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Review

Anaerobic digestion for bioenergy production: Global status, environmental and techno-economic implications, and government policies

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ABSTRACT

Anaerobic digestion (AD) is a mature technology that can transform organic matter into a bioenergy source – biogas (composed mainly of methane and carbon dioxide), while stabilizing waste. AD implementation around the world varies significantly, from small-scale household digesters in developing countries to large farm-scale or centralized digesters in developed countries. These differences in the implementation of AD technology are due to a complex set of conditions, including economic and environmental implications of the AD technology, and stimulus provided by a variety of polices and incentives related to agricultural systems, waste management, and renewable energy production. This review explores the current status of the AD technology worldwide and some of the environmental, economic and policy-related drivers that have shaped the implementation of this technology. The findings show that the regulations and incentives have been the primary factor influencing the steady growth of this technology, in both developing and developed countries.

1. Introduction

Anaerobic digestion (AD) is the microbial decomposition of organic matter in an oxygen-depleted environment. It occurs naturally in wetlands, marshes, and landfills, as well as inside the stomach of ruminants (Nizami, 2012). The main products of AD are biogas, which is a mixture of gases, mainly methane (CH_4) and carbon dioxide (CO_2), and a nutrient rich effluent that can be used as a fertilizer (Korres et al., 2013). AD has been used for decades as a waste stabilization process, but more recently, there has been increased interest on its potential for bioenergy production (Sawatdeenarunat et al., 2016), as the biogas, composed of 40–70% CH_4, can be either burnt directly in a clean way for heat and power generation, or upgraded to be used as a transportation fuel (Korres et al., 2013).

AD is mostly used for treatment of liquid and solid wastes, such as industrial wastewater with high organic content, organic fraction of municipal solid waste (MSW), and sewage sludge. It has also been used for other substrates depending on location and availability, including animal manure, food and feed waste, agricultural residues, and energy crops (Korres et al., 2013). AD is performed by a community of microorganisms that complete different tasks in the conversion phases of the organic matter into biogas. First, large organic molecules, such as carbohydrates, lipids, and proteins, are hydrolyzed into monomers. Second, these monomers are converted into volatile fatty acids (VFAs) during the phase called acidogenesis. Third, in the acetogenesis phase, VFAs are transformed into acetic acid, CO_2, and H_2. Finally, methanogens convert the acetic acid and some of the H_2 into CH_4 and CO_2 (Mao et al., 2015).

AD has several advantages over other waste treatment and/or bioenergy processes. It is ideal for feedstocks with high water content because it is performed in an aqueous environment. In comparison to leaving the organic matter untreated, AD reduces odors and greenhouse gases emissions (GHGe) (Abbasi et al., 2012), especially CH_4 and nitrous oxide (Clemens et al., 2006), which, respectively, have 25 and 298 times more global warming potential than CO_2. AD produces both a fuel (biogas) that burns cleaner than combusting the biomass directly, and a nutrient rich fertilizer that can be land applied for agronomic benefits (KC et al., 2014).

AD has been used worldwide, but there is a vast difference in the way this technology has been adopted. Europe is the leader in AD technology, and its implementation has been driven mainly by the establishment of strict environmental regulations for waste disposal (Yousuf et al., 2016). Asia has the largest number of anaerobic digesters installed, most of them being small-scale household digesters that are used in rural communities for cooking and lighting (KC et al., 2014). The United States has been slower in the implementation of AD, but its value has been increasingly recognized (USDA, 2015), with about 2,100 current operational AD plants (ABC, 2016). Rural regions in Africa and

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Latin America could also benefit from the small-scale digesters, but this technology has only been implemented successfully in the last few years (REN21, 2016). All these differences in AD implementation around the world are mainly due to policy drivers, socio-economic barriers, existing infrastructure, and technology availability and reliability (Wilkinson, 2011).

The objective of this review is to explore the main drivers that have caused the extensive differences in AD implementation around the world. For that purpose, this article provides a review on: (1) current status of the AD industry, (2) environmental implications of AD implementation, (3) economic considerations for the AD technology implementation, and (4) major policies, incentives, and regulations influencing the AD industries worldwide.

2. Global status of anaerobic digestion

Biogas production gained popularity in the first half of the twentieth century, but it decreased after the 1950s because of low fossil fuels prices and their high accessibility. However, it remained prevalent in rural communities in Asia with low access to other types of energy sources (Appels et al., 2011). After the energy crisis in the 1970s, AD regained appeal as a source of renewable energy, but its implementation then slowed down due to high cost and high failure rates of the digesters caused by limited knowledge, design issues, and inability for appropriate management; however, these have been mostly addressed now (Wilkinson, 2011). Currently, most biogas production occurs in Europe and the United States, but Asia leads in terms of the numbers of digesters installed, which are mostly small-scale units (REN21, 2016). The global energy production from biogas in 2000 was around 280,000 TJ, and it reached almost 1.3 million TJ by 2014, with an annual average increase in biogas production of 13.2% (IEA, 2016). By 2013, the production of biogas was estimated to be around 59 billion m^3, with almost half of it being produced in the European Union (WBA, 2014).

Unlike other bioenergy technologies, AD could be feasible at many scales, from small-scale digesters that produce just enough biogas for a household to large centralized biogas plants with digester capacities of several thousand cubic meters (Angelidaki and Ellegaard, 2003; KC et al., 2014). Small-scale household anaerobic digesters are more popular in rural areas in developing countries, while large-scale digesters are more common in developed countries, especially in Europe (Holm-Nielsen et al., 2009).

2.1. Digester scale as a regional practice

2.1.1. Large-scale AD systems

Large-scale digesters (i.e., hundreds to thousands cubic meters) are historically more popular in developed countries, since they require larger infrastructure and high capital investment. In most of the cases, the produced biogas is used for combined heat and power (CHP) applications, and sometimes upgraded to use as transportation fuel (Holm-Nielsen et al., 2009).

Europe, which is the pioneer region in AD technology, mainly has two models for the operation of the digesters: the "centralized" systems and the "farm-scale" digesters. A centralized or joint system codigest animal manure of several farms with other organic matter, such as food waste and organic fraction of MSW, and agricultural residues. In this model, a fraction of the digestate is sent back to the farms to be used as fertilizer, and the excess is sold to other farms (Holm-Nielsen et al., 2009; Wilkinson, 2011). Denmark is the pioneer in the development of the "centralized" or joint biogas plants (Holm-Nielsen et al., 2009; Raven and Gregersen, 2007). These centralized plants have digesters of large capacity, up to 8,000 m^3 (Nielsen and Angelidaki, 2008). There are about 150 biogas plants in Denmark (EBA, 2015), including about 20 centralized plants, and they have plans to increase their capacity by about 50% by 2020 (Holm-Nielsen et al., 2009). Farm-scale AD plants usually have a digester capacity between 200–1,200 m^3, and are generally built in large dairy or swine farms (Weiland, 2003). They codigest the animal manure from 1 to 3 farms with agricultural residues and other available organic matter, including energy crops grown in that same farm (Wilkinson, 2011). Germany is the leader in the number of farm-scale digesters, with about 9,000 of them, and its goal is to have about 10,000–12,000 digesters by 2020 (Wilkinson, 2011).

In the United States, AD for the treatment of sewage sludge in wastewater treatment plants is a well-established industry (Edwards et al., 2015). There are about 250 farm-scale anaerobic digesters, around 1,250 wastewater treatment plants, and only 38 industrial (stand-alone) AD plants (ABC, 2016). About 90% of the on-farm AD plants were installed in the last ten years, and 86% of them use cattle manure as their main feedstock (Edwards et al., 2015). There is a great prospective for the growth of the AD industry in the United States with a potential to generate enough energy to power 1.09 million homes utilizing manure from 8,000 dairy and swine farms (USDA, 2015). Also, there are almost 2,500 wastewater treatment plants that could produce biogas, including a significant number of which are currently generating it but not utilizing it (ABC, 2016). The rest of North America has also been increasing its interest in AD. Canada has over 100 biogas plants (CBA, 2017a), and has recently established several initiatives that aim to incentivize this technology (CBA, 2017b); also, Mexico's interest in new biogas projects and in the use of the current biogas production for energy generation instead of flaring has be rising (Alemán-Nava et al., 2015).

2.1.2. Small-scale AD systems

Small-scale digesters are mostly household units that are usually about 2–10 m^3, and are located in rural areas in Asia and other developing regions (KC et al., 2014). There are mainly three types of digesters: the Chinese fixed dome digester, the Indian floating drum digester, and the tube digester. All of these designs lack mechanical mixing and heating systems (Bond and Templeton, 2011; KC et al., 2014). Biogas produced from AD is used mostly for stoves and lamps. The amount of biogas required for a household stove used twice a day for a family of five is around 1,500–2,400 L, which requires manure from one pig, five cows, or 130 chickens (Bond and Templeton, 2011). The use of biogas at this scale generates environmental, health, and social benefits associated with burning a cleaner fuel and stabilizing residues, besides reducing deforestation by replacing the use of firewood, and creating a source of fuel and fertilizer at the same time (KC et al., 2014).

The price of these household digesters is usually less than 1,000 USD ($) (REN21, 2014), which is still relatively high for the farmers in these areas (Bond and Templeton, 2011). Thus, they are usually subsidized in some way by the government or a non-profit organization. For example, SNV (Stichting Nederlandse Vrijwilligers), a non-profit international development organization founded in the Netherlands, has supported national biogas programs in Asia, Africa, and Latin America. This led to the installation of 579,000 biogas plants by 2013 (Ghimire, 2013; REN21, 2014). This program started in Nepal with the Biogas Support Program (BSP) in 1992 and expanded to other Asian countries, such as Vietnam, Bangladesh, and Cambodia, and later to the other continents, impacting more than 2.9 million people by 2012 (Ghimire, 2013).

Asia is the leader of the small-scale digesters. China has a long history of implementing AD in rural areas, with more than 100 years of development, and it is therefore the country with the largest number of operating digesters (Chen et al., 2010). China is reported to have more than 43 million digesters, serving about 100 million people in rural areas. India, in second place, has about 4.7 million digesters (REN21, 2014). Other places in Asia, such as Thailand and Indonesia, are also implementing AD for treatment of waste from processes such as palm oil, ethanol, and cassava starch production. In 2015, Bangladesh reached 90,000 biogas cook stoves installed (REN21, 2016). Nepal has installed more than 300,000 digesters (REN21, 2016), mostly because of the financial assistance from the Netherlands through the BSP (Katuwal and Bohara, 2009), and the influence of the AD systems proliferation in neighboring India (Gautam et al., 2009). The success of this implementation is due to a combination of factors, including increased awareness of the advantages of the systems, availability of the technology, the construction materials, and the feedstocks for digestion in the rural communities, and support from the government and non-profit organizations (Gautam et al., 2009).

Africa has a lot of potential for these household digesters in rural communities that have little to no access to fossil fuels. However, the first efforts for their implementation were mostly unsuccessful due to lack of knowledge, trained personnel, proper policies and incentives, and involvement of authorities and academia, generating a negative feedback for the technology (Bond and Templeton, 2011; Parawira, 2009). Recently, some places in Africa have been changing this trend and implementing small-scale digesters in rural areas, mainly through government programs. By 2015, about 60,000 digesters were in operation, in places such as Kenya, Burkina Faso, Ethiopia, Tanzania, and Uganda (REN21, 2016). These are mostly small-scale digesters that use different types of waste, such as manure, organic fraction of MSW, and industrial waste (Parawira, 2009). South Africa implemented an AD project in 2015 that processes cattle waste and sells about 4.4 MW of electricity. Similar systems were also implemented in Kenya and Senegal (REN21, 2016). A similar case has been observed in Latin America, where despite the significant potential of AD, its implementation has been slow. Recent efforts from SNV have tried to established similar programs to the ones in Asia for the development of small-scale digesters in rural areas in Central and South America (SNV, 2012b), and the Network for Biodigesters in Latin America and the Caribbean (RedBioLAC) was created in 2009 with the purpose of share information and overcome barriers of this technology in the region (Garfí et al., 2016). Most of these recent AD projects have implemented tube plastic digesters (Garfí et al., 2016). On the other hand, Latin America has been using AD for wastewater treatment for several decades, but most of that biogas is not utilized.

2.2. Feedstocks for anaerobic digestion

There is a high range of organic material that can be used as feedstock for AD, and the feedstock choice depends mostly on regional availability. The most common feedstocks used for AD are listed in Table 1. The choice of feedstock has high influence in different aspects of the AD process, including pre-processing (separation, reduction size, mixing); pretreatment, which is performed to enhace the digestibility of some feedstocks and could contribute significant to the cost of the processing (Carlsson et al., 2012); retention time, which is dependent on the digestiblity of the material; biogas yield and overall economics of the process; and composition of the digestate (Weiland, 2010).

Most feedstocks used for AD have an intrinsic variability that could significantly affect the AD process. The total solids content (TS) of the most common feedstocks varies from 2% in manure and other liquid wastes to 80% in agricultural residues (Table 1). AD can be performed at low TS content for wastewater or highly diluted feedstocks, at a moderate TS content of less than 15% for most feedstocks, or at TS content higher than 15% in “dry digestion” for the organic fraction of MSW, agricultural residues, and energy crops. Increasing the TS content up to 15–20% increases the volumetric productivity of AD, but further increments reduce the volumetric productivity due to mass transfer limitations (Li and Khanal, 2016). AD is sensitive to the balance of nutrients, and a carbon-to-nitrogen (C/N) ratio of 20–30 is usually recommended. Codigestion of different feedstocks is the most common practice to balance nutrients when the feedstock C/N ratio is outside this range (Li and Khanal, 2016). The feedstock composition and digestibility are the main factors that affect the biogas yield.

2.3. Biogas utilization

Biogas can be utilized directly or upgraded in different ways. Biogas from household digesters is burned directly in stoves and lamps. However, in larger plants, biogas needs to be cooled and dried, and the very corrosive hydrogen sulfide (H_2S) produced during AD needs to be removed (Holm-Nielsen et al., 2009; Weiland, 2010). Biogas can be burned for heat or steam (boiler), but the most common use of biogas is for electricity and heat in a combined heat and power (CHP) unit, since it is a more efficient process. Nevertheless, biogas has a lower heating value compared to natural gas (22 MJ/Nm^3 vs 31–40 MJ/Nm^3), mostly because the concentration of CH_4 in biogas is lower (40–70% vs 81–89%) (Korres et al., 2013). Thus, biogas can be upgraded into biomethane, by removing CO_2. Biomethane can be injected into the natural gas grid, which allows its distribution to larger distances, or it can be compressed and used as a transportation fuel (bio-CNG) for vehicles adapted to use compressed natural gas (CNG) (Holm-Nielsen et al., 2009). Sweden has been recognized as the leading country for the use of biomethane as transportation fuel. From the 1.7 TWh energy produced in 2013 from biogas, 54% was upgraded, fueling mostly buses and commercial cars (Larsson et al., 2016). By 2013 there were almost 1,000 fueling stations in Europe offering either 100% bio-CNG or blends with natural gas (REN21, 2014).

Biomethane can also be used in fuel cells to produce electricity with less emissions and higher efficiency, but the high cost and the requirement for upgrading the biogas are significant barriers for this technology (KC et al., 2015). Biogas can also be converted into other fuels and/or chemicals with higher value, such as methanol, via thermochemical or biological pathways. Thermochemical routes to convert biogas into methanol are catalytic reactions that require biogas upgrading. Biochemical pathways can utilize biogas directly and use microorganisms, such as methanotrophic bacteria, which can convert CH_4 into methanol (Sheets et al., 2016). Biomethane can also be reformed into bio-syngas and further converted into liquid drop-in fuels via Fisher-Tropsch synthesis or syngas fermentation (Yang et al., 2014).

2.4. Anaerobic digestion biorefinery

The biorefinery, a concept analogous to the petroleum refinery, converts biomass into multiple chemicals, fuels, and energy. Several biorefinery concepts are being developed, and most of them include AD as a side process, mostly to treat effluents such as fermentation stillage, vinasses, or spent microbial biomass from other processes. An emerging concept is the AD biorefinery, which is centered in the anaerobic digester, and would produce both high-value, low-volume products, such as drop-in fuels, chemicals, and building materials, and high-volume low-value products, such as heat, electricity, renewable natural gas, organic fertilizer, and bedding for livestock (Sawatdeenarunat et al., 2016). This would improve the economics and sustainability of the process, diversify the portfolio of the AD industry, and help achieve energy security (KC et al., 2015).

The AD biorefinery would produce several products besides biogas, mostly derived from the digestate and liquid effluent. These products would be highly dependent on the feedstock used for AD. Leftover carbohydrates can be used directly, fermented into alcohols, or dehydrated into furans, which are used as platform chemicals. Solid residues can be used to produce bio-oil and bio-char via pyrolysis. Lignin can be transformed through thermochemical processes into heat and electricity, syngas, or liquid fuels, or it can be used to produce aromatic compounds of high added-value. The nutrients in the liquid effluent can be used for algae farming or to produce struvite, a slow release fertilizer (Sawatdeenarunat et al., 2016). Biogas can also be transformed to obtain higher value products including methanol and other chemicals, bio-CNG and liquid drop-in fuels. In the small-scale household digester, other products could also be obtained besides biogas. The digestate or bioslurry has been employed as fertilizer increasing agricultural

Table 1
Common feedstock used for anaerobic digestion with their main features.

Feedstock	Main features	Biogas yield (m^3/kg VS)	Total solids (TS) (%)	C/N ratio	References
Animal manure	– Usually codigested with bedding material (straw) or other biomass high in carbon. – High buffer capacity. – Complete source of nutrients and trace elements.	0.1–0.6	2–20	3–15	Atandi & Rahman (2012), Cantrell et al. (2008), EU-AGRO-BIOGAS (2010) and Sawatdeenarunat et al. (2016)
Organic fraction of municipal solid waste	– Needs separation at the source, or high pre-processing. – Requires size reduction. – High variability in composition.	0.3–0.6	20–50	35	EU-AGRO-BIOGAS (2010), Fricke et al. (2007), Li et al. (2011) and Ward et al. (2008)
Food waste	– Produced by hotels, restaurants, markets, and food processing companies. – Requires size reduction. – High variability in composition. – Easily digestible, could generate inhibition by acidification.	0.3–0.8	5–30	15–30	EU-AGRO-BIOGAS (2010), Ward et al. (2008) and Zhang et al. (2014)
Agricultural residues and energy crops	– Abundant in availability. – Composed mostly of cellulose, hemicellulose and lignin, and/or starch. – Residues include leaves, stover, straws, etc. – Energy crops can be ensiled for storage. – Highly recalcitrant: needs pretreatment to enhance digestibility.	0.2–0.5	20–80	40–150	EU-AGRO-BIOGAS (2010), Sawatdeenarunat et al. (2015) and Weiland (2003)
Sewage sludge	– Byproduct of wastewater treatment. – High in solids, pathogens, and nutrients. – Highly contaminant: needs stabilization. – Low digestibility: pretreatment or codigestion with other feedstocks could improve it.	0.8–1.2	20–35	40–70	Neumann et al. (2016) and Shen et al. (2015)
Algae	– Macroalgae (seaweed) or microalgae. – Low digestibility, recalcitrant structure, especially if cell wall have not been disrupted. Could improve with pretreatment.	0.5–0.8	2–30	5–25	Ward et al. (2014) and Zhang et al. (2016)

production, and also has been used safely as fish feed (Sawatdeenarunat et al., 2016).

3. Environmental impacts of anaerobic digestion

AD has multiple environmental benefits such as treatment and reduction of waste, renewable energy production, and reduction in mineral fertilizer use. All these displaced processes otherwise contribute to higher environmental emissions related to nutrient leaching, methanogenic emissions from biodegradation, and ammonia evaporation. For instance, poorly managed animal manure leads to substantial environmental emissions, with the animal production sector being responsible for 18% of the overall GHGe, 37% of the anthropogenic CH_4, 65% of anthropogenic nitrous oxide, and 64% of anthropogenic ammonia emissions (Steinfeld et al., 2006). The importance of waste minimization is further evident in countries such as Germany and Sweden implementing zero waste to landfill policies. However, the environmental impacts related to installing and operating AD plants and proper use of digestate needs to be accounted for meaningful results. Further, financial incentives to install AD plants have resulted in increased number of AD plants around the world (Whiting and Azapagic, 2014). These AD plants generate large quantities of digestate that need to be utilized or disposed in an environment-friendly manner, because otherwise it can be a source of environmental contamination due to nutrient runoff (Börjesson and Berglund, 2007; Gebrezgabher et al., 2010). Also, methane and carbon dioxide emissions due to leakage during biogas production and digestate storage contribute to the overall GHGe from AD plants (Bachmaier et al., 2010; Prapaspongsa et al., 2010; Vu et al., 2015).

Various researchers have used life cycle assessment (LCA) method to study the environmental impacts of AD plants (Fig. 1). LCA studies have been performed for AD systems around the world but most of them are based in Europe. The feedstocks considered mainly fall into two categories, 1) agricultural crops grown to be used in the AD plants, such as corn silage, starch crops, and grass; and 2) organic wastes, such as animal manure/slurry, corn stover, agricultural residues, food and municipal waste. Accordingly, the outputs considered are biogas and digestate. Biogas is used as is, upgraded to transportation fuels, or combusted in an internal combustion or a CHP plant to produced heat and electricity. These studies have highlighted the benefits of AD systems due to reduced waste, reduced fossil fuel use for electricity production, and substitution of chemical fertilizers. Information from these studies could help engineers and developers to improve systems efficiency and policymakers to identify suitable systems for large-scale implementation, thus leading to overall reduction of environmental impacts.

Studies assessing the GHGe of AD systems utilizing different feedstocks, at various geographical locations are summarized in Fig. 1. Biogas from AD of different feedstocks can be used in different ways, such as heat, electricity, and fuel. Thus, various functional units are selected based on the scope of the study, the output products, feedstock inputs, or land use for the AD systems. The results presented in Fig. 1 have been converted to a uniform unit of kg-CO_2 eq./m^3 of biogas as it is either a final or intermediary product for all the studies considered.

The range of GHGe includes emissions occurring during different stages of biogas production from feedstock farming or collection to conversion of biogas into the final usable form (Fig. 1a). The environmental credits during feedstock cultivations, biogas production, and final use are also considered (Fig. 1a). The net GHGe for most these studies range between -4 and 3 kg CO_2 eq./m^3 of biogas produced. The GHGe for most of these studies were lower when compared to the respective reference systems. Some of the common reference systems for these studies (Fig. 1b) include fossil fuels, electricity from the local grid, energy from coal fired power plant, and pre-existing manure and waste management practices such as wastewater treatment plants and landfills. The emissions for the reference systems were estimated based on the functional unit considered in these specific studies.

The GHGe from AD vary depending on each system's feedstock

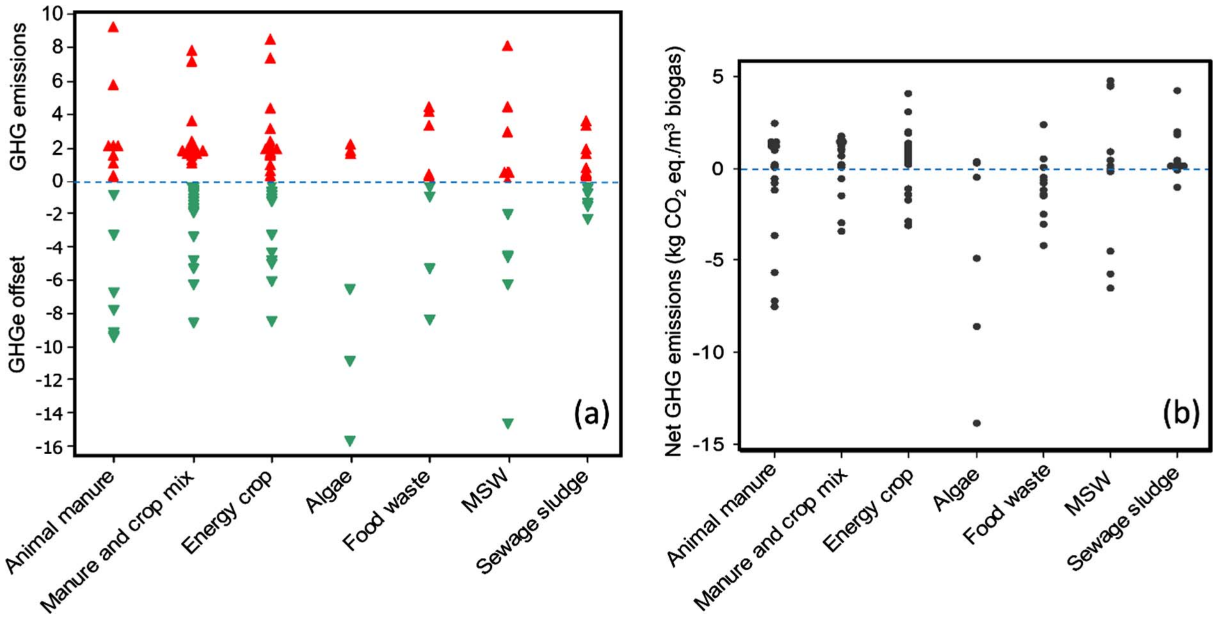

Fig. 1. Range of GHGe for AD plants utilizing different feedstocks. a) GHGe during biogas production and GHG offsets due to environmental credits, and b) net GHGe. Data from: Adelt et al., 2011; Aitken et al., 2014; Alvarado-Morales et al., 2013; Bacenetti et al., 2013; Bachmaier et al., 2010; Bhattacharya and Salam, 2002; Börjesson and Mattiasson, 2008; Boulamanti et al., 2013; Buratti et al., 2013; Campos et al., 2016; Carlsson et al., 2015; Chaya and Gheewala, 2007; Coats et al., 2013; Collet et al., 2011; Dressler et al., 2012; Ebner et al., 2015; Ertem et al., 2017; Evangelisti et al., 2014; Fuchsz and Kohlheb, 2015; Hamelin et al., 2014; Hennig and Gawor, 2012; Hung and Solli, 2012; Ishikawa et al., 2006; Jin et al., 2015; Lijó et al., 2014; Liu et al., 2012; Meyer-aurich et al., 2012; Mills et al., 2014; Monteith et al., 2005; Otoma and Diaz, 2017; Parravicini et al., 2016; Pérez et al., 2014; Prapaspongsa et al., 2010; Quinn et al., 2014; Vu et al., 2015; Whiting and Azapagic, 2014; Xu et al., 2015. *Note:* some results have been estimated based on graphs.

category, construction and operation of the system, CHP unit for electricity production, methane losses during biogas production and digestate storage, and transportation of feedstocks and wastes. In addition to this, GHGe also occur due to fertilizers and chemicals used for crop production, methane losses during storage of animal manure feedstocks, and energy used for sorting the organic fraction in the MSW for use in AD systems (Fig. 1). The environmental credits for GHGe from AD systems are also considered due to reductions in the fossil fuel used for heating and electricity production, minimization of the emissions from animal waste, and replacement of chemical fertilizers with organic fertilizers from digestate. Environmental credits are also considered for GHGe that are consumed during agricultural energy crops and algae production, and for reductions in municipal waste sent to landfills (Fig. 1). Food wastes have a higher organic fraction compared to most AD feedstocks, and, thus, have a higher biogas yield and lower GHGe because no resources are needed for feedstock production (Carlsson et al., 2015; Evangelisti et al., 2014; Xu et al., 2015). These two factors contribute to most of the environmental credits in this feedstock category.

Different feedstocks, location of AD plants, end-products, functional unit, impact categories, and the reference system determine the different possible outcomes of the LCA study of the AD system. For example, organic waste with high moisture content processed by AD has lower environmental footprints compared to incineration. The high moisture content of the organic waste is suitable for AD. However, for incineration, the moisture content needs to be lower and a higher amount of energy is required to drive off the moisture content before incineration, leading to higher environmental footprint. Also, feedstocks such as corn silage or grains, although have higher biogas yields, also have higher environmental footprints during the feedstock production. The main environmental benefits of AD are realized in terms of lower energy demand, global warming potential (GWP), and resource consumption (RC) (Bacenetti et al., 2013; Börjesson and Mattiasson, 2008; Boulamanti et al., 2013; Claus et al., 2014; Labutong, 2012; Mezzullo et al., 2013). These reductions are due to energy production from biogas and the replacement of chemical fertilizers by digestate. For other impact categories such as acidification potential (AP), eutrophication potential (EP), photochemical oxidant formation (PO), human health impacts (HH), and ozone depletion potential (ODP), studies found that the environmental impacts of AD vary mainly due to the reference system, geographical location, and system boundaries (Boulamanti et al., 2013; Carlsson et al., 2015; Evangelisti et al., 2014; Hennig and Gawor, 2012; Hung and Solli, 2012; Whiting and Azapagic, 2014). For instance, electricity produced from AD systems can be compared with electricity from reference systems such as coal or natural gas power plants, or from grids having lower GWP, such as Norway, which has a higher renewable energy mix. For example, an AD system could be environmentally favorable, in terms of GWP, when compared with a coal fired power plant that has higher GHGe; whereas, it might not be preferred when compared with natural gas or an electricity grid that includes renewable energy sources. The system boundaries for LCA studies for AD systems using agricultural based feedstocks often include land use for agricultural production, which could potentially increase the environmental impacts (Smyth et al., 2009). The potential emissions from the AD systems are mainly due to CH_4 losses, CHP unit, AD digester, and emissions from digestate storage (Evangelisti et al., 2014; Whiting and Azapagic, 2014). In addition to these, other environmental advantages of AD systems, especially in the developing world, include reduced odor from the manure, reduced deforestation due to decreased fuelwood consumption, and reduced health impacts due to lower indoor smoke formation than when cooking with fuelwood (Akinbami et al., 2001; KC et al., 2014).

Few measures are suggested for reducing emissions and environmental impacts from the AD plants. For example, GWP could be reduced by the use of flare to minimize CH_4 emissions to the atmosphere during CHP outages. Reducing the biogas leakages from the AD plant and digestate storage will also reduce CH_4 emissions and correspondingly the GWP from the AD system (Baldé et al., 2016; Flesch et al., 2011). Proper storage and management of high volumes of digestate could minimize GWP and eutrophication. External electricity demand of the AD plant could be reduced by utilizing the biogas produced. Further, installing efficient CHP units and maximum heat recovery from them will reduce the resource requirements and result in lower GWP, RC, AP and eutrophication.

4. Economic analysis of anaerobic digestion systems

AD systems result in several economic benefits including reduction in expenses for fossil fuel in waste management systems by utilizing the energy produced in the form of biogas, electricity and heat, generating income by selling excess energy, and reduction in fertilizer input and associated costs while improving soil fertility and structure (Taleghani and Kia, 2005). However, AD systems developed around the world have variations in feedstock types and compositions, digester scale, operating conditions, government incentives, and potential use of products. Also, depending on the geographic location and the season, the energy required to control the digester temperature varies significantly. A farm based AD system can be profitable through full utilization of energy products from the AD system, charging gate fees for accepting solid wastes, generating income from co-products such as compost/organic fertilizer, and potentially selling carbon credits obtained from offsetting the GHGe (Beddoes et al., 2007). The synergistic management of AD plant and farm could share resources such as labor and machineries, thus contributing towards positive economics of these systems. A major challenge for AD systems is to operate at maximum capacity throughout the year. Logistics of feedstocks and products are also important for the economic and environmental feasibility of the AD systems as long distance transportation could increase the biogas production costs as well as associated emissions. In addition to this, in certain regions such as Europe, the majority of AD systems are installed with subsidies from government agencies and various state incentive programs. Thus, AD systems need to be assessed for their economic feasibility considering the variability of all those specific aspects.

Economics of AD systems can be better understood by classifying them into two categories: (1) large-scale AD systems, most popular in developed countries, and (2) small-scale AD systems, such as households and community scale farms in rural areas (Marchaim, 1992).

4.1. Economics of large-scale AD systems

Large-scale AD systems require high capital investment and maintenance, and use a variety of feedstocks including wastes from agricultural or animal farms, food waste, and wastewater/sewage sludge (Table 2). Due to the nature of these systems, the economics of these plants vary considerably.

Capital and feedstock costs have a major share of the total energy generation cost, depending on the selected AD system and feedstock source (Chynoweth et al., 2001; Hennig and Gawor, 2012). For instance, feedstocks such as animal manure might have negligible feedstock cost, but due to its low biogas yield per wet tonne, they might require larger digester size, thus leading to increased capital cost (Redman, 2010). Table 2 presents the key findings from studies focused on economic feasibility of AD systems for various feedstocks. These studies considered AD plant life to be normally between 15 and 20 years.

Capital cost is the main contributor to the production cost for AD systems (Table 2). Operating cost depends on AD plant size, and was found to vary from \$20 to \$110/t of feedstock handled by the plant. A study of 38 AD systems in the United States indicated that electrical generation equipment costs approximately 36% of the total capital cost (Beddoes et al., 2007). The cost of electricity production varies from \$0.06 to \$0.23 for each kWh of electricity generated by the AD systems (Table 2). The electricity production cost depends on the type of AD plant used in the system as well as the feedstock used (Hennig and Gawor, 2012). For instance, organic fraction of MSW is a more economic feedstock than animal manure (Murphy and McCarthy, 2005). Higher gate fee for MSW compared to animal manure and higher biogas yield from the MSW contributed favorably to the economics in this case. Electricity generation cost is usually lower for higher plant size due to the effect of economies of scale (Hennig and Gawor, 2012; Murphy and McKeogh, 2004).

Table 2
Cost analysis of AD plants using from different feedstocks.

Feedstock	Product	Feedstock cost (USD)	Plant Size	Capital cost (USD)	Operational cost (USD)	Product cost (USD)	Study region	References
Animal manure	Electricity	0	29,000–36,000 t/annum	–	–	0.06–0.19/kWh	Turkey, U.S.	Akbulut (2012), Beddoes et al. (2007), Enahoro and Gloy (2008) and Prasodjo et al. (2013)
	Heat	0	–	–	–	0.04/kWh_{th}	Turkey	Akbulut (2012)
	Solid fertilizer	0	–	–	–	134/t fertilizer	Turkey	Akbulut (2012)
	Liquid fertilizer	0	–	–	–	37/t fertilizer	Turkey	Akbulut (2012)
Animal manure and energy crops	Electricity	+65/t feedstock (revenue)	–	450–600/t feedstock	34–90/t feedstock	0.11–0.19/kWh	Germany, U.S., Canada, Italy	Balussou et al. (2012), Cavinato et al. (2010), Hennig and Gawor (2012) and Institute for Local Self-reliance (2010)
Energy crops	Electricity	29–34/t feedstock	–	–	–	0.17–0.23/kWh	Turkey, Germany, Ireland	Akbulut (2012), Balussou et al. (2012), Hennig and Gawor (2012) and Nolan et al. (2012)
Food waste	Electricity	+67/t feedstock (revenue)	10,000–40,000 t/annum	502–670/t feedstock	38–100/t feedstock	–	U.S., Canada	Institute for Local Self-reliance (2010)
Municipal solid waste	Electricity	+49 to 58/t feedstock (revenue)	5000–100,000 t/annum	245–630/t feedstock	20–111/t feedstock	–	Ireland, U.K, Canada, Spain, Denmark	Arsova (2010), Murphy and McKeogh (2004), Redman (2010) and Whyte (2001)
	Biogas	–	1000–10,000 t/annum	122,550	75/t feedstock	367/t biogas	Thailand	Ali et al. (2012)

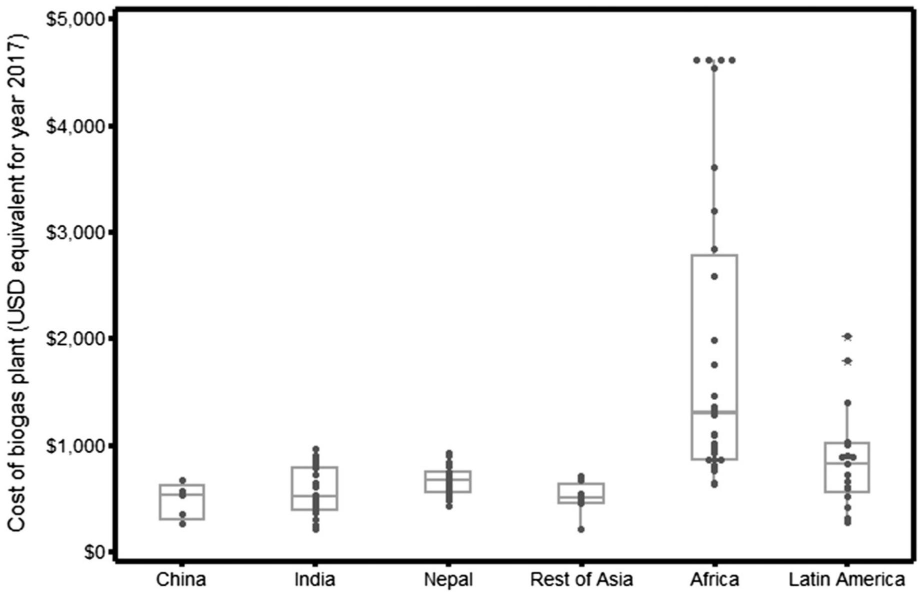

Fig. 2. Cost of small-scale anaerobic digesters by region. Data from: Amigun and Von Blottnitz, 2010; Ashden, 2007, 2006a,b, 2005; Dhakal, 2008; Mwirigi et al., 2014; Potherign, 2016; Rajendran et al., 2012; Singh and Sooch, 2004; SNV, 2012a,b; Wisions, 2010; Zuzhang, 2013. *Note:* digesters in the range of 1–16 m^3 were included, and prices were converted to USD and adjusted with inflation to year 2017.

4.2. Economics of small-scale AD systems

Small-scale digesters are expected to be low cost, since they are usually implemented in low income households. Fig. 2 summarizes the cost of small-scale digesters in different regions. Several factors influenced the large variability in the cost of these systems, including both the cost of construction materials (brick, concrete, and plastic) and labour. In Asia, where these systems have been implemented for longer time, the cost is more consistent (Fig. 2). But in Africa in Latin America there is high variability, mainly due to the lack of established technologies that could be reproduced consistently (Mwirigi et al., 2014). Also, in some regions in Africa, the low volume of suppliers of certain construction materials and the transportation requirements could significantly increase the cost of certain supplies, such as cement (Amigun and Von Blottnitz, 2010; Mwirigi et al., 2014). For example, a 10 m^3 plant in Vietnam costed about $550 in 2010, but a similar plant costed more than $1,500 in Kenya (Wheldon, 2010).

Operating costs for these AD systems include feedstock (usually manure or food waste) cost, maintenance, and repair. The repair and maintenance costs could vary considerably depending on the location and the availability of skilled labor for repair. Also, challenges exist for effective economic analysis of these small systems as the commercial value of the feedstocks and most of the economic benefits of the system are usually not quantified. Further, strong incentives and subsidies programs exist in some regions, especially in Asia, while other regions lack this government support (KC et al., 2014).

5. Policies, regulations and incentives for anaerobic digestion

Progress in AD technology is inextricably tied with policies, regulations, and incentives in energy, environmental, and agricultural sectors that are targeted to enhance energy security, rural economy, mitigate climate change concerns, and improve environmental quality. Most of these policies are not designed specifically to promote AD technology, but are found to have positive impacts on the adoption of the technology. Thus, in countries where there are stringent energy, agricultural, environmental, and human health regulations that encourage waste reuse and renewable energy generation, AD technologies are found to be more prevalent. For example, in Europe, there is a strong presence of government policies and incentive programs in the areas of renewable energy, agriculture, and waste management compared to the United States. Thus, the AD technology has proliferated in Europe to a greater extent than in the United States (Edwards et al., 2015). This section synthesizes government policies and incentives throughout the world, and discusses their goals, effects on AD growth, and impacts on barriers for AD use.

5.1. Policies and regulations

The policies and regulations that have encouraged the implementation of AD technology can be classified into three categories: (1) renewable energy-related policies and regulations, (2) comprehensive agricultural regulations, and (3) waste management-related policies (Fig. 3).

5.1.1. Renewable energy-related policies and regulations

5.1.1.1. Renewable energy generation targets. Because biogas and biomethane from AD plants are mixable and interchangeable with natural gas, and can be used directly for heat and/or electricity generation or as CNG in vehicles, national policies and regulations focused on promoting renewable energy and fuels have directly stimulated the use of biogas, and thus, the development of AD technology. Many countries around the world have policy targets for renewable energy requiring that a specific proportion of the energy consumed comes from renewable energy sources within a certain period. For instance, the European Union and the United States, respectively, have renewable energy targets (RETs) of 17 and 18% of the total energy used for 2020. Brazil has a goal of 70% for renewable energy by 2020 and New Zealand has a goal of 90% by 2025 (GMI, 2014a). In Canada, each of the country's nine provinces has an RET. In addition, many countries, particularly from the European Union, have RETs specific for biogas and biomethane. To meet these targets, governments have established production requirements as well as offered various incentives that stimulate the production of renewable energy. For instance, in Germany, the Renewable Energy Sources Act of 2000 (and amended in 2014) provides incentives for electricity generation from renewable energy by offering above market feed-in tariffs (FiT), priority connection rights to feed into the grid, and the passing of transmission system costs to electricity consumers. Germany also has the Biofuels Quota Act of 2007 that requires a minimum share of biofuels to be sold in the energy market. Due to these policies and regulations, Germany has the most AD plants, and 65% of total annual biogas production is directed to electricity generation, 34% to heat, and the remaining 1% to vehicle use (ATB, 2014).

5.1.1.2. Greenhouse gas emission reduction targets. The requirements to

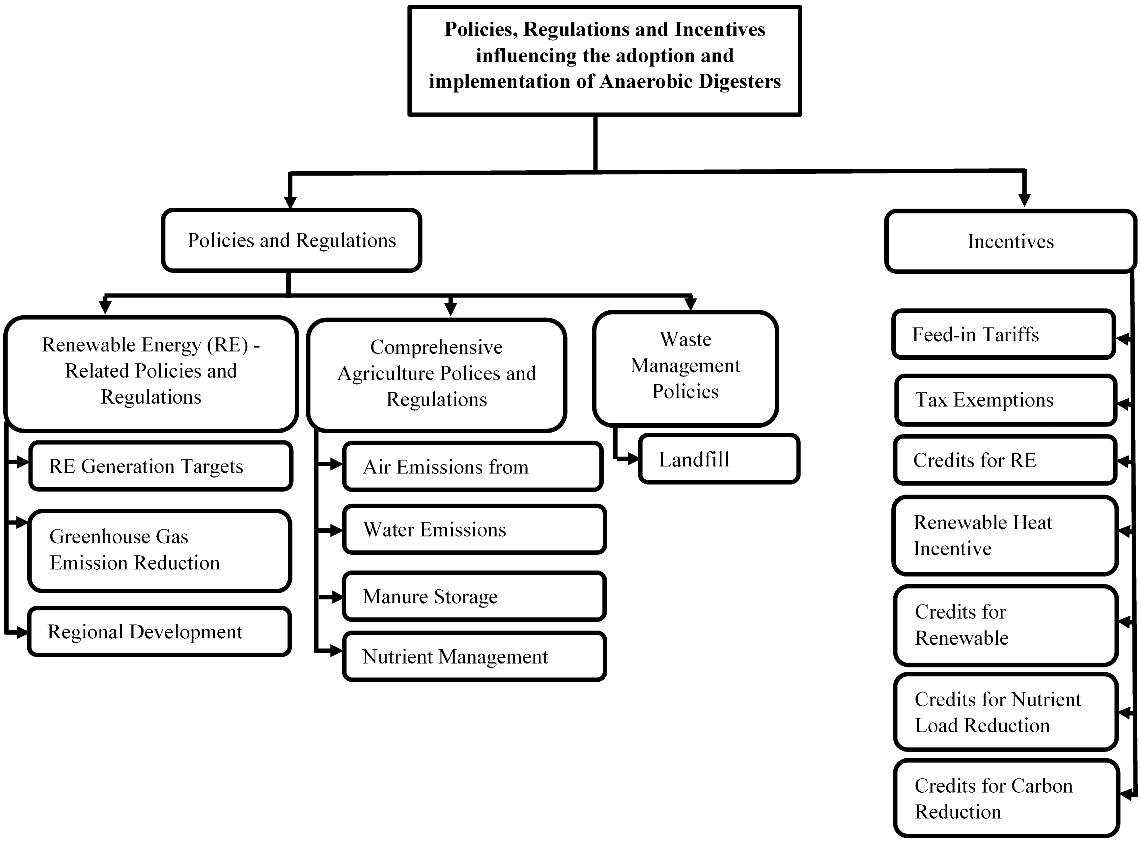

Fig. 3. Policies, regulations, and incentives as drivers to the implementation of AD.

reduce GHGe by several countries under the Kyoto protocol have also promoted the use of AD technology. Countries such as Germany, the United Kingdom, and Finland have pledged to reduce their GHGe to amounts 80% below 1990 levels by 2050. The United States have a target of reducing GHGe by 17% by 2020 (GMI, 2014a). In addition to providing significant research and development investments for carbon capture and storage capacity for coal power stations to lower GHGe, these countries have regulated the GHGe from coal power plants and promoted the use of renewable energy, and some have specifically addressed the use of AD to meet the GHGe reduction targets. The Renewable Energy Directive (RED) in the European Union provides a framework for the member countries to meet CO_2 emission reduction targets while promoting security of energy supplies (Edwards et al., 2015). It promotes AD bioenergy generation from organic waste because of its GHG savings potential and significant environmental advantages (European Parliament, 2009).

5.1.1.3. Rural development. In some countries, AD technology benefits from regulatory frameworks targeted for rural developments because of the quantity of biodegradable feedstocks available in rural settings. These policies provide direct financial assistance for AD construction and operational costs as well as training support for farmers. For example, in the UK, a large number of grants for AD facilities come from regional development agencies and the Rural Communities Renewable Energy Fund (Lukehurst, 2014). In the United States, the Renewable Energy for America Program provides grants and loan guarantees for AD systems in rural areas (USDA, 2017).

5.1.2. Comprehensive agriculture policies and regulations

Because air and water pollutants emitted from animal wastes from livestock operations can cause serious environmental concerns and health problems, regulatory agencies require facilities and farmers to meet certain requirements and obtain permissions before discharging wastes to the land, a water body, or to the atmosphere. These facilities need to have best management practices or similar guidelines for feedstock collection, manure handling and storage, and strategies to reduce odors, liquid effluent, and dust. Since AD treats organic wastes and reduces the amount of GHGe, nutrients, and odors, the comprehensive agricultural policies and regulations that include the provisions for air emissions, water discharge, and nutrient management promote the development of AD technologies to some level.

5.1.2.1. Water and air emissions from farms. Generally, the countries with stringent air and water emission policies in the agricultural sector tend to provide more support for AD technologies. For example, in Europe there is the Nitrate Directives 1991 regulation; the United States has the Clean Water Act; and Canada (British Columbia) has the Environmental Management Act (The Province of British Columbia (1992)). In Italy, under the National Environmental Framework Law, large farms need to apply best available technologies for manure storage, handling, and spreading, as well as ensure continuous monitoring and improvement of the environmental parameters. In Indonesia, the Indonesian Sustainable Palm Oil policy mandates a reduction in GHGe from the palm oil sector. Similarly, the Air Quality Amendment Act (2013) in South Africa imposes stricter standards to control dust, noise, and offensive odors (GMI, 2014a). These types of legislation promote best management practices, including use of AD for farming and livestock management to protect air and water quality.

5.1.2.2. Manure nutrient management. Agricultural on-farm AD has flourished in some countries, in part, due to policies that regulate the use of animal manure. For example, the Manure Decree 2007 policy in Belgium sets limits on the amount of nitrate and phosphate fertilizers that can be applied to specific soil types or crops. The Chesapeake Bay Program in the United States aims at reducing the nutrient contents in animal manure by practicing feed management and coordinating manure transport (Devereux, 2009). In the UK, regulation on nitrate pollution prevention limits the amount of time that manure can be stored, and aims to reduce the amount of manure-derived nitrates from entering surface and groundwater. Also, it allows farmers to transfer manure to nearby sites without a license (Edwards et al., 2015; GMI, 2014a). These different regulations place the burden on the producers to meet the requirements to minimize the pollution of air, water and soil, and push agricultural waste producers to adopt enclosed waste management technologies, including AD.

5.1.3. Waste management policies

Mandatory requirements to divert organic materials from landfills are also significant drivers in the growth of AD treatment of biowaste and industrial feedstocks (Edwards et al., 2015; Goldstein, 2011; Wilkinson, 2011). The European Union implemented the Landfill Directive in 1999 that enforces mandatory targets for member nations to minimize the amount of biodegradable municipal waste entering landfills. The UK has a Landfill Allowance Trading Scheme that allows regions with poor diversion of municipal solid waste from landfill to purchase surplus allowances from regions that have high diversion efficiencies. Also, it has increased significantly landfill levies, which have risen from \$11.62 in 1997 to \$132.8 in 2014. Thus, a positive correlation ($r = 0.84$) was found between the number of AD plants commissioned and the landfill levies in the UK (Edwards et al., 2015). In the United States, some states and cities have enacted legislation that help preserve landfill sites either through import levies or bans. In New York City, organic waste has been banned from entering the landfill, and thus the organic waste must be sent to compost facilities or AD (Edwards et al., 2015).

5.2. Incentives

Currently, AD technology presents financial challenges and risks such as high capital and long-term operation and maintenance costs including equipment, labor, and training that often cannot be recovered easily through normal agricultural business practices. Thus, the growth of AD technology is dependent upon various existing incentive programs, including feed-in tariffs (FiTs), credits for carbon reductions, credits for renewable energy, credits for renewable transportation fuel, credits for nutrient load reduction, payments for producing renewable heat, and tax exemptions. These incentives help to offset costs and generate revenue as well as advance AD technology to compete against established energy generating technologies (Edwards et al., 2015; GMI, 2014a).

5.2.1. Feed-in tariff

AD in some countries is prioritized through generous FiTs. In Germany, AD installations receive higher FiT rates than wind energy, landfill gas, and hydropower (German Federal Government, 2011). Germany has fixed FiT rate of \$0.35/kWh for up to 150 kW, and the United States has FiTs in the range of \$0.10 to \$0.54/kWh for the electricity generated from biogas (Edwards et al., 2015). Germany has also introduced bonuses for using selected feedstocks, including animal manure (manure bonus), garden and plant biomass (landscape bonus), or crop residues (biomass bonus) for AD. Increase in incentives might be the reason for the increase in the number of biogas plants in this country. In Germany, AD plants increased from about 140 in 1992 to about 7,720 by the end of 2013 (Fig. 4). Edwards et al. (2015) found a positive correlation between incentives and number of AD plants with capacity < 150 kW ($r = 0.815$, $p < 0.001$) and capacity < 500 kW ($r = 0.757$, $p < 0.001$).

5.2.2. Credits for carbon reduction and carbon trading

AD systems can qualify for marketable carbon credits by avoiding CH_4 emissions and generating electricity that reduces the use of fossil fuels. Thus, carbon credits and carbon trading programs that provide a mechanism for regulating GHGe, measured in terms of CO_2 equivalent (Li and Khanal, 2016), are found to encourage AD projects at agro-industrial facilities or large farms (GMI, 2014b). For example, Australian farmers receive carbon credits for AD systems fed with pig and/or cow manure (German Federal Government, 2011), and the AD projects in California are eligible for carbon credits under the California's Low Carbon Fuel Standard (German Federal Government, 2011).

5.2.3. Tax exemptions and tax credits

Tax exemptions and tax credits for renewable energy have also been found to be significant drivers in the growth of AD systems in some countries. For example, under the Renewable Energy Development Act in Dominican Republic, tax exemptions are available for equipment and accessories related to the installation of biodigesters (GMI, 2014a). In Finland, biomethane is exempted from production and use excise taxes (GMI, 2014b). In the United States, the Renewable Electricity Production Tax Credit provides a corporate tax credit of 1.1 cents/kWh for technologies that use "open-loop" biomass (i.e., farm and forest wastes rather than dedicated energy crops), landfill gas, and MSW for the first ten years of operation (DOE, 2017). In the UK, AD facilities are eligible for a Climate Change Levy tax exemption that is given to businesses associated with industrial, commercial, agricultural, and public services on the energy use (GMI, 2014a).

5.2.4. Credits for renewable energy and renewable transportation fuel

AD has been promoted in some countries by offering renewable transportation fuel credits to encourage the displacement of fossil fuels with renewable sources. For example, in the United States, the revised Renewable Fuel Standard (RFS2) authorized under the Energy Independence and Security Act of 2007 mandates that a certain percentage of fuels sold in the United States come from renewable energy sources. To ensure the compliance, the U.S. Environmental Protection Agency has developed the Renewable Identification Number (RIN) system that relates with volumes of renewable fuel produced or imported. As a result, every year gasoline producers, diesel producers, and importers are required to meet their RFS mandated amounts by either earning RINs through fuel blending or purchasing RINs from other parties (GMI, 2014a). Germany has set up the "Initiative for Natural-Gas-Based Mobility" in 2010 to remove existing market constraints and increase the market share of natural gas vehicles by 2020. This is targeted to grow the share of methane to 4% by 2020 with an increase in natural gas vehicles from 94,000 to ~1.4 million as well as reduce 1 million tonnes/year of CO_2 emissions annually. With this, the share of methane in the transport fuel mix at the end of 2011 was 0.47%, and biogas is expected to play a major role in transportation primarily through a 20% blend with natural gas (Le Fevre, 2014). AD systems are also qualified for the renewable energy credits that attempt to monetize the environmental benefits associated with the use of renewable energy.

5.2.5. Credits for nutrient load reduction

Similar to carbon trading programs, nutrient trading programs focused on reducing nutrient load limits to water bodies (i.e. river, streams, ponds) are found to boost AD technology. Farmers could maximize revenue through the implementation of AD systems that help their facilities to reduce nutrient loads and sell excess credits to other facilities that do not fulfill their load reduction requirement. Unlike other programs, this trading program is not widespread, and is used in only few countries such as Canada, Italy, and the United States. Some examples include the Chesapeake Bay Nutrient Credit Trading program in the U.S, and the total phosphorus management program developed by South Nation Conservation in Canada in 2000 (GMI, 2014a). Due to the Chesapeake Bay Nutrient Credit Trading program, Pennsylvania is promoting enhanced regional AD digesters to digest manure, produce electricity and substantially reduce nutrients (Chesapeake Bay Commission, 2010).

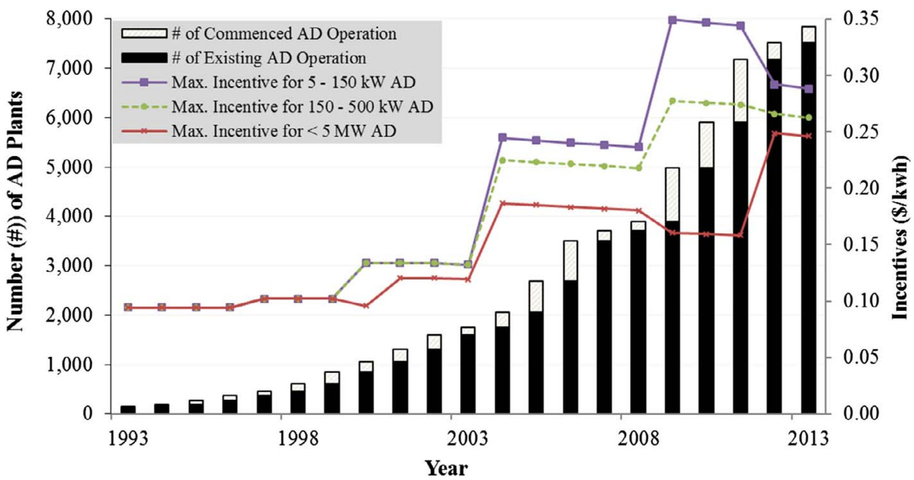

Fig. 4. AD systems growth in Germany compared with the maximum available performance based incentives (1993–2013). Modified from: Edwards et al. (2015).

5.2.6. Renewable heat incentive

AD technology in some countries such as Italy and the UK has also benefitted from the renewable heat incentive (RHI) program that offers financial compensation to property owners for using renewable energy sources to provide heat for buildings rather than using fossil fuels or electricity from the grid (UK DECC, 2015). In the UK, under the RHI program, tariffs are paid at $0.10/kWh for biomethane injected to the grid (GMI, 2014a).

6. Perspectives

AD is an industry with high global growth potential. The current trend of increasing biogas production worldwide is likely to continue in the future years, in light of increasing concerns about GHGe and poor water quality. This is reflected in new regulations and incentives that favor AD and other renewable energy technologies and waste management alternatives. Increasing awareness about the possible environmental and economic benefits of this technology could allow the emergence of policies and investment in this sector around the globe.

The recent boost in installation of household digesters is likely to keep rising, especially in new regions of the world with high potential for these systems, such as rural areas of Africa and Latin America. Areas without access to electricity and that rely in wood biomass and other fuels for cooking and lighting are the most adequate for the implementation of these systems, since they have a unique potential to supply renewable energy while stabilizing waste and improving life quality of the farmers. For this purpose, supports from government and non-governmental agencies are fundamental, and this would probably continue to be the main driver for small-scale AD promotion. The keys to the long-term success of these systems are: (1) installing high quality digesters that require less maintenance and repair, and stay operational for a longer period, (2) accessibility to knowledge in maintenance and troubleshooting of these systems.

Similarly, the number of large-scale digesters is expected to keep increasing, and other regions besides Europe, such as North America, are expected to be involved in this growth. The main barrier for the expansion of AD technology is the proper management of the large quantities of digestate produced, since digestate has low solids content, making its transportation and storage costly. In addition, digestate could also cause some potential environmental hazards due to high heavy metals, microbial pathogens, and unbalanced nutrients (Alburquerque et al., 2012). For the wider adoption of AD technology, in the short term, alternative methods for digestate processing and management need to become available. In the long term, the development of the AD biorefinery would have to include processes for transforming the digestate into higher value products, such as active chars, and bio-oil.

With regard to biogas utilization, CHP units would continue to be the most economical alternative in the near term. In the long term, technological breakthroughs in the biogas cleaning and upgrading processes would be necessary to allow the efficient transformation of biogas into transportation fuels and/or other chemicals. Therefore, currently, the use of bio-CNG would probably continue to be limited to small regions and for mostly government or companies' vehicles.

7. Conclusions

AD has been adopted worldwide using small-scale household digesters in rural areas of developing countries to large-scale systems in developed countries, influenced by a complex pool of factors including technological limitations, feedstocks availability, economic drivers, environmental regulations, and government policies. Currently, AD technology is costly, and thus, policies, regulations, and incentives targeted for controlling GHGe and proper management of solid waste, have been the key drivers to the growth of the AD technology. In the future, technological advancements towards digestate management and biogas utilization could enhance the economics associated with AD plants, and spur the growth of AD industry.

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