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Lessons Learned From the Deployment of Biogas Technology in Thailand, Ghana and Denmark: a Case Study Analysis of Emerging Organizational and Technical Concepts

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Abstract: *This paper investigates the current situation for the biogas industry within Thailand, Ghana and Denmark, with an emphasis on the available biomass feedstock for biogas production, the technologies applied, and the production and utilization of energy services and digestate. In addition, the framework conditions for supporting dissemination of the biogas technology, including the socio-cultural conditions for this, are assessed within the three countries. The Energy Chain approach is adopted as a theoretical concept of how to support the development and deployment of biogas technology, combined with a literature review, and primary and secondary empirical data. Six case studies of promising biogas applications – some already implemented – have been studied and are described in this paper, demonstrating promising technical and organizational concepts that can increase the efficiency of the Energy Chain within the countries investigated. The analysis reveals, among other aspects, that the biogas industry in Thailand lacks emphasis on the supply side of the energy chain to increase energy efficiency, and that the utilization of digestate as fertilizer in Ghana must receive more attention. In Denmark, focus should be given to the production of organic digestate as fertilizer to stimulate a transition of the agricultural sector towards higher sustainability. For all three countries, the analysis shows that large amounts of unused biomass resources are available as feedstock for biogas, and that more effort should be made to utilize these renewable sources in an effort to combat climate change. It is concluded that knowledge sharing, and support policies can promote a further development of the biogas technology, and recommendations to establish a 'North–South–South' communication infrastructure are made. This cooperation could be facilitated by multilateral, bilateral or private NGO actors, etc., and revolve around peer-to-peer learning and a bottom-up participatory approach to policy formulation and adaptation.*

Keywords: Biogas, developed and developing countries, Energy Chain, organization, technology concepts

1. Introduction

Biogas technology relies on renewable energy resources like animal manure, municipal organic waste and agricultural crop residues, and is noted for its unique and myriad benefits (Jørgensen, 2009). It provides, for example, hygienic treatment of solid waste and wastewater and generation of clean energy for power and heat production. It also contributes nutrient-rich fertilizer (digestate) for agricultural usage. The production of biogas can reduce the need to import fossil fuels and substitute for inorganic fertilizer, which requires large amounts of energy to produce and enhanced national energy security. It can also provide clean energy to rural and isolated communities, contribute to the reduction of greenhouse gas emissions and create new job opportunities in rural communities (Paolini et al., 2018). In developing countries, it can significantly reduce indoor air pollution by substituting for traditional wood fuels or costly liquid petroleum gas (LPG), thereby improving people's livelihood (Fan et al., 2011; Krantz, 2001). Where the power grids are non-existent, biogas technology can also address the lack of energy access by parts of the population in many rural and remote communities (Mandelli et al., 2016). Implementation of the technology can thus help to reach developing countries' sustainable development goals (SDG) (UN, 2020); that is, '*affordable, reliable, sustainable and modern energy for all targets*' (SDG7) (Sustainable Energy for All, 2020), and, for example, to '*increase substantially the share of renewable energy in the global energy mix*' (Ibid.) within both developed and developing countries. This can assist in the attainment of the nationally determined contribution (NDC) targets for greenhouse gas (GHG) emission reductions, as decided by the Paris Agreement in 2015 (UNFCCC, 2020).

In our quest to provide enough food to meet growing populations, locally and globally, the advantages of biogas technology are reinforced by the need to substitute inorganic fertilizers on farmlands with an environmentally benign alternative. The use of inorganic fertilizers on farmlands negatively affects the soil structure in the long term and contributes to hypoxia in water bodies, as a result of the run-off of nutrients from agricultural lands (Gomez, 2013). Furthermore, effluents from industrial sectors and municipalities, when not properly treated but instead discharged directly into water bodies, also result in hypoxia and the destruction of fish and other biological lives from excessive build-up of nutrient and eutrophication (Holm-Nielsen, 2009; Jørgensen, 2009). Thus, many benefits are to be harvested from the biogas technology (Vlachos and Iakovou, 2016), but there are significant differences on how biogas systems are integrated into the economies of developing countries, (also in between), and developed countries, which this paper among others will illuminate.

In many developed countries – Denmark, for example – highly technically mature and automated biogas digesters are deployed, which treat diverse materials including sewage sludge, agricultural residues, energy crops, municipal solid waste (MSW), as well as animal manure, usually in large quantities. The options for gas utilization include combined heat and power (CHP) with combinations of, for example, district heating (DH), injection of compressed gas to the natural gas network and vehicle fuel, among others. Besides this, environmental pollution standards relating to discharge of wastewater and industrial effluents are more effectively enforced in developed countries, with quite well-established and functioning regulatory and institutional frameworks (Foreest, 2012; Pazera et al., 2015). Mixes of and pre-treatment of various feedstock is applied in Denmark, but large amounts of unused manure are still available (Food & Bio-Cluster Denmark, 2020), which could be integrated in a transition of the Danish biogas industry towards more organic farming.

In developing countries – Ghana, for example – animal manure, agricultural residues and MSW are available in large quantities; however, they are yet to be exploited (Bensah et al., 2015). The biogas industry in Ghana, and in many other African countries, is characterized mainly by dissemination of small-scale individual digesters and bio-latrines for treatment of human faeces and/or animal manure (Suwanasri et al., 2015; Bond & Templeton, 2011). A high level of design and construction error is connected to these plants, leading to poor performance with high incidence of plant breakdowns. Besides this, ineffective national framework conditions for biogas development are noted (Bond & Templeton, 2011; Amigun et al., 2008; Bensah & Brew-Hamond, 2010). Identification of relevant sectors to drive the biogas dissemination forward are thus needed in

Ghana. In contrast, in Thailand, biogas technology in medium- to large-scale animal farms and industrial sectors has been applied and has been supported by national programs for decades (Aggarangsi et al., 2013), where agro-industries and larger pig farms have widely deployed the biogas technology. Some parts of the agricultural sector in Thailand, however, still need to be included in the biogas development, and other organizational concepts that increase the efficiency of biogas system could eventually support this.

This paper looks at the biogas industry in Thailand, Ghana and Denmark and reveals opportunities for the three countries to learn from one another. Developing countries could learn from the successes and failures of biogas systems in more advanced countries, enabling them to plan and develop viable initiatives within their own contexts. Many developing countries are still dealing with a number of issues, including, for example, limited or weak infrastructure conditions and regulations, which hamper further development of their biogas industry sector (Atuguba and Tuokuu, 2020). Knowledge transfer between developing countries can also be fruitful, as many similar conditions can be identified between such countries. Again, developed countries could also learn from solutions adopted within developing countries; hence, a platform for cooperation between countries in the north and countries in the south should be established. This paper analyzes the biogas industry within the three countries addressed, where new opportunities for implementing biogas technology are investigated by looking at, for example, organizational and technical concepts. Through case studies, lessons learned and practical examples from the three countries, new perspectives and knowledge will be captured, which addresses the existing knowledge gap. Current literature lacks investigations and comparisons of developed and developing countries' biogas industry, with the latter being several countries at *different* development stages, and with emphasis on *where* to focus the deployment of biogas technology in the future. In the concluding part of this paper, we suggest how knowledge exchange can be initiated, and how a communication infrastructure can be created for policy policy formulation and dissemination

2. Methodology

In the following section we will present the methodology applied in this paper, and elaborate on the research design, collection of empirical data, field study cases investigated, and knowledge obtained from journal articles and reports. Finally, we present our conceptual framework with a focus on the Energy Chain approach.

2.1 Research design

This paper combines a literature review, case studies, field data/interviews and theoretical concepts to retrieve information and to provide a conceptual framework for the analysis and investigation of the biogas industry within Thailand, Ghana and Denmark. The conceptual framework applied departs from the Energy Chain concept (Blok, 2007) seeking optimizations of the entire Energy Chain and not only within parts of it, as well as knowledge of the biogas industry within the countries addressed, retrieved from field trips and interviews with relevant stakeholders in the biogas industry. Besides this, reports and literature on the biogas industry in Thailand, Ghana and Denmark is examined, and relevant journal articles assessed to provide further knowledge of the biogas industry. This triangulation (Yin, 2013) of information provides a platform for identifying arenas where biogas can be developed within the three countries and where the benefits of the technology can be fully harvested. Three countries with different development stages are selected: Thailand, which is an Asian 'tiger country' (Krongkaew, 1995), adopting both national and donor aid programs in its support of biogas deployment (Aggarangsi et al., 2013); Ghana, a traditional developing country that struggles to provide appropriate incentives for its renewable energy promotion (Atuguba & Tuokuu, 2020); and Denmark, a developed country, which has supported the implementation of the biogas industry since the 1970s (Lybæk et al., 2013). We will utilize this country assessment to identify how a future optimization of the biogas industry can be deployed, looking at the biogas sector through the lens of the Energy Chain approach, and see whether knowledge from one country can be favorable for another country.

2.2 Case studies (field data and interviews)

Case studies (Yin, 2013) and qualitative semi-structured interviews (Brinkmann & Kvale, 2015) were conducted to research how Thailand, Ghana and Denmark can benefit more from biogas through new organizational and technical concepts identified by the Energy Chain analysis. In Thailand, two cases are investigated, both situated in the northern part of Thailand, looking into 1) biogas from dairy cattle manure, combined with organic waste from the local community; and 2) supply of surplus biogas from a biogas plant to a local village by gas pipes. The cases are based on our data from field studies conducted within Thailand. In Ghana, two agro-industry cases are presented, based on literature studies, emphasizing digestion of wastewater from the processing of 1) fresh and dry fruits; and treatment of 2) palm oil mill effluents (POME). The Danish examples also rely on our data from field data collated after visits to1) a farm biogas plant, and 2) a centralized biogas plant, both of which digest and supply organic digestate as fertilizer to farmers. The case studies in Thailand and Denmark were conducted over a period of four years from 2016–2020. Besides this, personal interviews and email correspondence with stakeholders within Thailand and Ghana have provided additional empirical data for this research.

2.3 Journal articles and reports

Journal articles emphasizing biogas in Thailand, Ghana and Denmark are identified by using keywords such as '*biogas*', '*biogas technology*', '*biogas feedstock*', '*energy production from biogas*', '*biogas policy*' etc., using Science Direct and Scopus as search engines. A snowball methodology (Greenhalgh & Peacock, 2005; D'Ippolito, 2014) was applied to identify additional articles, looking into the reference list of the journal articles to find additional relevant papers. Other appropriate literature is, for example, background knowledge of Ghana provided by GIZ, the German aid organization, or renewable energy plans from the Thai Government, as well as regulatory frameworks from the Danish government emphasizing support schemes for biogas.

2.4 Conceptual framework: Energy Chain approach

This paper applies an Energy Chain approach to the identification of emerging organizational and technical concepts that can be adopted or further developed within Thailand, Ghana and Denmark. It applies a systemic approach (Gracceva & Zeniewski, 2014; Marius & Roméro, 2013) to the use of resources, the application of technology and the distribution of digestate, supply of energy and energy usage. The Energy Chain emphasis falls on optimizations all along the Energy Chain and not only on parts of it for enhancing the environmental benefits of renewable energy production, but also to enhance socio-economic benefits. Various literature and practical case studies revolve around Energy Chain analysis; see, for example, Blok (2007) and Damsø et al. (2014).

The underlying perception of the Energy Chain approach is to increase the efficiency of energy systems by optimizations in the Energy Chain as a whole. Thus, biomass residues readily available and in large quantities must be identified for biogas production, not competing with other meaningful usages. The specific energy conversion must be provided with as many energy services as possible; preferably generating both power and heat (co-generation or Combined Heat and Power, CHP), or even power, heat and cooling where applicable (tri-generation) in order to avoid loss of energy that otherwise could have been used. A final utilization of the energy must be assessed to provide as many energy services as possible, here identifying new markets for distribution of energy or finding new ways of using the energy within, for example, a company. Optimizations of the end-use also applies to the digestate, where users must be identified and the value of the digestate established. The Energy Chain entails a synergy between its elements, which cannot be optimized individually. In some cultures, as in the case of Ghana, feedstock from human faeces are unwanted in biogas digestate, meaning that valuable fertilizer is lost in the system. Furthermore, due to the small scale of the plant facilities, the biogas is not being utilized for energy, but simply flared or released as methane to the atmosphere. This is unfortunate.

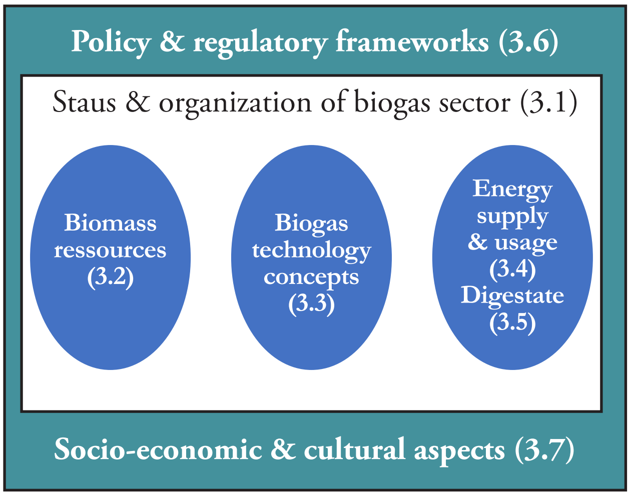

Figure 1 Energy Chain approach.
Synergetic relation between feedstock, converting technology and energy and digestate end-uses. The figure indicates in which sections of this paper specific parts of the Energy Chain are investigated, and which additional outer frameworks, as, for example, policy and culture issues, are included.

Thus, the Energy Chain approach adopted in this paper (blue color interconnected triangles in Figure 1 above) is a synergetic effort to identify appropriate and available 'Biomass resources' (3.2), being converted in the most appropriate way, by 'Biogas technology concepts' (3.3.), providing the highest energy output as a result. This is combined with the utilization of large amounts of 'Digestate' (3.5), preferably not conflicting with any cultural perceptions, leading to increases in the total 'Energy supply & usage' (3.4). Besides the Energy Chain approach presented above, we also adopt a set of important 'outer frameworks' (green color triangles in Figure 1) to be investigated for qualifying this study further, which will be detailed in the following. Prior to the Energy Chain approach, we initially include a description of 'Status and organization of biogas sector' (3.1). The 'status' part briefly addresses state-of-the-art knowledge from within the three countries; for example, the number/capacity of biogas plants being deployed, type of technology applied and current utilization of feedstock, etc. The 'organizational' part is emphasized to understand whether the biogas plants are primarily publicly or privately owned, and whether one single or several actors are engaged in the plant ownership. The purpose of the above is to provide a state-of-the-art picture of the biogas 'landscape' within the three countries, and an assessment of whether other types of technical and organizational concepts could be viable within the specific contexts addressed.

After the Energy Chain approach, we emphasize 'Policy and regulatory frameworks' (3.6), being another outer framework with high implications for the deployment of biogas technology. Here, the emphasis is primarily on financial support provided to disseminate the technology, as, for example, feed-in tariffs (FIT) and construction cost support. Policy frameworks, or lack of policy frameworks, impact the conditions under which biogas technology is implemented and which actors can become a part of the biogas industry and promotion. Moreover, we emphasize 'Socio-economic and cultural aspects' (3.7) as another important outer framework for biogas dissemination, where we detail how digested animal manure is perceived as to be utilized for fertilizer and the biogas for cooking gas, respectively. Also, we examine which benefits are connected to the use of biogas as a low-cost renewable energy, instead of the purchase of increasingly expensive and polluting fossil fuels. All elements of the Energy Chain, as well as the outer frameworks, impact the type of biogas technology and organizational concepts possible to deploy.

This paper now proceeds to analyse the biogas industries within Thailand, Ghana and Denmark, respectively. In Figure 1, the elements, which are investigated in the following, is marked by section numbers (3.1, 3.2, 3.3….). This illustrates in which part of Chapter 3, as well as where in the Energy Chain or outer frameworks, they are situated. Having conducted these analyses, the chapter ends with some remarks on the need to adopt new organizational and technical concepts within the three countries investigated. In Chapter 4, these concepts will be addressed and exemplified further by case studies from within the three countries. Finally, the findings of the paper are discussed in Chapter 5, and in Chapter 6, we provide a conclusion together with recommendations of how to share knowledge and initiate policy formulation and dissemination.

3. Findings and analysis

In the following, we present the analysis of the Energy Chain concept applied to the biogas industry within Thailand, Ghana and Denmark. At the end of the chapter, we suggest how new organizational and technical concepts can strengthen the investigated countries' biogas Energy Chain in the future.

3.1. Status and organization of the biogas sector

Thailand: The status is that biogas technology with a capacity of approximately 412 MW is implemented in Thailand today, comprising farm biogas plants as well as agro-industrial biogas plants. Approximately ~300 MW supplies power to the grid, whereas the remainder is off-grid installations – primarily smaller farm biogas plants (Potisat, 2016). No reliable data is available on the actual number of plants implemented, but several thousand biogas plants (~2.300) are estimated to be spread throughout Thailand (Aggarangsi et al., 2013). Farm biogas plants vary from relatively large plants fed by, for example, pig manure, to numerous small-scale plants with a reactor volume size of, for example, 8, 12, 16, 30 m3, the 16 m3 being the most common. They typically digest livestock manure from a few farm cows and pigs, applying additional waste such as organic kitchen waste and human excreta (Asia Biogas, 2015). Besides farm plants, approximately 230 large-scale agro-industry biogas projects are also implemented, generating the majority of the biogas in Thailand based on the digestion of rubber waste, cassava starch, palm oil residues, etc. (Tonrangklang et al., 2017).

The biogas plants in Thailand, being farm or agro-industrial plants, are mainly organized as privately owned plants, with limited engagement with the local community besides the sale of solid fertilizer from the biogas plants, which often happens from larger plant facilities. They are thus mainly privately owned and financed, whereas others are privately owned but co-funded by governmental grants, programs or donor aid; yet others are privately owned but have received support from the Clean Development Mechanism (CDM). Besides this soft loan, Energy Service Company (ESCO) and tax incentives, for the purchase of equipment and machinery, has been provided to support biogas in Thailand (Suwanasri et al., 2015). So far, however, no joint ownership of biogas plants has been established in Thailand, unlike the Danish centralised biogas plant concepts. Unharvested potentials in Thailand includes the deployment of centralized biogas concepts, especially in the north-east part of Thailand, where the majority of the country's dairy cows are situated, and with a short distance between farms for efficient manure collection. Here, centralized biogas plants could be adopted in an organizational structure already based on the cooperative idea in existing farm cooperatives (Lybæk and Kritapon, 2016). Another concept is to adopt new organizational structures related to the energy supply side, by, for example, piping biogas from larger biogas plants to local citizens, thus involving the local community closer in biogas production and energy usage (Damrongsak and Chaichana, 2020).

Ghana: The status is that the majority of Ganesan biogas plants have been installed for the treatment of kitchen waste and toilet excreta within wealthy households in Ghana, sizes ranging from 8–12 m3 reactor volume. Besides these, several such bio-sanitation facilities are also deployed within educational and health institutions in urban areas. It is estimated that around 400 biogas plants have been implemented in Ghana over the years (Hanakamp & Ahiekpor, 2015), with many not being operated today due to technical issues (Arthur et al., 2011a). Farm biogas plants are few and the effort to promote the technology among farmers, with little support from agricultural-sector bodies in the country, has been weak. The current number of farm biogas plants is thus unknown, as registered service providers have not been reporting the number of plants installed to regulatory bodies. At the same time, many unregistered artisans operate within the country with no monitoring of their actual activities. Within the agro-industrial sector, only a few biogas plants have been deployed to digest, for example, liquid and solid waste, palm oil mill effluent, or brewery wastewater and fruit waste, even though the potential is high (GIZ, 2014).

Household sanitation plants in Ghana, as well as the few farm and agro-industry biogas plants, are *organized* as privately owned and initiated facilities, and have received limited – if any – economic support

(Hanakamp & Ahiekpor, 2015). The bio-sanitation plants deployed within the educational and health institutions are, on the other hand, a mix of publicly and privately owned facilities, where extensive donor aid has facilitated this implementation. Future potentials for Ghana are to benefit more from the biogas technology, as only a few advantages have so far been captured due to the deployment of most biogas plants mainly within a few households. The digestate is not being utilized just as the biogas most often is flared. Undoubtedly an emphasis on sanitation issues is important (Quashie et al., 2019), but looking at the farm and agro-industry in Ghana, the benefits of both energy production and digestate could be harvested further (GIZ, 2014). Unlimited biomass residuals from this sector are currently being produced, farmland for distributing fertilizer is available, and the demand for energy clearly present within the agro-industry and nearby community substituting wood fuel for cooking.

Denmark: The *status* is that 36 centralized biogas plants in Denmark that receive livestock manure from several participating farmers, primarily from pig and dairy cow farms, as well as from other types of feedstock; for example, mink and poultry manure. Source separated household waste is also increasingly being utilized for biogas production. Denmark hosts approximately 64 farm biogas plants, which are located at a single farm, and most often based on feedstock from a large stock of dairy cows or slaughter pigs. Apart from this, 51 biogas plants are operated in connection with wastewater treatment plants and digest sludge from the cleaning process. Moreover, 28 plants utilize landfill gas, and finally, seven industrial plants have been established, digesting sludge from, for example, medical and food manufacturing industries (DEA, 2020b). The capacity reaches 20 PJ, where approximately one-third of the plants produce power and heat, and two-thirds upgrade to natural gas for the national gas network (Food & Bio-cluster Denmark, 2020).

Centralized biogas plants are *organized* most commonly as jointly owned by farmers and the local municipality. The plants are then established with low interest rate municipal loan guaranties (4 % p.a.), due to their contribution to the municipal heat supply. Within recent years, biogas plants have, however, mainly been established as a joint ownership between farmers and natural gas companies, allowing sale and distribution of upgraded biogas to the natural gas network, which accounts for 11 % of the natural gas consumption today (DGC, 2020). Private natural gas companies tend to establish individually owned biogas plants and develop supply contracts with their own corporate business systems, increasing the company's value chain connected to operating biogas technology by developing, for example, feedstock supply companies, etc. Traditional biogas plants in Denmark are based on local CHP and non-upgraded biogas, given the new type of biogas plants' economic advantages, due to upgrading facilities and the development of new corporate business structure, as emphasized above. As far as the potential for biogas in Denmark, more emphasis should be given to the deployment of organic biogas plants in the future with a focus on producing organic fertilizer to increase the area of organic farming and hence to develop a more sustainable agricultural sector. This implies higher value of the digestate in the future compared to today. The challenge is, therefore, to develop technical and organizational concepts that support such production, where biogas yields are not the main purpose of the plant facility. Hence, circular economy initiatives could be further integrated in the biogas industry in Denmark for the future.

3.2 Biomass resources

Thailand: Despite economic support from EPPO for the promotion of biogas within the *agro-industry*, vast amounts of wastewater from the following industries are still readily available: ethanol, rubber, palm oil, cassava starch and sugar residues, just as the processing of pineapple, canned tuna, sardines and baby corn, frozen shrimp and squid, fruit and vegetables, are potential resources for biogas that still need to be harvested (Tonrangklang et al., 2017). Thus, the potential for deploying biogas plants, based on wastewater from the agro-industry, is possible in Thailand. The use of *livestock manure* for biogas has, as mentioned earlier, been promoted by EPPO for several years, especially within pig farms and on smaller farms with a few animals. With a pig production surpassing 11 million in 2018, and still increasing (Sritrakul & Hudakorn, 2020), this resource could be utilized more efficiently. Also, cattle and poultry manure could receive more attention. Especially in north-eastern part of Thailand, where the majority of the increasing dairy livestock sector is situated, a vast amount of cattle manure is being produced. It is, however, more challenging to collect than pig and poultry manure, as the farms are relatively small and proper infrastructure and manure collection systems within the stable are not yet available, with the result that manure is dumped randomly on the farm soil (Lybæk and Kritapon, 2016). Thailand's extensive rice cultivation produces *crop residues* like straw and rice husk, just as green tops of cassava and tapioca plants can provide biomass residual appropriate for biogas production if pre-treated. Napier grass, as a sort of energy crop, is expected to be cultivated and utilized more for biogas in the future in Thailand (DEDE, 2014). Finally, municipal waste has a huge biogas potential in Thailand, but is scarcely utilized, creating various problems in Thailand connected to landfill development, random burning of *municipal waste*, and dumping of the waste on land and in water bodies. As noted by Aggarangsi et al. (2013), this type of organic biomass waste is the least utilized resource for biogas production in Thailand today.

Ghana: *Municipal waste* like food and kitchen waste is available in large quantities from households, schools, institutions, hotels etc., and are distributed (10 %) to be used as feed for dogs or cattle in households or farms respectively, but mainly dumped directly as waste in dumpsites (Agyenim et. al, 2020). Raw faecal and sewage sludge is mostly dumped at landfills or discharges to water bodies (GIZ, 2014). In Ghana, to utilize such feedstock on a larger scale will require profound waste collection initiatives, as well as infrastructure and storage facilities (Präger et al., 2019). Besides such biomass waste, an abundant amount of agricultural waste is available throughout Ghana that is ideal for biogas production (Präger et al., 2019), as shown in the following. In Ghana, feedstock potentials from *livestock manure* are cattle dung and manure, goat dung, poultry and pig manure (Arthur et al., 2011b), which currently are being utilized scarcely for biogas production. It is difficult to collect the manure on farm fields due to poor infrastructure and long distance between farmers. The latter also account for crop residues appropriate for biogas by co-digestion with manure – for example, rice, yam and millet straw, maize cobs and stalks – and will require some sort of pre-treatment in most cases (GIZ, 2014). The *agro-industrial* waste in Ghana is connected to the processing of palm oil mill effluents (POME), fruit, cocoa, starch, cashew and breweries (GIZ, 2014) on larger facilities. Within these industries, an actual collection of the biomass waste can be applied, as either solid waste or wastewater appropriate for biogas production.

Denmark: Unused *livestock manure* adds up to 24 million tons annually, which indicates that a large unused potential is present within the agricultural sector. The manure can be characterized as liquid manure, solid manure and deep litter, which is a mix of manure and straw used as bedding materials for livestock cattle (Al Seadi et al., 2013a). The manure resources derive from dairy cow, pigs, mink, horse and chicken farms, and are collected in manure storage tanks at the farm site and thus readily available for biogas production. As far as *crop residues* are concerned, more than two million tons of cereal straw is available for biogas in Denmark (Wittrup & Jeppesen, 2020), just as vegetable green tops from beets, carrots and potatoes, etc., can be fed to biogas plants. Most crop residues are pre-treated mechanically before being fed to the biogas reactor. Grass clover is another biomass crop beneficial for biogas production as leading to high a gas yield, and if stored as silage together with straw, for example, it enhances the gas yield of straw residues even further (Lybæk et al., 2020). Especially in organic biogas plants the use of grass clover is important, as the amount of organic manure is limited. Maize and beets are only to a limited extent applied in biogas plants due to stricter regulations. Organized and controlled national collection and source separation of household waste, municipal waste, is widely practised and is now regarded as important future feedstock for biogas production in Denmark (Food & Bio-Cluster Denmark, 2020), despite earlier not so successful efforts to utilize this resource this way (Lybæk, et al., 2013). Several plants already digest this type of feedstock, which will increase in the future supported by governmental program and legislation (Danish Government, 2013).

3.3 Biogas technology concepts

The fixed-dome and floating-drum digesters (Figures 4 and 5 below) have been disseminated in both Thailand and Ghana within agriculture at farm level, and at household and institutional levels respectively.

However, the former has found more success due to advantages such as lower cost per unit volume, lower maintenance cost and longer lifetime. The 'classic' fixed-dome concept, the Chinese model (Figure 3), was introduced in Thailand and Ghana in the 1960s but has undergone modifications to suit local conditions.

Thailand: Thailand has financially promoted the biogas technology development for many years, primarily through the Department of Agricultural Extension and funded by Energy Policy and Planning Office (EPPO), and through research by the agricultural university of Chiang Mai (CMU). Besides the fixed-dome technology concept, which has been extensively promoted by EPPO over the years and deployed primarily within smaller farms, more advanced digesters have been developed by CMU, such as the channel digester with upflow anaerobic sludge blanket (UASB) technology (Figure 2). Also, the upflow anaerobic digester (Figure 3) has been applied in larger farms for treatment of animal manure and within the agro-industries. Besides these concepts, other technologies like fixed film, baffle reactor, covered lagoon, complete-mix reactor and different hybrid reactor are also found (Aggarangsi et al., 2013). Within the agro-industry, biogas concepts like the channel UASB technology and the continuous stirred tank reactor CTTR are also adopted. The channel UASB technology has proved successful within the large tapioca industry in Thailand, where the CSTR technology has been deployed in the palm oil industry to treat palm oil mill effluents (POME) (Tantitham et al., 2009). At more advanced biogas plants, a scrubber will normally remove H2S contents, and the biogas is blown to a chiller to remove excess moisture before the biogas is sent to a converting unit, most often a gas engine, for CHP production. If the gas cannot be fully utilized, it is most often flared. The plants are normally operated at mesophilic temperature levels (Tantitham et al., 2009). On smaller farm plants, the biogas is simply led to the atmosphere without flaring, if the demand for gas is limited.

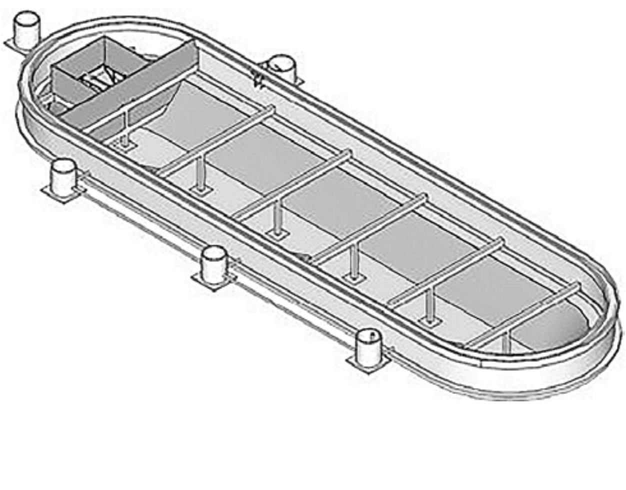

Figure 2: Channel digester with internal integrated semi-UASB including biogas storage, gas flare and biogas conversion unit (Aggarangsi et al., 2013

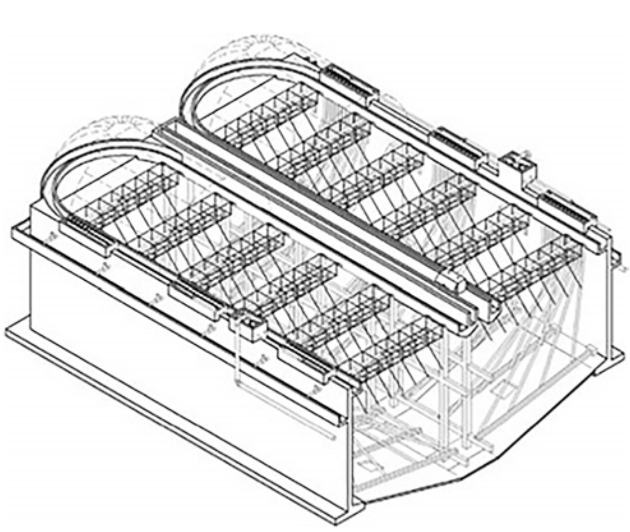

Figure 3: Upflow anaerobic digester including biogas storage, gas flare and biogas conversion unit (Aggarangsi et al., 2013).

Ghana: In contrast to Thailand, Ghana has never implemented national programs with the purpose of developing a standardized digester concept, and the deployment of the technology has depended heavily on donor aid. Some support for biogas construction has been offered by the Ghana Ministry of Energy. Models like the fixed-dome and floating-drum concepts (Figure 4 and 5) have, as mentioned, been disseminated in Ghana by local biogas companies and artisans, where they have undergone various modifications. Unlike the other models, the concrete Puxin digester (Figure 6) is a patented Chinese technology and promoted within the country by one company. Some part of it is prefabricated and assembled on site, as opposed to the brick plants (Hanekamp and Ahiekpor, 2015). The floating-drum concept has also received much attention, but due to the floating drum and thus moving parts (water jacket), it requires more attention as far as operation and maintenance (O&M). By far the most disseminated biogas concept in Ghana is the fixed-dome technology, applied within households, institutions, farms and the agro-industry. It is a traditional brick-made construction with a reactor volume of 10–100 m3, the smallest being household applications. Few, more advanced biogas plants are implemented in the agro-industry based on, for example, the USAB-technology – as, for example, the 800 m3 digester deployed in connection with a large brewery in Ghana (Bensah & Brew-Mammond, 2010). All biogas concepts in Ghana are based on the mesophile temperature level, indicating that the average temperature in Ghana is relatively high.

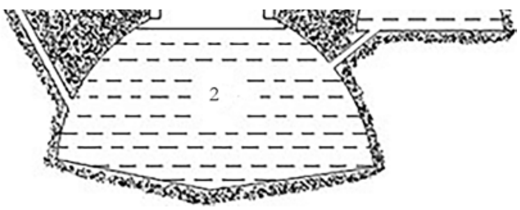

Figure 4: Floating drum digester: 1. Mining tank with inlet pipe. 2. Digester. 3. Compensation tank. 4. Gasholder. 5. Water jacket. 6. Gas pipe (Arthur et al., 2011a)

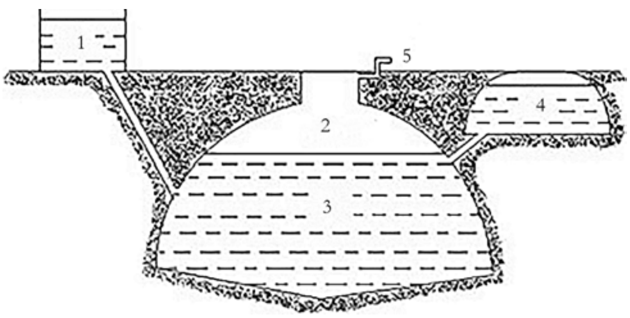

Figure 5: Fixed dome digester: Mixing tank with inlet pipe. 2. Gasholder. 3. Digester. 4. Compensation tank. 5. Gas pipe (Arthur et al., 2011a)

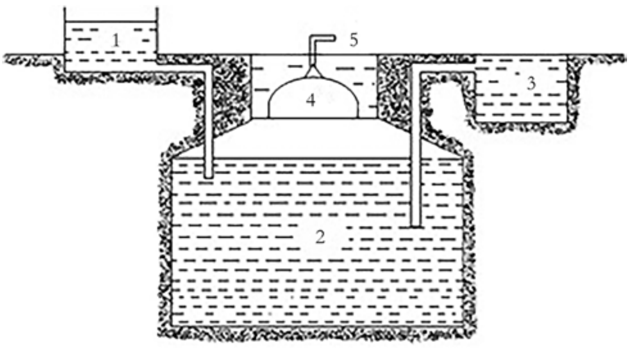

Figure 6: Puxin digester: 1. Mixing tank with inlet pipe. 2. Digester. 3. Compensation tank. 4. Gasholder. 5. Gas pipe (Arthur et al., 2011a; paper 8).

Denmark: Danish biogas digesters are mostly of the continuous stirred reactor tank type (CSRT), where the substrate (manure and other organic waste) is fully mixed, with new substrate constantly replacing already digested substrate through an inlet pipe in the top of the reactor tank and outlet pipe in the bottom. The reactor tank temperature varies between mesophilic (35–37˚C) and thermophilic temperatures (52–55˚C), where most new plants are designed with thermophilic temperatures to facilitate a faster digestion process. The substrate stays in the reactor tank for between 15 and 35 days before it is fully substituted by new material, as described above (Jørgensen, 2009). Danish biogas plants are designed to digest 75 % manure and 25 % other organic waste; e.g. industrial waste, household waste, energy crops, etc. This accounts for both large-scale centralized biogas plants and the farm plants and makes pumping and stirring of the substrate possible, as the dry matter content stays below 12–15 % (Lybæk, 2014). The digesters on smaller farm plants are concrete or iron reactor tanks and, on larger plants, they are tall vertical iron reactor tanks; reactor tank volumes are 50 m3 for the smallest farm plants and up to 3.000 m3 in total for the largest, respectively. Most larger biogas plants have two or more reactor tanks to avoid a full production stop if one tank fails, and to enhance the stirring and mixing of the substrate. Figure 6 below illustrates the process in which digestate, manure and organic waste are fed to the receiving tank first. Here it is mixed, stirred and sent to the reactor tank and heated to facilitate the digestion process. If the

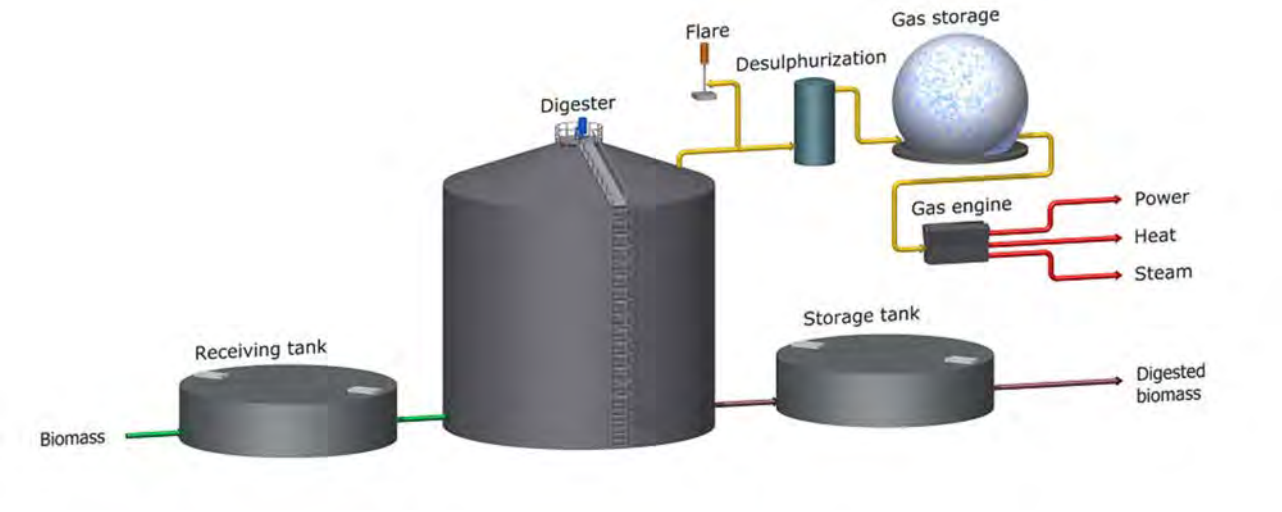

Figure 7: Danish biogas plant layout (Renewable Energy, 2020)

biogas plant is receiving industrial and household waste, it will be hygenized before being mixed with manure in the receiving tank to avoid problematic substances being spread to the environment (pests, germs, bacteria, etc.) (Renewable Energy, 2020). Hygenization takes place in a separate small tank (not illustrated in Figure 7), where the waste is heated to 70˚C for at least one hour (Lybæk, 2014; Renewable Energy, 2020). Most newer biogas plants also upgrade biogas in an upgrading facility (Urban, 2013) (not illustrated in Figure 6), where biogas from the gas storage tank has its content of CO2 extracted and injected directly into the national gas grid or used for transport purposes.

3.4 Energy supply and usage

Thailand: The energy use from biogas production in Thailand varies a lot and depends on technology, feedstock and context. In general, farm-based biogas plants have lower energy efficiency compared to agro-industrial plants. In larger farm plants, the biogas will normally be utilized for power production, supplying electricity to the grid benefitting from the Thai FIT (Suwanasri et al., 2015). The heat utilization is normally low, and in most cases simply wastes, unless the excess heat can be used for drying crops or breeding piggeries, or the like. On smaller farm plants, there is no electricity production and the biogas is normally just utilized in the household kitchen as cooking gas. On agro-industrial plants, the technology can be quite advanced; e.g. with production of CHP in a motor/generator unit, with both internal use of power and heat as well as export of power to the grid. Internally, heat is used; for example, for process heat purposes and the power to operate engines and cooling systems, etc. (Tonrangklang et al., 2017). Biogas for transportation purposes is being developed in Thailand, and many vehicles thus run on compressed natural gas (CNG) but so far rely mainly on conventional natural gas. Several test locations are developed, as, for example, at Khon Kaen University, which operates its campus buses on biogas CNG produced by the campus biogas plant. The feedstock is campus waste, pig manure, napier grass and various agricultural residues. (Field Study Thailand, 2016). Thailand has a target of producing 1,200 tons of biogas for transportation by year 2021, which should replace conventional compressed natural gas (CNG) (DEDE, 2014).

Ghana: The majority of biogas plants are installed in households and do not produce enough gas to meet the energy requirements of the average family. This is primarily due to the nature of the feedstock (blackwater from toilets), which consists of large amounts of water and small quantities of organic materials. Such plants are, as mentioned earlier, primarily implemented for hygienic and sanitary treatment of the household's organic waste (Osei-Marfo et al., 2018). On farm plants, co-digestion of animal manure, kitchen waste and grasses is sometimes practised, and where the gas production is substantial enough, it is used for cooking purposes, and sometimes even for power production by means of a small motor-generator. On larger agro-industry plants, the biogas energy recovery can be prioritized (GIZ, 2014). In most cases, the biogas is combusted in a gas engine with the power being used internally or distributed on the national grid at an agreed feed-in tariff. Alternatively, the gas is burned in a boiler for process heat generation to be used for, for example, drying or heating within the industry. Application of biogas as transport fuel is not yet practised in Ghana.

Denmark: Centralized biogas plants typically distribute heat to a local market of heat consumers by means of district heating (DH) networks. The size of the market can vary greatly from a few hundred customers to several thousand, depending on whether the DH network is a smaller local network or connected to a large network in the region. Historically, biogas has been utilized almost exclusively through combined heat and power (CHP), but newer plants are mainly designed to distribute gas on the well-developed natural gas network equal to 20,000 km of pipeline (DGC, 2020; Lybæk and Kjær, 2015). Here, the biogas is upgraded in a process where CO2, sulphur and moisture are removed and the gas cleaned and dried, resulting in a quality similar to natural gas (Holm-Nielsen et al., 2009; Prasat et al., 2013). This is injected into and distributed further on the gas network (Nature Energy, 2016). On farm plants, the biogas is also converted in a motor/generator for CHP, where the heat covers internal heat demands in, for example, pig stables and the farmhouse, and any surplus heat is wasted (Lybæk and Kjær, 2015). On newer and larger farm plants, the gas yield is so high that upgrading to natural gas is applied (Urban, 2013) and hence distributed on the natural gas network, where it is expected to account for 30 % of the gas in 2023 (Food and Bio Cluster Denmark, 2020). Agro-industry plants are few and comprise plants connected to dairy product companies and pharmaceutical industries with fermentation waste, where the quantity of organic matter in the effluent wastewater is high and the economy in applying a biogas plant viable. Some plants supply power to the national grid and excess heat to a DH network in the local community. Finally, biogas for transportation is not widely developed in Denmark, and only a few petrol stations (< 20) sell compressed biogas, or a mix of biogas and natural gas, to vehicles, and mainly to municipal waste collection trucks and city buses. The EU target of 10 % renewable energy fuel mix by 2020 (EUR-Lex, 2020) was reached in Denmark mainly by adding imported first generation ethanol from sugar cane to the petrol.

3.5 Digestate

Thailand: In the agricultural sector in Thailand, digestate is normally not applied as a liquid fertilizer as it is in Denmark. On smaller farms, it is most often dried in the sun on the farmland, and in large ponds on bigger farms and on agro-industry applications; e.g., palm oil mills, pineapple, tuna and starch factories, etc. When dried in the sun, the digestate becomes solid and is collected, put in plastic bags and sold and distributed to nearby crop farmers as fertilizer. Due to the drying process, GHG emissions occur in this process, just as the risk of ground water, lake and river pollution is also present. Proper handling of both manure and digestate in Thailand, seeking to preserve the nutrients in the manure and distributing the digestate applying methods that benefit them the most, is therefore important. As not all farm or agro-industries have adopted biogas plants, untreated leakages – discharge of manure and wastewater into the environment – are seen in Thailand. Thus, even though digestate is valued in Thailand as a cheap and high-quality fertilizer (Al Seadi et al., 2013b; Vlachos & Iakovou, 2016), some environmental challenges still exist (Lybæk & Kritapon, 2016).

Ghana: Most biogas plants are deployed at the household and institutional levels in Ghana and are sanitary based (Quashie et al., 2019), implying that digestate from these plants is discharged into public drains or the immediate environment with no further plans for its utilization in irrigation or crop production. The lack of useful utilization of digestate is also partly connected to socio-cultural constraints against the application of 'excreta-containing slurry' in irrigation or soil fertilization. Most farmers utilize manure as nutrients for crop cultivation, but it has not been digested, leading to less value of the manure as fertilizer. Ghanaian farmers need fertilizers to sustain their livelihood and to maintain cropland productivity. Digested manure provides farmers with a high-quality fertilizer at no cost, where the N, P and K is readily available, as opposed to imported artificial fertilizer (Arthur et al., 2011a). Digestate from agro-industries is rarely utilized for agricultural purposes, and the method is most often to discharge the wastewater into the ocean or nearby water bodies or ponds, which has severe impact for the local population as far as odor (GIZ, 2014; Hanekamp & Ahiekpor, 2015). Thus, more focus on the benefits of digesting manure in Ghana and thus producing a high-quality fertilizer must be emphasized more in the future.

Denmark: Digestate is distributed on farmland as valuable fertilizer, and farmers are generally interested in this type of nutrient because of the increased crop yielded compared to the use of artificial fertilizer. The annual production of livestock manure in Denmark accounts for 30 million tons, and around 20 % of this amount is digested in Danish biogas plants (Food & Bio-Cluster Denmark, 2020). Digested together with various other types of feedstock in the reactor tank, it becomes a liquid that is easy to distribute on farmland by drag hoses. Nutrients in the fertilizer become more directly accessible for the crops as the chemical form converts to ammonium. This means that the risk of nutrient pollution to rivers, lakes and ground water reservoirs is reduced. Also, odours connected with distribution of manure on farm fields decreases by as much as 30 % (Jørgensen, 2009). As the digested manure in many cases receives a declaration of its content of N, P, K, it enhances the opportunities for controlling and regulating the distribution of nutrients on farmland even further. The price of transporting manure between farms and biogas plant is, however, relatively high. It is not unusual for 30–35 % of the operational costs of a centralized biogas plant to be attributed to transportation (Jørgensen, 2009). Today, up to 50 kg N/acres of non-organic digestate is allowed to be distributed on organic farmland in Denmark, with a total of 170 kg N/acres (Landbrug og Fødevarer, 2020), which should be substituted with, for example, legumes such as grass clover in a crop rotation scheme, to enable a transition of the agricultural sector with more emphasis on organic cropping.

3.6 Policy & regulatory framework

Thailand: The policy targets set forth in the Alternative Energy Development Plan (AEDP) for the period of 2012–2021 imply that Thailand should have reached 25 % renewable energy within its energy mix before 2021, with biogas providing 600 MW. Under the previous Renewable Energy Development Plan (REDP 2008–2022), the target for biogas was 120 MW, which was reached already by 2011 and so stressed the need for more ambitious biogas targets (DEDE, 2014; Siteur, 2012). A revised AEDP was launched in 2016, with the target year being 2036. It is expected that biogas will contribute to 600 MW from digestion of industrial and agricultural waste, and to 680 MW from digestion of energy crops – such as napier grass (Theeraratatananoon, 2015; Laorucchupong, 2015) – thus, in total, 1.280 MW before 2036. The current feed-in tariff (FIT) scheme for energy from biogas in Thailand is 0,3 or 0,5 baht/kWh (Euro 0,008-0,014) for plants smaller or larger than 1 MW. This is quite low compared to the FIT on MSW of 2,5 or 3,5 baht/kWh (Euro 0,069-0,097) for landfill or digestion/thermal respectively, but low compared to 6,5 baht/kWh (Euro 0,18) for solar and for wind with 3,5 to 4,50 baht/kWh (Euro 0,097-0,12) for smaller or larger than 50 kW capacity (Pattanapongchai & Limmeechokchai, 2013; DEDE, 2014). The FIT system in Thailand focuses on MSW for biogas, and it would therefore be beneficial for the Thai biogas industry to emphasize co-digestion of manure and MSW to benefit from the high gas yield of MWS, as well as the high FIT. In 2010, Thailand changed from a flexible ADDER to a fixed FIT with a roof on the renewable energy capacity installed being able to benefit from the financial support (ERIA, 2019; Supriyasilp et al., 2017).

Ghana: Under the Renewable Energy Act (Act 832) of 2011, consumption of fossil fuel (petroleum) energy was expected to be substituted by renewable energy from biofuels through the production of power and heat from the private sector and independent power producers (IPP) (GIZ, 2014), adding up to by 10 % and 20 % in 2020 and 2030 respectively (Energy Commission Ghana, 2006). This would guarantee Ghana's energy security, as well as mitigate negative environmental consequences of the present energy production, including climate change (Atuguba and Tuokuu, 2020). The introduction of the law resulted in the formulation of feed-in tariffs (FIT) to support deployment of renewable energy including biogas, but no beneficiaries were, however, identified (Sakah et al., 2017). The tariff was set to Ghp/31,46 per kWh (Euro 4,46), which should be reviewed periodically. According to Atuguba and Tuokuu (2020), Act 832, however, exists only on paper, as no specific authority in Ghana is responsible and supporting the content of the act, and the renewable energy funds – accompanying the FITs – have never been launched. Thus, the energy policy in Ghana does not currently facilitate a FIT to support any large- or small-scale renewable energy generation, and all projects undergo tender through a competitive bidding process (Yeboah, 2020). The biogas industry is still in its infancy stage with limited projects conducted in this field, and new regulations are currently being drafted (Akuffo, 2020). Lack of appropriate infrastructure for biogas makes it relatively costly to deploy this technology in Ghana, and beyond the capacity of many agricultural households and institutions to pay for it. For example, the costs of deploying a small-scale fixed-dome digester in Ghana is USD 370 per m3 (Euro 309) (Mohammed et al., 2017), which is much more costly than applying the same technology in Thailand, where it is USD 40-57 per m3 (Euro 33,4-47,6) (Limmeechokchai & Chawana, 2007; Suwanasri et al., 2015). In the National Renewable Action Plan (2015–2020), there are no targets for biofuel energy supply to the grid. The total target for 2020 was 6.947 GWh, which consisted primarily of large hydropower plants, and smaller shares of wind energy and solar (NREAP, 2015).

Denmark: Danish biogas applications contributes nearly 20 PJ or 2,7 % to the national energy consumption, which totals 750 PJ (Food & Bio Cluster Denmark, 2020). The Energy Agreement, launched in 2008, stated that by 2025, 30 % of the manure in Denmark should be digested, amounting to 12 PJ (Danish Government, 2008). This was extended in 2009, when the Danish Government launched its Green Growth Strategy, with a target of 50 % of the manure being digested by 2020 (Danish Government, 2009), providing up to 20 PJ of energy. This target was reached and will provide Green House Gas (GHG) emission reductions equal to 580.000 tons of CO2 annually. From 2012–2020, the Danish Government supported biogas technology with a 30 % construction grant, a feed-in tariff (FIT) of 123 DKK/GWh (16,4 Euro) and the upgrading of biogas with 122,6 DKK/GJ (16,35 Euro) for higher burning value, and 110,5 DKK/GJ (14,73 Euro) for lower burning value. Economic support was also provided to industries that own and operate a biogas plant and utilize the energy for internal processes. Since January 2020, no government support for new biogas applications has been provided, but from 2022 a new support scheme is likely to be introduced and will focus primarily on PTX and circular bio-economy. The use of energy crops is also regulated in Denmark, allowing up to 12 % – measured by weight – of the feedstock being energy crops (maize, beets, etc.). This political statement indicates that the biogas industry should utilize other types of feedstock in the future to increase the gas yield (DEA, 2020).

3.7 Socio-economic and cultural aspects

Thailand: The socio-economic benefits connected with biogas in Thailand, especially on the larger farm plants and agro-industrial plants, are primarily related to the production of renewable energy for internal use, income from export of power to the grid and sale of digestate as fertilizer. Substituting the use of fossil fuel energy in Thailand, with a 50 % share being imported from other countries (Aggarangsi et al., 2013), will provide a buffer for increasing energy expenses in a country with constantly growing energy demands (Aggarangsi et al., 2013). Besides this, better handling of manure, crop residues and wastewaters will help avoid emissions of GHG to the atmosphere, and the spill of nitrogen, etc, to surrounding lakes, rivers and groundwater. On smaller farms, the socio-economic benefits are mainly connected to the production of kitchen gas, and thus substitution of expensive and nevertheless increasing utilization of petroleum products like LPG (Damrongsak and Chaichana, 2020; Pradhan and Limmeechokchai, 2017). Also, income from sale of digestate as fertilizer to neighbour farmers is beneficial, and recycling nutrients to farmland assists in increasing the humus and carbon content of the soil. Besides this, treatment of organic waste from the household and livestock will provide better sanitation at the farm. In Thailand, there is no concern, in contrast to other developing countries, regarding the use of biogas made from manure or human faecal matter as cooking fuel. On the contrary, the benefit of substituting expensive cooking gas is highly valued. Thus, the acceptability and social benefits of using the biogas within households are high. The investment cost of an agriculturally based biogas plant in Thailand is between 4.300 and 7.150

USD/kWe of installed capacity (Pattanapongchai & Limmeechokchai, 2013), or 40–57 USD per m3 (Euro 33,4–47,6) (Suwanasri, 2015). The price decreases when the plant capacity increases. For larger plants that require gas cleaning for efficient CHP production, or upgrade raw gas to natural gas standard, the cost price will eventually increase, but the potential income for sale of high-quality gas will be higher, too.

Ghana: In sanitary plants implemented within households and institutions in Ghana, the benefits from the low cost and treatment of blackwater are highly appreciated. Compared to septic systems where periodically emptying and disposal of septage incur costs and time, biogas plants allow for discharge into public drains at no cost to owners. This is, however, an environmental concern for Ghana, as the retention time often is too short to secure appropriate treatment (Bensah et al., 2015), with the risk of build-up of toxins in the human and animal food chains (Tulayakul et al., 2011). But, if handled appropriately, biogas technology can destroy many disease-causing microbes including hookworm, bilharzia, typhoid, cholera and dysentery bacteria (Sasse, 1988), as well as campylobacter, Escherichia coli and salmonella (Manyi-Loh et al., 2014). In cases where both animal manure, kitchen and other solid biomass waste are included, the gas produced is utilised for cooking and sometimes for power production, substituting for the use of LPG, diesel oil and purchase of power from the grid. On small farms, biogas is a substitute for wood fuel, which is extensively used in Ghana for cooking (87 % of all households) and causes deforestation and various health issues related to the combustion smoke and time required to collect (Kemausuor et al., 2014; Arthur et al., 2011a). There are, however, socio-cultural attitudes militating against the use of biogas from human waste, as it is viewed as unclean to use for cooking, which should be reflected upon in future Ghanaian biogas initiatives. Within the agro-industry the benefits are mostly like Thailand, where costly fossil fuels are substituted by renewable energy, lowering the pressure of energy imports and providing an opportunity to supply power to the grid and provide farmers with digestate for fertilization. The cost of small-scale biogas plants in Ghana is in the range of 235–446 USD (Euro 196,3–372,5) per m3, whereas expenses for materials account for the largest part (Bensah et al., 2011). This is relatively high compared to Thailand, where the cost was assessed at 40–57 USD (Euro 33,4–47,6) per m3. This has made the biogas technology unreachable for many farmers in Ghana, as well as households and institutions, who have not yet been supported by financial instruments as in Thailand and Denmark.

Denmark: The socio-economic benefits related to biogas in a Danish context are associated with the production of renewable energy that can replace fossil fuels, primarily natural gas and coal, the latter of which is imported. The biogas technology and the organization around these plants have also included, for example, local farmers, citizens and municipalities, and thus provided a more democratic development and ownership of the energy supply systems. Also, benefits are associated with the recycling of nutrients to agricultural soil, as N, P, K and minerals are returned to farmland with the digestate, originally being a part of source-separated household waste, and organic waste from commerce and industry that otherwise would be incinerated. The biogas thus assists in applying a more circular thinking to resource utilization (Food & Bio-Cluster Denmark, 2020). Besides this, farmers receive a valuable fertilizer (Al Seadi et al., 2013b; Vlachos and Iakovou, 2016), which saves import of artificial fertilizer, and water environments are improved due to lower leakage of nitrogen (Jørgensen, 2009). Most Danish farmers look at digestate as a cheap quality substitute to import as artificial fertilizer, where others are concerned about distributing digestate mixed with various substances on their fields. The concern is traces of plastic, hormones and heavy metals, especially from biogas plants co-digesting household waste, industrial waste, etc. Acceptance among farmers is, however, high for applying digestate without such particles, as it helps to build up the carbon stock humus content in the soil. Thus, for society, the benefits of biogas are related to the re-circulation of nutrients, the production of renewable energy reducing GHG emissions and import costs of fossil fuels, expenses associated with purchase of artificial fertilizer, and the empowerment or democratization of local citizens in the energy sector. Total investment in the biogas technology varies depending on size and feedstock used and thus need for pre-treatment technology and upgrading facilities, etc. To better compare with the Thai context, where other types of feedstock is mixed only to a limited extent in the reactor with animal manure on farm biogas plants, the investment costs of Danish biogas plants, treating 300, 550 and 800 tons of manure respectively, are as follows: 502, 384, 325 DKK respectively (100 DKK = 13,44 Euro) (Landbrug og Fødevarer, 2010).

3.8 Concluding remarks

As seen from the outline of the biogas industry within Thailand, Ghana and Denmark, all countries can apply optimization related to the Energy Chain of biogas, which is briefly addressed in the following.

Thailand has adopted the biogas technology all along the Energy Chain, but efficiency related to the supply side of energy could be improved; e.g. by including local citizens more. Also, a better utilization of animal manure from increasing amounts of livestock cattle, which currently is difficult to collect (Kritapon, 2014), requiring new organization of the biogas industry and a tighter corporation between stakeholder in the local community, must also be addressed in the future. In animal-dense areas, larger cooperative plants are assessed to be more economically feasible than many smaller units (Tybirk and Jensen, 2013). The use of cattle manure could be combined and hence co-digested with MSW. Thus, the 'biomass resources' and 'energy supply and usage' side of the Energy Chain needs to be emphasized more, whereas the 'biogas technology concept' has been a focus of Thai organisations for many years, and thus is regarded as relatively mature technologies, especially those adopted at larger farm plants and within the agro-industry.

Ghana, on the other hand, needs to focus on optimizing the whole Energy Chain in order to fully benefit from the biogas technology. Cultural barriers and lack of economic incentives hamper an effective use of the 'biomass resources' within households, institutions and even small farm holders, as human excreta is often mixed with the feedstock or is the sole content of feedstock. Such 'biogas technology concepts' contribute neither to usable 'digestate' nor to renewable 'energy supply and usage'. To initiate a biogas industry within Ghana, emphasis could therefore be on the agro-industry with more economic muscle, where a large amount of non-contaminated and easily collected 'biomass residues' is readily available. Here, the need for process heat and power is represented by the agro-industry itself, and efficient supply and use of the energy produced is present. As far as the 'digestate' part of the Energy Chain, local farmers can collect and utilize this resource as a substitute for importing costly artificial fertilizer.

In **Denmark**, activities along the entire Energy Chain have been applied for many years, and the 'biogas technology concepts' are regarded as mature applications. High efficiency in the whole energy chain can be observed, but large amounts of unused 'biomass resources' exist and could be utilized to facilitate an expansion of organic farming. Thus, 'digestate' supporting such development is currently lacking, and new ways of organizing the biogas industry might be needed to reach this. Much emphasis is currently on renewable 'energy supply and usage' in the Danish context, but a further development of the technologies already applied, with more emphasis on organic digestate, might bring the biogas industry into a new arena that more strongly revolves around the transition of the agricultural sector as well.

In the following, we emphasize what new biogas concepts within Thailand, Ghana and Denmark could look like – some already implemented, while others are ideas for the future. These schemes apply activities and optimizations all along the energy chain, or parts of it, which strengthen the overall environmental and societal impacts of the technology. We will provide two small case examples for each country addressed.

4.0 Case studies of emerging organizational and technical concepts

In a few cases within Ghana, donor projects include the use of digestate for fertilization, as well as utilization of the energy, and have been integrated in the layout of larger biogas plants from the beginning. In the following, however, we focus on projects that have not received foreign donor aid or have been donor initiated, but solely on local projects driven by local/national stakeholders. This illustrates the capabilities of the countries addressed to deploy biogas technology, which is exemplified below.

4.1 Thailand

Case A: Pig farm biogas plant supplies biogas to local village

A field study to Phairat Farm was conducted to visit the large pig farm located in Chai Nat Province in Thailand, which produces approximately 5.600 slaughter pigs annually, which is treated in a channel biogas digester with a size of 1.000 m3. Surplus biogas from the pig farm is piped in a distance of 8,6 km to 206 households in the village of Bo Rae, replacing the purchase of LPG for cooking purposes (Figure 8c). The project has been supported financially by the Ministry of Energy (MoE) in Thailand. To make the project economically viable, each household pays 50 baht/month (Euro 1,32) for the biogas supply, which is a substitute for 104.250 m3 LPG per year, and thus the costs associated with the purchase of fossil fuel gas. Besides this, Phairat Farm sells dried digestate (Figure 8a) from the manure treatment to local farmers as fertilizer (Figure 8b) amounting to 84 tons annually at a cost of 2 baht/kg (Euro 0,055). According to analysis conducted by Sritrakul and Hudakorn (2020), the case shows that the biogas plant and gas pipe networks significantly reduce the environmental problems – odor, wastewater and flies/insects – associated with the pig farm's proximity to a village. Besides this, local citizens benefit from the renewable energy production and are content with the biogas supply, which has proven reliable and affordable. The Phairat Farm and MoE has managed to encourage community engagement around the pig farm, and consequently obtained multiple economic and environmental benefits for the local community.

Case B: Centralized biogas plant treat manure, etc., from dairy cattle farmers

A field study to a dairy cooperative in Tambon Ban Kor located in Khon Kaen province was conducted to propose the implementation of a centralized biogas plants in the local community – the first of its kind in Thailand – to substitute for the use of 26,700 litres of diesel oil per year at the dairy company, and to collect and treat dairy cow manure from 188 farmers engaging in the cooperative, as well as untreated wastewater from the dairy company that

Figure 8: (a) Digestate from the biogas plant dried by the sun in ponds. (b) Packaged digestate to be collected by local farmers as fertilizer. (c) Biogas supply to village used for cooking gas that substitutes for the purchase of LPG

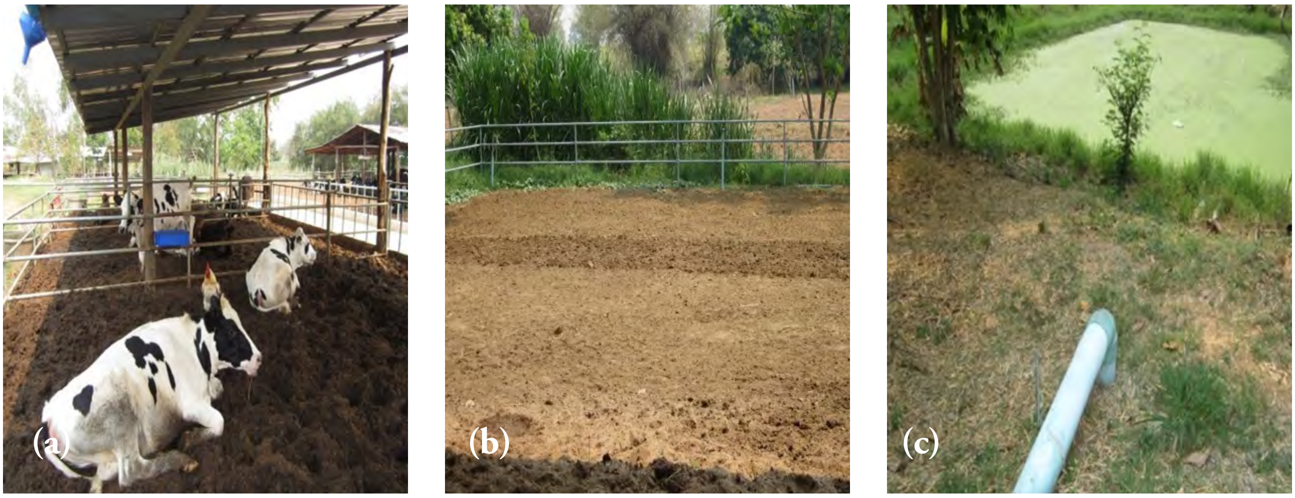

Figure 9: (a) Livestock dairy cattle rest in bedding materials composed of moistures/wet manure. (b) Manure from stable areas is distributed on farmland to dry in the sun for use as fertilizer. (c) Wastewater from the cooperative dairy company is discharged untreated to a pool, but relevant for biogas production together with animal manure and, for example, MSW and agro-industrial waste from the local community.

adds up to 20 m3/day (Figure 9c). Each farm holds between 43 and 53 cattle, with an average milk production of 14 litres per day. Surplus electricity from the biogas plant can be sold to the national grid and substitute own consumption of grid power equal to 240.000 KWh/year, and the digestate be returned to dairy farmers and sold to other local farmers. The necessary retrofitting of farm stables to be able to collect dairy cow manure will lower GHG emissions, nitrogen pollutants to water environment and significantly increase animal welfare and the quality of the milk supplied to the dairy company. Currently, livestock animal is not provided bedding materials besides their own manure (Figure 9a), which among other things leads to udder diseases and unnecessary and expensive use of medicine. The manure is dried in the sun (Figure 9b) and utilized on the farm as fertilizer or sold to other farmers for 2 baht/kg. The proposed biogas application system can be combined with co-digestion of MSW or agro-industrial waste from the local community, as, for example, wastewater from rubber trees, cassava, etc. From interviews conducted with seven farmers and the dairy company, the idea of implementing a centralized CSTR biogas plant was welcomed, and the financial capability of implementing such project was assessed to be within the reach of the farm–dairy cooperative. The cooperative exemplified above is one out of more than 7,000 beef and dairy cattle cooperatives in Thailand. For further information on this case, see Lybæk and Kritapon (2016).

4.2 Ghana

Case C: Agro-industry biogas plant treats wastewater from dry and fresh fruit processing
The HPW fresh and Dry Ltd. Company is an agro-industry located in Adeiso in the eastern part of Ghana. It produces dry fruits for the export markets (GIZ, 2014). The company employs more than a thousand people who reside in the local community. The plant comprises two 450 m3 concrete biodigesters (900 m3 in total) (Figure 10a) with a 200 kW heat boiler, as well as a thermal solar plant, providing process heat for the processing (drying) of the fresh fruits, etc. Three 100 m3 gas balloons are installed to store the daily gas yield, which amounts to 500 m3, also illustrated in Figure 10a. Besides this, a 120 kW motor-generator is used to supply power to the company, together with a 109 kW PV installation (Agyenim et al., 2020) shown in Figure 10b. The biogas feedstock is fruit residues such as mango, pineapple, coconut and banana cashew shells (GIZ, 2014). The biogas operates satisfactorily for long periods, but also faces operational challenges (Ahiataku-Togobo and Owusu-Obeng, 2019), mainly connected to the following issues: high pH-level of the feedstock fed to the biogas digester leading to low contents of CH_4 in the resulting gas and low energy output as a consequence. The acid content of the gas weakens the structure of the concrete digesters, and gas storage balloons are vulnerable as they are unprotected

Figure 10: (a) The two 450 m3 biodigesters constructed in concrete with balloon gas storage facilities. (b) PV installation to substitute the purchase of grid power. (c) Utilization of digestate from the company to fertilize the fruit plantations; here pineapple, as well as local farmers cropland (HPW fresh and Dry Ltd. Company, 2020)

and exposed to the natural environment. Benefits have also been obtained as the plant was established to substitute parts of the power purchased from the national grid to dry the company's fruit, and thus to provide higher energy security in a context where the energy supply system often faces blackouts (Amoah et al., 2019). The HPW Fresh & Dry Ltd. company utilizes the digestate on its own farms where they cultivate fruit for production, just as local farmers collect digestate to distribute on their farmland (Figure 10c). Initially, some farmers were unfamiliar with the use of liquid digestate (not solid), but, in general, there were no observed issues related to the value of the digestate as not originating from household sanitary wastewater (Fact Foundation, 2014).

Case D: Agro-industry biogas plant treats wastewater from processing palm fruits

The agro-industry Ghana Oil Palm Development Company (GOPDC) is located in Kwae in the eastern part of Ghana. It treats palm oil mill effluents (POME) from the processing of palm fruits. The processing plant produces 210,000 tons of palm oil annually from its 22,500 acres of plantation land within Kwae and Okumaning Estates. The wastewater was previously led to an open pond with GHG emissions to the atmosphere as

Figure 11: (a) Untreated POME wastewater from the production of 210,000 tons of oil annually is led to open ponds with emissions of GHG as a consequence. (b) The wastewater is now pumped from the refinery to the facility where biogas is harnessed. (c) The covered lagoon type biogas plant produces 18.000 m3 biogas per day, substituting for 615 tons of diesel oil. The digestate is utilized on farmland within the plantation and local community (Ahiataku-Togobo and Owusu-Obeng, 2019).

a consequence (Figure 11a). The two 1,000 m3 biogas reactors (Figure 11c) fed by POME as illustrated in Figure 11b – of the covered anaerobic lagoon digester type – now replaces the use of 615 tons of diesel oil/year at the company's refinery (GIZ, 2014). The plant produces 18,000 m3 of biogas on a daily basis, which is utilized for power and steam generation to be utilized mainly within the company. Surplus power is distributed to three local communities in the area as a replacement for wood fuel for cooking. The economy has been challenged on the plant due to insufficient palm fruits for processing, but the technology functioned well (Ahiataku-Togobo and Owusu-Obeng, 2019). Besides energy production, the plant produces a large amount of digestate, which is applied to farmland in the area, substituting for artificial and imported fertilizer (Danso and Owusu-Obeng, 2016) as well as some bio-oil and charcoal to be utilized within the local community (GIZ, 2014).

Thus, as seen from case studies C and D, some progress has been made in the use of digestate, especially in large-scale biogas installations within agro-industries, but there is a need to create more awareness among local farmers on the long-term benefits of using this digestate (GIZ, 2014). Also, more efficient energy production and utilization have been applied within these companies.

4.3 Denmark

Case E: Farm biogas plant produces organic digestate

A field study to the Månnson farm and biogas plant was undertaken to gain knowledge of how to integrate the production of organic fertilizer with renewable energy production at the farm level. The Månsson farm is a 1.100-acre farm (plus 400 acres of rented farmland) cultivating organic crops and breeding hens for egg production, with approximately 50 employees. In the summer period, around 250 additional people are hired. The farm is the largest organic egg producer in Denmark and supplier of 80 % of the national demand for iceberg salad, as well as of cabbages and onions. The farm has recently implemented a biogas upgrading plant (Figure 12a), together with the energy company Nature Energy (39 % owned by Nature Energy & 61 % by the Månsson farm). The plant currently produces six million m3 of biogas that it supplies to the gas grid. The biogas application provides CO2 neutral summer-heat supply to 3.600 inhabitants in the city of Brande, but the plan is to expand it to double the energy production, and to treat 255,000 tons of biomass. The main purpose of the Månsson biogas plant is to supply nutrients to the farm's production of vegetable, legumes, cabbages, etc., to become more independent of an external supply. Manure from the production of 45 million eggs an-

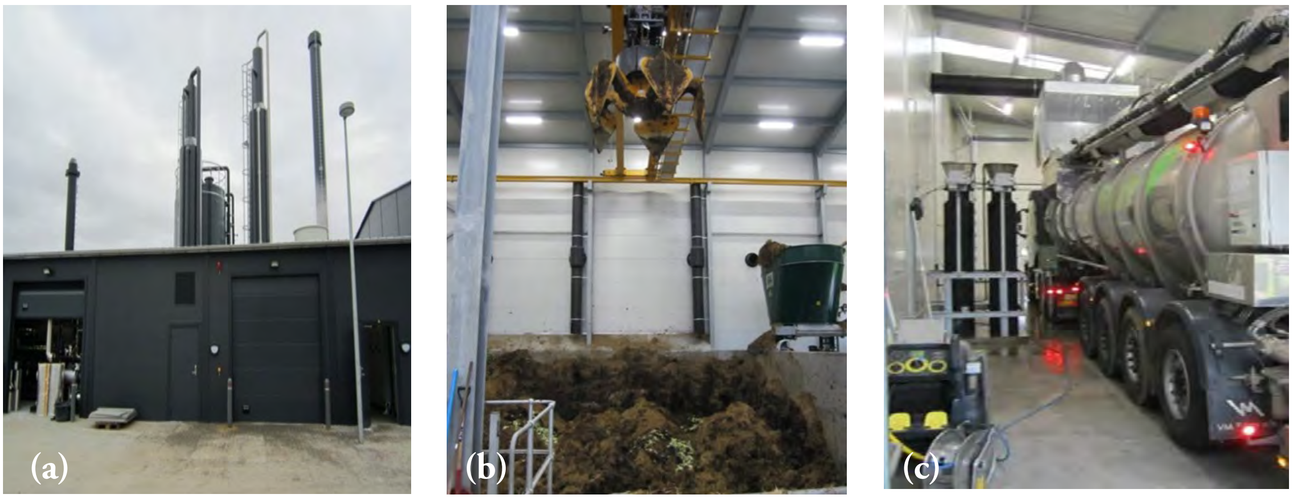

Figure 12: (a) The gas upgrading application at the Månsson farm biogas plant supplying gas to the citizens in Brande.(b) Clover grass, poultry manure and deep litter are utilized in a combination to produce biogas and organic digestate. (c) The digestate is used as fertilizer on the farm, as well as transported to organic dairy farmers within the local community

nually is favorable for biogas production, as the gas yield of poultry/hens' manure is high. In the farm's crop rotation, 70 acres is designated grass clover, just as lupine and peas are cultivated to fertilize the soil. Clover grass, poultry manure, potato pulp, as well as deep litter (Figure 12b) from organic dairy cattle farms in the area is fed to the digester and the legumes utilized as fodder for the hens, where the ambition is to have 200.000 hens within the next few years. The production of organic digestate has made it possible to expand the area of farmland being organically cultivated due to the production of organic fertilizer, also being distributed to farmers in the community (Figure 12c). At the Månsson farm and biogas plant, the ambition is to be able to extract clover grass proteins as fodder for hens and to utilize the dry matter from clover grass as feedstock for the biogas plant.

Case F: Centralized biogas plant produces organic digestate in sideline with high N content.
A field study to Solrød biogas plant was conducted to investigate the application of an organic sideline of digestate production. The plant also uses nitrogen-rich (N) feedstock composed of seaweed and MSW, which increases the N level of the digestate. The plant can receive up to 200,000 tons of different biomass feedstock annually, mainly from two pharmaceutical companies named CP Kelco (now Weber) (pectin citrus waste) and Christian Hansen (eluate enzyme waste, shown in Figure 13b), livestock manure from local farmers, cast seaweed from the nearby beach of Køge Bay and MSW. Seaweed is rinsed clean of sand in a cyclone (Figure 13a) to avoid damage to the equipment and sand inside the reactor tank. Solrød has recently invested in an upgrading facility to supply biogas to the gas network, and also in equipment for treating MSW as a new organic sideline. Digested source separated MSW has status as organic fertilizer, being on a 'positive substrate list', and must be distributed on organic farmland with 100 kg N/acres, where an additional 50 kg N/acres of non-organic manure can be utilized (in total, 170 acres N/acres) (Landbrug og Fødevarer, 2020). Lack of organic digestate in the region makes the use of MSW favorable for local organic farmers providing N-rich fertilizer. The biomass feedstock (organic or conventional) is digested under anaerobical conditions in two reactor tanks with a thermophilic temperature of around 52°C and equal to the production of 9,3 million m3 of biogas. Besides upgraded biogas, the plant delivers (non-upgraded) biogas to Solrød municipal CHP plant via a short gas pipe, where the gas is combusted in a motor-generator and the energy supplied as CHP to the grid and district heating (DH) to the citizens of the greater Køge area (24.500 MWh of electricity and 28.600 MWh of heat). The digested biomass (organic digestate separated from the conventional) is pumped to storage tanks with

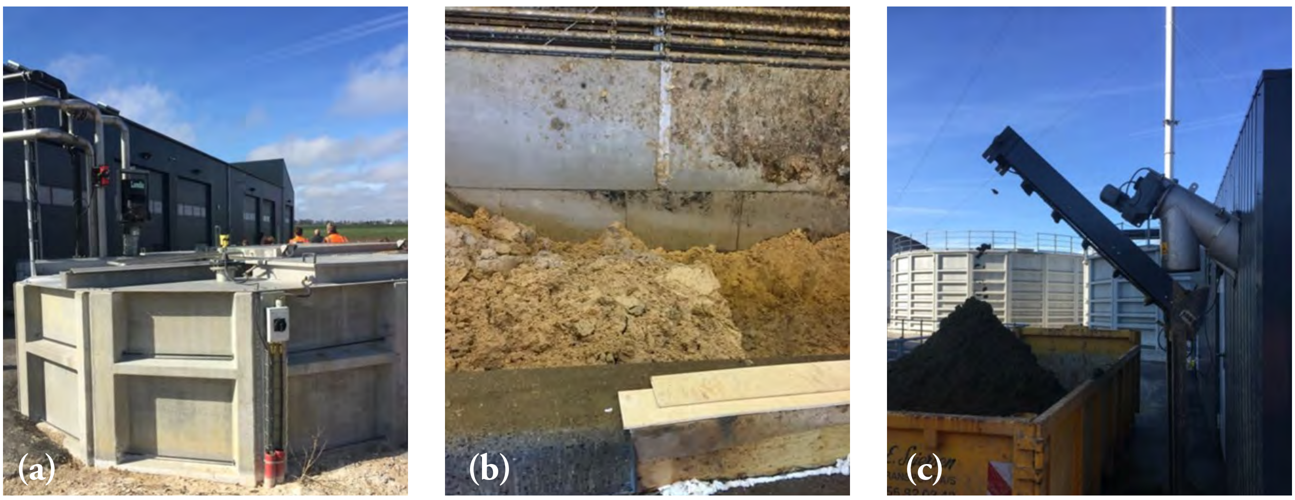

Figure 13: (a) Cyclone rinsing cast seaweed from the Bay of Køge from sand before it is fed to the reactor tank, and later used as N-rich fertilizer on farmland. (b) Feedstock from eluate, a residual from the production of enzymes from Chr. Hansen Company. (C) Manure storage facilities in the back with a capacity to hold four days of biogas production, and, in the front, manure fibres being produced for livestock bedding materials.

a capacity of five days of production (Figure 13c, at the far end). When farm trucks transport manure to the plant, they also collect digestate and return it to farmers as soil fertilizer. Production of manure fibre bedding is also practised at Solrød, where manure is dehydrated and utilized within dairy farm stables, being yet another way to utilize digested manure (Lybæk and Kjær, 2019) (Figure 13c, at the front).

5. Discussion

Thailand's governmental framework conditions and incentives for supporting biogas have been relatively limited when it comes to the agricultural livestock sector, not being pig rearing, or, for example, dairy cattle, beef cattle and poultry rearing. Biogas has also been extensively supported in the agro-industrial sector in Thailand by the Energy Policy and Planning Office (EPPO) in recent years, which has provided financial support for implementing biogas plants within this area. Thailand already has a developed biogas industry organized as privately owned biogas plants and is in a phase where the development of larger biogas plants, which to a higher extent engage the local community, could be developed further. Focus on manure from dairy cattle should be initiated, treated together with MSW and other residual biomass waste from communities. This was illustrated in case study B above. Despite the emphasis on pig manure, vast amounts of this type of manure are still available in Thailand, and the biogas solution potential for increasing energy efficiency and outreach to the local community needs to be addressed more strongly. This was exemplified in case study A. In both cases, the technologies required are well known and mature, but new organizational concepts based on the ownership of several stakeholders will have to be adopted, where stronger engagement, corporation and planning are required within the community to support such biogas concepts.

Due to the reluctance to utilize digestate from human faces as crop fertilizer in Ghana, and the lack of energy production from the biogas in general, we provide two cases in this paper showing how the agro-industry sector in Ghana can push the biogas industry forward, providing positive examples. This choice is further argued by the fact that small-scale biogas plants are relatively expensive and thus difficult to deploy among average inhabitants on a larger scale in Ghana. Agro-industries, on the other hand, could provide the financial power to implement the technology, taking into account that the costs of purchasing fossil fuels will be phased out, sale of excess power to the grid can be applied, and digestate can be distributed on farmland within the local community and substitute for the purchase of artificial fertilizer. In case studies C and D, we illustrate how agro-industries in Ghana can increase their energy security, cost related to the purchase of fossil fuels, improve the local environment as far as wastewater discharges, reduce GHG emissions, and engage with the local community in the distribution of digestate as fertilizer. The technology is already adopted within the agro-industries but could be improved to become more reliable. The need for organizational changes is limited, as the companies already are engaged in the local community. Ghana is still to develop its biogas industry (Akuffo, 2020), and within the agro-industry sector the case examples have shown that promising technical and organizational solutions can be deployed with a collaboration with local farmers and villages as far as digestate utilization and distribution of energy is concerned. A spillover effect to other sectors in Ghana must, however, be supported and new infrastructure established to fully harvest the benefits of biogas applications.

In the future, Danish biogas technology will most likely be used as a transition pathway to develop a more sustainable agricultural sector. Huge amounts of manure are still not being utilized for biogas in Denmark, and many farmers would like to convert to organic farming but lack organic fertilizer to distribute on farmland. A synergy can be established, whereby organic biogas plants produce organic digestate based on various agricultural residues – not only manure – substituting for the lack of organic manure, which is then distributed on organic farmland. Case studies E and F illustrated this, just as case study F showed, that emphasis on the content of nitrogen in the digestate might be an issue in the future as well. Thus, new biogas opportunities in Denmark are to utilize this technology for more sustainable agriculture, rather than deploying more biogas plants as we know them. In Denmark, the organization of the biogas industry is based on both public (municipal) and private engagement, where the public is often included in the ownership of the plants and is the main target group for the supply of energy. New organization of the biogas industry does not, however, revolve around centralized biogas plants engaging the local community, nor around making better use of the generated energy. Future organizational issues will most likely revolve around a more efficient use of the digestate and various feedstocks for producing organic fertilizer to enhance a transition towards a more sustainable agricultural sector in Denmark with better harmony between farmland and livestock animals.

Learning from each other's successes and failures within the biogas industry, we will in the following concluding part address how knowledge sharing, and relevant policies can be adopted as a lever for biogas technology dissemination within Denmark, Thailand and Ghana with the main emphasis falling on the latter two.

6. Conclusion and recommendations

As opposed to Ghana and Thailand, newer Danish biogas applications are often very large and highly advanced technical installations with high initial costs and running expenses, especially for the transportation of manure. Despite governmental incentives, like FIT and construction grants, etc., the total number of plants installed is relatively limited. Smaller plants, digesting manure from a single farm, or from the neighboring farm as well, could, however, also be emphasized in the future. This would facilitate the utilization of the entire manure potential within more simple biogas technology concepts, learning from the current situation in Thailand and Ghana, where many such small-scale biogas plants are deployed. In a Danish situation, the heat supply could be utilized within farm stables and the farmhouse and surplus power distributed on the grid. Manure could be piped from one farm to another to avoid transport inconvenience. This 'neighbor-farm' biogas concept is detailed more in Lybæk (2014). In Ghana, on the other hand, there is a need to learn from experiences within Thailand, as far as policy frameworks supporting biogas are concerned, thus setting up improved policy programs and strategies, which actually are being deployed within the society. This would potentially mature the technology, but also bring the application into other sectors where it could be utilized more effectively – as, for example, the MSW sector. Besides this, the cultural issue related to the use of digestate as fertilizer from animal livestock and households – and the use of biogas for cooking – could be included in activities increasing knowledge among the people of Ghana, revolving around farmer organizations, village representatives, school children, and chefs and kitchen staff within institutions, etc. In Thailand, new organizational concepts connected to biogas technology could be emphasized, and important in the future to fully utilize the manure potentials from many small farms, thereby developing economically viable concepts. Knowledge regarding the implementation of centralized biogas plants could be valuable within a Thai context. Finally, efficiency improvements related to the supply side of energy could be valuable knowledge to communicate from Denmark to Thailand.

The recommendations outlined above, as well as others being identified locally, could, for example, be disseminated through a 'North–South–South' cooperation between Denmark, Ghana and Thailand, which emphasizes bottom-up initiatives and a participatory approach to the transfer of knowledge and formulation of policies. As opposed to 'North–South' cooperation, the aim of North–South–South cooperation is to establish a communication infrastructure (GNESD, 2011) financed and facilitated by the 'North' – where developing countries in the South interact, and where knowledge and best practices are transferred between countries through peer-to-peer learning (Kruckenberg, 2015; Chen, 2018). The 'North' can be multilateral organizations, such as the United Nations Environmental Program (UNEP) or International Energy Agency (IEA); bilateral through, for example, the Danish Development Aid Organization (DANIDA); or through private non-governmental organizations (NGOs) like Practical Actions from the UK (Practical Action, 2019). A North–South–South corporation similar to that initiated by UNEP, named Global Network on Energy for Sustainable Development (GNESD) (GNESD, 2011; 2015; 2016), could be developed between countries located in South East Asia (including Thailand) and West Coast African countries (including Ghana). The purpose is here to establish peer-to-peer knowledge exchange and policy development revolving biogas technology. Through bottom-up learning processes, local NGOs and community-based organizations (CBOs) can be included in awareness raising at village level, where knowledge of how to adopt centralized biogas concepts in the specific local context can be investigated. Also, knowledge of the correct use and value of livestock manure and household latrine digestate as fertilizer can be disseminated to farmers, households, village schools and institutions, etc. The formulation of relevant policies could be developed through a policy dialogue panel (PDP), as adopted by GNESD in their effort to increase energy access in developing countries (GNESD, 2016). The panel can include researchers, decision makers, local mayors, NGOs, and CBO members, who formulate local policies based on thorough investigations of best policy practices applied within the cooperating countries. Investigations within the local communities on the need for support policies, and how policies – most importantly – should be adopted in the specific contexts, can be carried out through participatory processes in the villages and, among others, include elders, artisans, and women's and farmers' groups.

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