation of larger mills (∼300 kW) was introduced by the implementation of the feed-in tariff guarantee for a period of 20 years (Markard et al. 2016).

From 2009, the EU Biomass Action Plan was presented to intensify the energetic use of biomass, adopting new specific incentives like manure bonus (using animal manure), landscape bonus (garden and plant biomass) and biomass bonus (rejected crops or crop residue) to avoid further pressure on food prices (Britz and Delzeit 2013; Edwards et al. 2015). In the same year, EEG was revised adding a special bonus for substrates composed of at least 30% of animal waste and minimum use of heat in cogeneration (Markard et al. 2016). In the biomass-based electricity generation in Germany 2017, of a total of 51.4 billion kWh, 63.2% resulted from biogas production (AGGE-Stat 2018). Thus, after the consolidation of large plants, EEG 2017 changed the funding for renewable energy sources from a fixed tariff to a tender system (Daniel-Gromke et al. 2018). It has also been imposed the condition need-based and flexible electricity generation and limited use of grain and maize until 50% by weight, for food security (FNR 2017), which led Scandinavia, for example, to ban the use of energy crops for biogas production (EurObserv'ER 2017). Currently, German has more than 10,000 plants in operation, where biogas production occurs mainly from agricultural substrates (87.8%) to generate electricity (58.1%), heat (32.9%), flaring (8.0%) and vehicle fuel (IEA 2017a).

The USA, the world's second largest producer of biogas, has the anaerobic digestion industry well established in terms of utilizing sewage sludge as a substrate, most of which supply combined heat and power (CHP) units (Edwards et al. 2015). The energy security is considered a key driver fostering renewable energy and anaerobic digestion in the country. Initially, the country relies on two pieces of legislation: The renewable portfolio standard (RPS), which administers the selling of renewable energy credits, as feed-in tariffs and setting of renewable energy quotas, is paramount in providing financial incentives for anaerobic digestion. In 2014, the White House released its strategy to reduce methane emissions under the Climate Action Plan—Strategy to Reduce Methane Emissions to accelerate the adoption of biogas systems, with the goal of reducing GHG emissions across the sector's value chain by 25% by 2020 (USDA 2014). Thus, there is a growing trend to upgrade the gas to biomethane for use in transport, where it qualifies as an advanced biofuel. California ranks first among USA states for methane production potential from biogas sources (ABC 2015). This sector grew some 15% in 2017 (REN21 2018). Actually, the USA has in operation over 2200 sites producing biogas, of which 1269 water resource recovery facilities using an anaerobic digester (∼860 currently use the biogas they produce), 652 landfill gas projects, 250 anaerobic digesters on farms, and 66 stand-alone systems that digest food waste (ABC 2018). Almost half of the biogas is used for electricity and half for heat production (IRENA 2017b).

Italy and UK stand out as the second and third largest European biogas producers, respectively, but with a production around 76.4% less than Germany. The biogas production in Italy is mainly used as electricity (78%) by commerce (55%) and industry (45%) (IRENA 2018b). In the country, support schemes for renewable energy sources (RES) are managed by Gestore dei Servizi Energetici (GSE—Manager of Electricity Services), using green certificates system. The Ministerial Decree from IT (2008) and the decrees that preceded it have provides that the qualification of the powered by renewable sources (IAFR qualification) was necessary prerequisite for obtaining green certificate or for access to the all-inclusive tariff based on the net electricity produced and fed into the grid. The higher incentives were for biogases obtained from agriculture, animal husbandry and forestry (Law no. 99/2009). However, the main incentive to electricity generation by biogas production occurred in 2012 with the DM 6/7/2012 (IT 2012), which included a different feed-in tariff (*tariffa onnicomprensiva*, TO, in italian) and premium tariff, where plants with a capacity up to 100 kW and between 1 kW to 5 MW can access incentives directly, respectively; and tenders eligible for capacities above 5 MW (Jimeno 2015). The number of plants under the TO regime increased from 33 (21 MW) in 2008 to 1082 (803 MW) in 2015 (GSE 2015) and still in 2015 there were a total of 414 biogas plants that requested government incentives and produced a total power of 159 MW (Carlini et al. 2017). From 2016, the green certificate was extinguished and two types of incentives were offered: (i) an all-inclusive tariff (TO); and (ii) an incentive (I), calculated as the difference between a fixed value and the zonal energy hour price (GSE 2017). For systems with power up to 500 kW, it is possible to choose both modes alternatively, but systems with a capacity of more than 500 kW can instead access only the incentive. Following the Germany example, Italy directed higher incentives to small-medium size biogas plants (IEA 2016). In the last six years, the country has invested more than 4 billion Euros in more than 1700 biogas plants already built, including agricultural, sewage, waste and industrial subproducts (Maggioni 2017), of which about 65% an electric performance below 500 kW (GSE 2015). Currently, the National Energy Strategy has designed strong incentives for the production of biomethane in the country, which uses about 3 billion N/m^3 biomethane equivalent per year (Maggioni 2017). According to CIB (Consorzio Italiano Biogas), the country is able to generate a potential of 10 billion m^3 by 2030, of which at least eight from agricultural feedstock.

In the UK, the renewable support scheme is based on the Energy Act 2008 (Hermann and Hermann 2018) and managed by the Office of Gas and Electricity Markets (OFGEM). The regulations and financial incentives apply to biogas production include the Renewables Obligation (RO) and the feed-in tariff (FIT) for electricity, and the Renewable Heat Incentive (RHI) for heat production from biogas combustion and biomethane injection to the grid. The scheme FIT scheme came into effect in 2010 and aimed to support small-scale renewable energy sources plants (<5 MW) and the RO system (revised by the FTO 2012; UK 2012) was to support mainly plants above 5 MM, besides tax regulation mechanism (Maroulis 2015; Hermann and Hermann 2018). While Italy is an example of selective collection, composting of food and garden waste was incentive later for AD industries in UK (Jain et al. 2018), and mainly driven by its conversion into electricity until 2016. By 2015, British per capita biogas production was 404 kWh compared to 284 kWh in 2005, a 42% increase (Deremince and Königsberger 2017). Between

2015 and 2016, the Department for Business, Energy and Industrial Strategy reports that biogas electricity production from anaerobic digestion increased to 2.1 TWh or by 40% (EurObserv'ER 2017). In 2017, UK had 557 operational plants and capacity of 730 MWe, with 83.6% related only to electricity or to CHP plants. Electricity generated by small biogas plants (<500 kWe) and mostly biomethane production uses agricultural feedstocks. Medium- and large-scale biogas plants (>500 kWe) preferably use sewage, followed by agricultural and municipal/ commercial waste as feedstocks (IEA 2017c). After a period of degressions in the FIT scheme (Maroulis 2015), new incentives are being directed toward upgrading biogas plants to biomethane, which is feasible in the UK because there is already an extensive gas distribution network. In October 2017, the UK adopted Clean Growth Strategy that targets government fundings of £2.5 billion mainly to accelerate the shift to low carbon transport (33%) and deliver clean, smart and flexible power (25%) (Damave 2018).

There have been an increasing number of countries, states or provinces adhering to the RED rules. Targets and policies for renewable energy had been established actually in more than 100 countries, a significant increase from 47 countries in 2007 (Song et al. 2014; REN21 2018). Germany, Austria, Denmark and Switzerland use more than 50% of the biogas produced in electricity. On the other hand, Finland and the Netherlands use most of it for heat generation and Sweden and Norway for biomethane (IEA 2016). Sweden leads Europe in the use of biogas fuel for vehicles (EurObserv'ER 2017). According to Energigas Sverige, 64% of total biogas output in 2016 (put at 2 TWh) was converted into biomethane, which was used almost exclusively for vehicle fuel. The country has 63 biogas enrichment plants that produced 1234 GWh of biomethane in 2016, and 13 plants that injected it directly into the country's two natural gas grids (EurObserv'ER 2017). The incentive to produce biomethane has been due to the need to reduce or even ban dependence on fossil fuels. In 2017, five countries announced their intention to ban sales of new diesel and petrol cars by 2030: India (Vidhi and Shrivastava 2018), the Netherlands and Slovenia (REN21 2018); and by 2040: France and the UK (EPRI 2017; IEEJ 2017). Since biomethane has a similar quality to natural gas, it is in fact a potentially substitute for fossil natural gas. Iran, China and Pakistan are the countries with greater number of natural gas vehicles (IRENA 2017b). Another incentive in the production and the consumption of biogas-derived electricity is the use and expansion of electric vehicles (Podkaminer et al. 2017).

In Asia, China has been producing biogas in a small scale (at household level), promoted by the government, since 1920. Currently, biogas production in rural areas of China comes from two primary sources: household biogas digester, and medium- and large-scale biogas plants. The Chinese government issued the renewable energy law and renewable energy prices and cost-sharing management trial procedures in 2005 to encourage various domestic enterprises to become involved in renewable energy development (revised by Song et al. 2014). In ten years, the offered financial incentive increased from 47 million dollars (in 2002) to 760 million dollars (in 2011) (Feng et al. 2012), which allowed the construction of 42 million small (8–12 m^3) household biogas digesters and 27 thousand medium-and large-scale biogas plants in China between 2003 and 2013 (IGU 2015) and 850 for large livestock and poultry farms between 2001 and 2005. After 2009, China has enhanced its support for biogas engineering projects by offering subsidies from 25 to 45% of the whole cost of projects, setting up policies similar to feed-in tariffs to promote power generation through biogas plants, for improving the efficiency of biogas production and utilization (Gu et al. 2016). Large-scale biogas projects focused mainly on agricultural and industrial (including municipal) wastes. In 2016, China produced 1863 GWh of biogas, Asia's second largest producer, behind only Thailand (IRENA 2018b).

Significant growth is also estimated for the South-Central and South-Eastern Asian countries such as Bangladesh, Cambodia, Vietnam, Indonesia and Nepal (REN21 2018), where the biogas will continue to be limited to meeting the primary energy needs (light and cooking), mainly in rural areas. In Bangladesh, for example, the National Domestic Biogas and Manure Programme has been supporting the expansion of biogas technology in rural areas, and an estimated 80,000 small-scale systems that use animal waste are in operation (IEA 2017b). In Vietnam, the Biogas Programme for the Animal Husbandry Sector was launched in 2003 and facilitated the construction of nearly 250,000 small biogas digesters (IRENA 2018a).

As in Asia, most heat demand in Africa is for cooking, with the majority supplied from traditional biomass, which can have serious impacts on health and generally is not sustainably produced (IEA 2014). More than 58,000 biogas cookstoves were installed by the end of 2016, from Africa Biogas Partnership Programme "Progress tracker" Burkina Faso, Ethiopia, Kenya, Tanzania and Uganda since 2009 (REN21 2018). Globally, a cumulative total of more than 50 million biogas cookstoves had been installed as of year-end 2016, with about 126 million people using biogas for cooking (IRENA 2017a). However, investment in access to clean cooking in developing countries reaches a cumulative $20 billion over the period to 2030, providing cleaner cooking access for almost 900 million more people (IEA 2017b).

In Latin America, Brazil stands out as the largest producer of biogas (873 GWh, in 2015), followed by Argentina (120 GWh) and Peru (50 GWh) (IRENA 2018b). Incentives in Brazil started effectively in 2009 with the institution of National Policies for Climate Change (Federal Law nº 12.187/2009; Brasil 2009) and Solid Waste (Federal Law nº 12.305/2010; Brasil 2010), which included the low-carbon program and the incentive program for alternative sources of energy. In 2012, the Rio de Janeiro state (State Law nº 6361/12; RJ 2012) made mandatory the injection of 10% of the biogas from municipal solid waste into the piped gas local distribution network. In the following year, the state of São Paulo reduced the tax on the internal exits of biogas and biomethane, as an incentive in its production (Decreto nº 60.001/13; SP 2013). In 2015, along with other 194 countries, Brazil adheres to the Paris Agreement and commits to meet targets for reducing GHG emissions by 37% by 2025, compared to 2005. Brazil currently has (2017) 127 biogas plants in operation (Itaipu 2017), and 22 registered units (CIBiogás 2017), where most of them (47%) utilized agricultural substrates and 34% used industry substrates, mainly for heat and electric power. However, in relation to the amount of biogas produced for energy purposes, 43% of it originates from sanitary landfills, 29% from agriculture substrates and 22% from industry (CIBiogás 2017).

14.3 Final Considerations

The current biogas scenario corroborates with decision-making and investment initiatives in world, aimed at reducing fossil-based emissions and increasing renewable energy. Even though the production and use of biogas have been considered feasible from the "sustainable economy" point of view, as discussed in this book, it is necessary news perspectives on cost reduction of deployment and operation of biogas units and political support to biogas production and use in the whole world.

References

ABC (2015) Biogas state profile: California. American Biogas Council, Washington, 5 p. https://www.americanbiogascouncil.org/State%20Profiles/ABCBiogasStateProfile_CA.pdf

ABC (2018) Operational and potential US biogas system. American Biogas Council, Washington, 2 p. https://www.americanbiogascouncil.org/pdf/ABC%20Biogas%20101%20Handout%20NEW.pdf

Abdelsalam E, Samer M, Attia YA, Abdel-Hadi MA, Hassan HE, Badr Y (2016) Comparison of nanoparticles effects on biogas and methane production from anaerobic digestion of cattle dung slurry. Renewable Energy 87:592–598

Abdullahi YA, Akunna JC, White NA, Hallett PD, Wheatley R (2008) Investigating the effects of anaerobic and aerobic post-treatment on quality and stability of organic fraction of municipal solid waste as soil amendment. Bioresour Technol 99:8631–8636

Adelard L, Poulsen TG, Rakotoniaina V (2015) Biogas and methane yield in response to co- and separate digestion of biomass wastes. Waste Manag Res 33:55–62

AGGE-Stat (2018) Development of renewable energy sources in Germany 2017. Renewable Energy-Statistics, Federal Ministry for Economic Affair and Energy, 44 p

Anjum M, Kumar R, Abdelbasir SM, Barakat MA (2018) Carbon nitride/titania nanotubes composite for photocatalytic degradation of organics in water and sludge: pretreatment of sludge, anaerobic digestion and biogas production. J Environ Manage 223:495–502

Bassani I, Kougias PG, Treu L, Porté H, Campanaro S, Angelidaki I (2017) Optimization of hydrogen dispersion in thermophilic up-flow reactors for ex situ biogas upgrading. Bioresour Technol 234:310–319

BRASIL (2009) Federal Law nº 12.187/2009. http://www.planalto.gov.br/ccivil_03/_ato2007-2010/2009/lei/l12187.htm

BRASIL (2010) Federal Law nº 12.305/2010. http://www.planalto.gov.br/ccivil_03/_Ato2007-2010/2010/Lei/L12305.htm

Britz W, Delzeit R (2013) The impact of German biogas production on European and global agricultural markets, land use and the environment. Energy Policy 62:1268–1275

Bu F, Dong N, Kumar Khanal S, Xie L, Zhou Q (2018) Effects of CO on hydrogenotrophic methanogenesis under thermophilic and extreme-thermophilic conditions: microbial community and biomethanation pathways. Bioresour Technol 266:364–373

Carlini M, Mosconi EM, Castellucci S, Villarini M, Colantoni A (2017) An economical evaluation of anaerobic digestion plants fed with organic agro-industrial waste. Energies 10:1165

Carpenter AW, Laughton SN, Wiesner MR (2015) Enhanced biogas production from nanoscale zero valent iron-amended anaerobic bioreactors. Environ Eng Sci 32:647–655

CIBiogás (2017) Mercosur biogas and biomethane report. GAHB—Mercosur Ad Hoc Group on Biofuels. CIBiogás, Foz do Iguaçu, 58 p

Córdoba V, Fernández M, Santalla E (2016) The effect of different inoculums on anaerobic digestion of swine wastewater. J Environ Chem Eng 4:115–122

Damave M-C (2018) Key points of the agr'iDay of 03/07/2018: innovating for the future: bioeconomy in the UK and France. 11 p

Daniel-Gromke J, Rensberg N, Denysenko V, Stinner W, Schmalfuβ T, Scheftelowitz M, Nelles M, Liebetrau J (2018) Current developments in production and utilization of biogas and biomethane in Germany. Chem Ing Tech 90:17–35

De Francisci D, Kougias PG, Treu L, Campanaro S, Angelidaki I (2015) Microbial diversity and dynamicity of biogas reactors due to radical changes of feedstock composition. Bioresour Technol 176:56–64

Deremince B, Königsberger S (2017) Statistical report 2017. European Biogas Association, Brussels, p 13

Edwards J, Othman M, Burn S (2015) A review of policy drivers and barriers for the use of anaerobic digestion in Europe, the United States and Australia. Renew Sustain Energy 52: 815–828

EPRI (2017) Implications of the UK's ban on petrol and diesel vehicles by 2040. Electric Power Research Institute: Quick Insights, California, p 7

EU (2006) Directive 2006/12/CE. https://eur-lex.europa.eu/eli/dir/2006/12/oj

EU (2009) Directive 2009/28/CE. https://eur-lex.europa.eu/eli/dir/2009/28/oj

EU (2014) Directive 2014/94/UE. https://eur-lex.europa.eu/eli/dir/2014/94/oj

EurObserv'ER (2017) Biogas barometer. 14 p. https://www.eurobserv-er.org/biogas-barometer-2017/

Fan YV, Klemeš JJ, Lee CT, Perry S (2018) Anaerobic digestion of municipal solid waste: energy and carbon emission footprint. J Environ Manage 223:888–897

Feng Y, Guo Y, Yang G, Qin X, Song Z (2012) Household biogas development in rural China: on policy support and other macro sustainable conditions. Renew Sustain Energy Rev 16: 5617–5624

Ferraro A, Dottorini G, Massini G, Mazzurco Miritana V, Signorini A, Lembo G, Fabbricino M (2018) Combined bioaugmentation with anaerobic ruminal fungi and fermentative bacteria to enhance biogas production from wheat straw and mushroom spent straw. Bioresour Technol 260:364–373

FNR (2017) Bioenergy in Germany—facts and figures 2016. Federal Ministry of Food and Agriculture, Gülzow-Prüzen, p 51

Forgács G, Lundin M, Taherzadeh MJ, Sárvári Horváth I (2013) Pretreatment of chicken feather waste for improved biogas production. Appl Biochem Biotechnol 169:2016–2028

Gómez X, Meredith W, Fernández C, Sánchez-García M, Díez-Antolínez R, Garzón-Santos J, Snape CE (2018) Evaluating the effect of biochar addition on the anaerobic digestion of swine manure: application of Py-GC/MS. Environ Sci Pollut Res Int. https://doi.org/10.1007/s11356-018-2644-4

Gonzalez-Fernandez C, Barreiro-Vescovo S, de Godos I, Fernandez M, Zouhayr A, Ballesteros M (2018) Biochemical methane potential of microalgae biomass using different microbial inocula. Biotechnol Biofuels 11:184

GSE (2015) Incentivazione delle fonti rinnovabili. Bollettino: Gestore Servizi Energetici. 77 p

GSE (2017) Incentivazione delle fonti rinnovabili. Bollettino: Gestore Servizi Energetici. 97 p

Gu L, Zhang Y-X, Wang J-Z, Chen G, Battye H (2016) Where is the future of China's biogas? Review, forecast, and policy implications. Pet Sci 13:604–624
Hermann L, Hermann R (2018) Report on regulations governing AD and NRR in EU member states. Systemis: circular solutions for biowaste. The Netherlands, 123 p
Hewetson BB, Zhang X, Mosier NS (2016) Enhanced acid-catalyzed biomass conversion to hydroxymethylfurfural following cellulose solvent-and organic solvent-based lignocellulosic fractionation pretreatment. Energy Fuels 30:9975–9977
IEA (2014) Africa energy outlook: a focus on energy prospects in sub-saharan Africa. World energy outlook special report. International Energy Agency, Paris, p 237
IEA (2016) Energy policies of IEA countries: Italy 2016 review. International Energy Agency, Paris, p 210
IEA (2017a) Bioenergy task 37 biogas: country report Germany. International Energy Agency
IEA (2017b) Energy access outlook 2017. International Energy Agency, Paris, p 140
IEA (2017c) UK country reports. IEA bioenergy task 37. International Energy Agency
IEEJ (2017) Outlook 2018—prospects and challenges until 2050: energy, environment and economy. The Institute of Energy Economics, Japan, p 22
IGU (2015) Biogas—from refuse to energy. International Gas Union, Fornebu, p 19
IRENA (2017a) Biogas for domestic cooking: technology brief. International Renewable Energy Agency, Abu Dhabi, p 31
IRENA (2017b) Biogas for road vehicles: technology brief. International Renewable Energy Agency, Abu Dhabi, p 61
IRENA (2018a) Off-grid renewable energy solutions: global and regional status and trends. International Renewable Energy Agency, Abu Dhabi, p 20
IRENA (2018b) Renewable energy statistics 2018. International Renewable Energy Agency, Abu Dhabi, p 347
IT (2008) Ministerial decree 18/12/2008. http://www.energia.provincia.tn.it/binary/pat_agenzia_energia/normativa/Min.svil.econ._DM%2018.12.08.1233048510.pdf
IT (2012) Ministerial decree 06/07/2012. https://www.gse.it/servizi-per-te/fonti-rinnovabili/fer-elettriche/incentivi-dm-06-07-2012
ITAIPU (2017) Relatório annual 2017. Itaipu Binacional, 141 p
Jain S, Newman D, Cepeda-Márquez R, Zeller K (2018) Global food waste management: an implementation guide for cities. World Biogas Association, London, p 143
Jimeno M (2015) Renewable energy policy database and support—RES-LEGAL EUROPE. National profile: Italy. Eclareon GmbH, Berlin, p 146
Kabir MM, Forgács G, Horváth IS (2013) Enhanced methane production from wool textile residues by thermal and enzymatic pretreatment. Process Biochem 48:575–580
Koçar G, Civaş N (2013) An overview of biofuels from energy crops: current status and future prospects. Renew Sustain Energy Rev 28:900–916
Kougias PG, Treu L, Benavente DP, Boe K, Campanaro S, Angelidaki I (2017) Ex-situ biogas upgrading and enhancement in different reactor systems. Bioresour Technol 225:429–437
Kuzmanova E, Zhelev N, Akunna JC (2018) Effect of liquid nitrogen pretreatment on various types of wool waste fibres for biogas production. Heliyon 4:e00619
Lu YQ, Xu Y, Dong B, Dai XH (2018) Enhancement of anaerobic methane production by removal of organic-bonding metals from sewage sludge. Huan Jing Ke Xue 39:284–291
Maggioni L (2017) Biomethane: the Italian way for sustainable mobility. https://www.ahk-italien.it/fileadmin/AHK_Italien/Documents/Events/2017/EEE_Biogas_26-28.09.2017/09_Consorzio_Italiano_Biogas_Maggioni.pdf
Markard J, Wirth S, Truffer B (2016) Institutional dynamics and technology legitimacy—a framework and a case study on biogas technology. Res Policy 45:330–344
Maroulis G (2015) Renewable energy policy database and support—RES-LEGAL EUROPE. National profile: United Kingdom. Eclareon GmbH, Berlin, p 117
Moscoviz R, Toledo-Alarcón J, Trably E, Bernet N (2016) Electro-fermentation: how to drive fermentation using electrochemical systems. Trends Biotechnol 34:856–865

Mulat DG, Huerta SG, Kalyani D, Horn SJ (2018) Enhancing methane production from lignocellulosic biomass by combined steam-explosion pretreatment and bioaugmentation with cellulolytic bacterium *Caldicellulosiruptor bescii*. Biotechnol Biofuels 11:19

Nzila A (2017) Mini review: update on bioaugmentation in anaerobic processes for biogas production. Anaerobe 46:3–12

Ozbayram EG, Akyol Ç, Ince B, Karakoç C, Ince O (2018) Rumen bacteria at work: bioaugmentation strategies to enhance biogas production from cow manure. J Appl Microbiol 124:491–502

Patinvoh RJ, Feuk-Lagerstedt E, Lundin M, Sárvári Horváth I, Taherzadeh MJ (2016) Biological pretreatment of chicken feather and biogas production from total broth. Appl Biochem Biotechnol 180:1401–1415

Paudel SR, Banjara SP, Choi OK, Park KY, Kim YM, Lee JW (2017) Pretreatment of agricultural biomass for anaerobic digestion: current state and challenges. Bioresour Technol 245:1194–1205

Pfau SF, Hagens JE, Dankbaar B (2017) Biogas between renewable energy and bio-economy policies—opportunities and constraints resulting from a dual role. Energy Sustain Soc 7:17

Podkaminer K, Xie F, Lin Z (2017) Analyzing the impacts of a biogas-to-electricity purchase incentive on electric vehicle deployment with the MA3T vehicle choice model. Oak Rodge National Laboratory, Oak Ridge, p 40

Quan W, Wang X, Song C (2017) Selective removal of H_2S from biogas using solid amine-based "molecular basket" sorbent. Energy Fuels 31:9517–9528

REN21 (2018) Renewables 2018: global status report. Renewable Energy Policy Network for the 21st Century, Paris, 324 p

RJ (2012) State Law nº 6361/12. https://gov-rj.jusbrasil.com.br/legislacao/1033645/lei-6361-12

Sasaki K, Sasaki D, Morita M, Hirano S, Matsumoto N, Ohmura N, Igarashi Y (2010) Bioelectrochemical system stabilizes methane fermentation from garbage slurry. Bioresour Technol 101:3415–3422

Sasaki K, Sasaki D, Kamiya K, Nakanishi S, Kondo A, Kato S (2018a) Electrochemical biotechnologies minimizing the required electrode assemblies. Curr Opin Biotechnol 50: 182–188

Sasaki K, Sasaki D, Tsuge Y, Morita M, Kondo A (2018b) Changes in the microbial consortium during dark hydrogen fermentation in a bioelectrochemical system increases methane production during a two-stage process. Biotechnol Biofuels 11:173

Schievano A, Pepé Sciarria T, Vanbroekhoven K, De Wever H, Puig S, Andersen SJ, Rabaey K, Pant D (2016) Electro-fermentation—merging electrochemistry with fermentation in industrial applications. Trends Biotechnol 34:866–878

Shiga TM, Xiao W, Yang H, Zhang X, Olek AT, Donohoe BS, Liu J, Makowski L, Hou T, McCann MC, Carpita NC, Mosier NS (2017) Enhanced rates of enzymatic saccharification and catalytic synthesis of biofuel substrates in gelatinized cellulose generated by trifluoroacetic acid. Biotechnol Biofuels 10:310

Song Z, Zhang C, Yang G, Feng Y, Ren G, Han X (2014) Comparison of biogas development from households and medium and large-scale biogas plants in rural China. Renew Sustain Energy Rev 33:204–213

SP (2013) Decreto nº 60.001/13. https://www.al.sp.gov.br/repositorio/legislacao/decreto/2013/decreto-60001-20.12.2013.html

Sun Q, Li H, Yan J, Liu L, Yu Z, Yu X (2015) Selection of appropriate biogas upgrading technology—a review of biogas cleaning, upgrading and utilization. Renew Sustain Energy Rev 51:521–532

Sutherland AD, Varela JC (2014) Comparison of various microbial inocula for the efficient anaerobic digestion of *Laminaria hyperborea*. BMC Biotechnol 14:7

Tambone F, Scaglia B, D'Imporzano G, Schievano A, Salati V, Adani F (2010) Assessing amendment and fertilizing properties of digestates from anaerobic digestion through a comparative study with digested sludge and compost. Chemosphere 81:577–583

Thomas HL, Seira J, Escudié R, Carrère H (2018) Lime pretreatment of miscanthus: impact on BMP and batch dry co-digestion with cattle manure. Molecules 23:E1608

UK (2012) The feed-in tariffs order (FTO) 2012. https://www.legislation.gov.uk/uksi/2012/2782/contents/made

UN Climate Change Conference (2017) COP23—governments meet to fast forward implementation of Paris agreement's goals UN climate change news. Bonn, 5 Nov 2017

USDA (2014) Biogas opportunities roadmap. U.S. Department of Agriculture, U.S. Environmental Protection Agency, U.S. Department of Energy, 27 p

Valenti F, Porto SMC, Selvaggi R, Pecorino B (2018) Evaluation of biomethane potential from by-products and agricultural residues co-digestion in southern Italy. J Environ Manage 223:834–840

Venturin B, Frumi Camargo A, Scapini T, Mulinari J, Bonatto C, Bazoti S, Pereira Siqueira D, Maria Colla L, Alves SL Jr, Paulo Bender J, Luís Radis Steinmetz R, Kunz A, Fongaro G, Treichel H (2018) Effect of pretreatments on corn stalk chemical properties for biogas production purposes. Bioresour Technol 266:116–124

Vidhi R, Shrivastava P (2018) A review of electric vehicle lifecycle emissions and policy recommendations to increase EV penetration in India. Energies 11:483

Wangliang L, Zhikai Z, Guangwen X (2016) Enhancement of biogas yield of poplar leaf by high-solid codigestion with swine manure. Appl Biochem Biotechnol 179:270–282

Wojnowska-Baryła I, Bernat K, Sartowska S (2018) Biological stability of multi-component agri-food digestates and post-digestates. Waste Manag 77:140–146

Wütenhagen R, Bilharz M (2006) Green energy market development in Germany: effective public policy and emerging customer demand. Energy Policy 34:1681–1696

Zhang X, Qu T, Mosier NS, Han L, Xiao W (2018) Cellulose modification by recyclable swelling solvents. Biotechnol Biofuels 11:191

Zhao K, Li Y, Zhou Y, Guo W, Jiang H, Xu Q (2018) Characterization of hydrothermal carbonization products (hydrochars and spent liquor) and their biomethane production performance. Bioresour Technol 267:9–16