CHEMICAL ENGINEERING TRANSACTIONS

VOL. 61, 2017

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.aidic.it/cet

Guest Editors: Petar S Varbanov, Rongxin Su, Hon Loong Lam, Xia Liu, Jiří J Klemeš

ISBN 978-88-95608-51-8; **ISSN** 2283-9216

DOI: 10.3303/CET1761279

Onion Diagram Implementation to the Synthesis of a Biogas Production Network

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Anaerobic digestion producing biogas is a complex process comprising of a population of anaerobic microorganisms at four key stages, hydrolysis, acidogenesis, acetogenesis and methanogenesis. Parameters such as selection of feedstocks, pH, temperature, dry matter content and others significantly influence the process. Anaerobic digestion represents the core of the biogas production process. It could be represented by a centre of the onion diagram – “reactor”. Anaerobic digestion directly influences the biogas production process (second layer of the onion), and further its supply network (third layer), the company (fourth layer) and finally material, energy and waste treatment system of the company (fifth layer). This contribution introduces a synthesis approach based on onion diagram applied to biogas production systems. Proposed approach consists of the following steps where the hierarchy/dependencies are considered between the onion layers: i) reaction layer using the models for anaerobic digestion, ii) process layer by optimising the biogas production process, iii) supply network layer by optimising the whole supply network of biogas production, iv) company layer by the synthesis of biogas production together with the surroundings (farm, food-processing industry, etc.), and v) integrated company layer which includes improved energy and mass integration and treatment of water, waste and emissions. A similar approach could also be applied in other fields, such as in wastewater treatment processes.

1. Introduction

In recent decades, there has been a progressively greater awareness on preserving the environment and on social sustainability. Focus has been put on renewable energy, resource efficiency, waste management, circular economy and some other issues. In many countries taxes on harmful waste and emissions have been adopted and also financial incentives in the form of subsidies or credits could be obtained for more environmentally friendly solutions. However, several authors considered them as imperfect, inadequate, discriminatory (He et al., 2016) and incoherent (Huttunen et al., 2014).

The subsidies to the biogas industry became the ongoing issue due to several externalities, such as odour, high cost, nitrogen footprint (Čuček, 2012), low efficiency and use of food crops and non-waste feedstocks in many cases (Lajdova et al., 2016). In several countries, many of the biogas plants would not be built without the financial subsidies. It is important that biogas plants are designed with the lowest externalities and possibly in a way that they do not require subsidies. There is also a need for research in reactors, processes, supply networks and integrated designs to be able to efficiently process unexploited waste resources (Bond and Templeton, 2011). Many possible designs exist which depend on the selection and ratios of feedstocks, process parameters and operating conditions which significantly affect the biogas process. It is important to optimise the biogas supply network design especially due to high transportation cost (Egieya et al., 2017). There are several types of biogas plants, such as landfill gas recovery plants, agricultural biogas plants, industrial biogas plants and biogas plants utilising municipal solid waste and sewage sludge as feedstocks (Al Seadi et al, 2008). All of them significantly affect the company performance. Finally, significant cost and improved environmental impact and social sustainability could be obtained by the process integration (Klemeš, 2013), and by the treatment of emissions, waste, polluted waters and aqueous effluents. As the process is

Please cite this article as: Čuček L., Hjaila K., Klemeš J.J., Kravanja Z., 2017, Onion diagram implementation to the synthesis of a biogas production network, Chemical Engineering Transactions, 61, 1687-1692 DOI:10.3303/CET1761279

highly complex, the sequential approach considering the hierarchy might be applied to cover sufficient level of details. The hierarchy could be represented by the onion diagram which shows dependencies between the layers (Linnhoff et al., 1982). In the case of using the simultaneous approach where the hierarchy is not considered, “only” integrated sustainable company might be optimised.

2. Onion Diagram of a Biogas Production Network

The sequential design and optimisation of integrated biogas production network are suggested to follow the onion diagram, starting from the inner reaction layer and moving towards the outer layers where the solutions from inner layer are used as an input to the outer layers. Onion diagram, shown in Figure 1, consists of five layers, which are explained and schematically represented in the following.

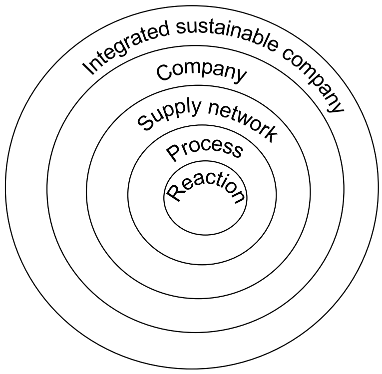

Figure 1: Onion diagram of a biogas production network (amended from Linnhoff et al., 1982)

2.1 Reaction layer

Anaerobic digestion production is a highly complex process. Due to the complexity of the process, a variety of experimental studies have been performed and models have been developed, from simple calculators to scientific models (Kythreotou et al., 2014), at the reaction layer to understand and optimise the process. Used feedstocks, their ratios and process parameters significantly affect biogas yield. Among the most important process parameters are temperature, organic loading rate, pH, mixing, retention time and the presence of inhibitors (Groce et al., 2016). As there is a variety of possibilities for optimisation, the models for anaerobic digestion might help to understand and optimise the process. The models typically take into account the kinetics of bacterial growth, substrate degradation and product formation. The most comprehensive and widely applied scientific model is IWA Anaerobic Digestion Model No 1 (ADM1) which includes biochemical and physico-chemical processes (Batstone et al., 2002). Biochemical processes describe disintegration and hydrolysis, acidogenesis, acetogenesis and methanogenesis steps, see also Figure 2.

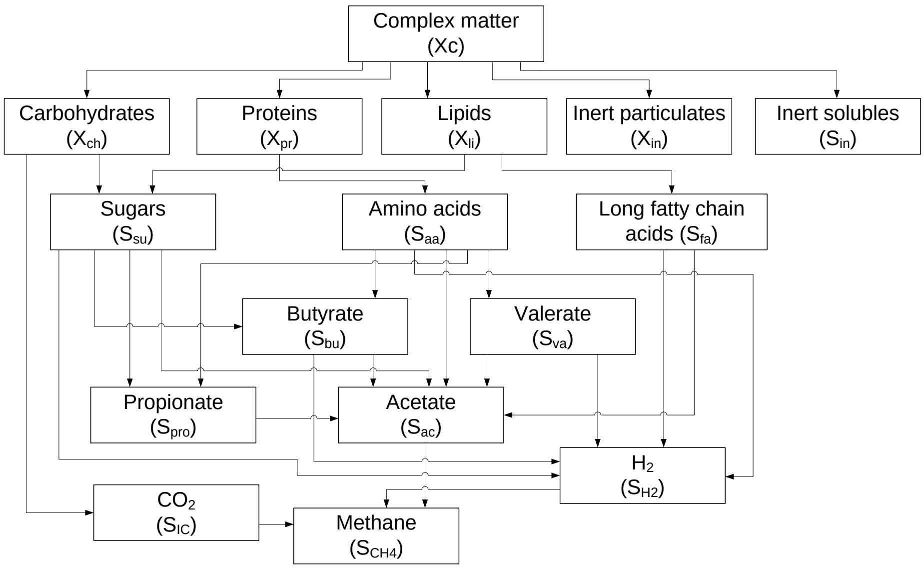

Figure 2: Schematic representation of anaerobic digestion model (modified from Batstone et al., 2002)

Physico-chemical processes describe relations of pH, gas concentrations, free acids and bases, and other. ADM1 became the norm for the modelling of anaerobic digestion (Xie et al., 2016). However, the proof of the results from ADM1 model might be difficult due to many parameters which should be obtained from the measurements. On the other hand, several studies are available that show the good prediction of ADM1 model compared with the experimental results (Chen et al., 2016).

2.2 Process layer

Several millions of biogas plants exist, and most of them are located in China and India (Bond and Templeton, 2011). They have been a number of biogas plants in Europe (11,670 in 2014), many of them located in Germany and Italy (Cavinato et al., 2017). Many different designs of biogas plants have been available world-wide (Gautam et al., 2009). The use of the feedstocks and their composition, water supply and handling, loading rate, temperature range (Drobež et al., 2011), retention time, reactor configuration, plant scale, treatment and use of biogas/biomethane and digestate, utilisation of heat, geographical location, infrastructure (Hijazi et al., 2016) and other significantly affect the biogas production design. Different types of biogas plants are having different sizes, designs and technologies (Al Seadi et al., 2008). Figure 3 shows an example of a simplified flow diagram of agricultural biogas plants, which typically use manure and energy crops, such as silage as co-substrates (Cavinato et al., 2017).

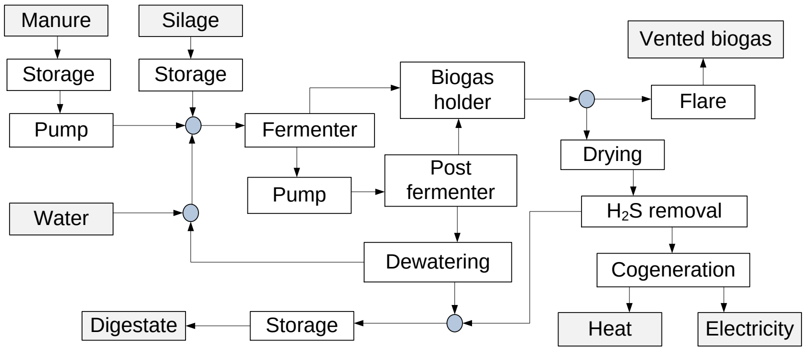

Figure 3: Simplified flow diagram of biogas production

Biogas plants typically use mesophilic range (Hijazi et al., 2016) and operate under wet conditions in a continuous process (Weiland, 2010). Anaerobic digestion takes place in one or two-stage digesters. The two-stage ones are preferred for digestion of energy crops (Weiland, 2010). Most common configuration is vertical continuously (mechanically) stirred tank fermenter, covered with a gas tight membrane roof ("biogas holder") to store gas before utilisation (Weiland, 2010). Produced biogas primarily consists of methane and CO_2, but also of smaller amounts of H_2S, ammonia and water vapour. H_2S and water vapour should be removed from biogas (typically by biological desulfurization and drying) to prevent damage on the gas utilisation units (gas engine based combined heat and power is mainly used) (Weiland, 2010). Digestate could be dewatered to reduce the transportation cost and recycle the process water. Produced biogas could be used for cooking, generating heat and electricity or could be upgraded to biomethane for use as a transportation fuel or as a replacement for natural gas. In developing countries biogas is typically used for cooking and lighting, and in developed ones for cogeneration producing heat and electricity (Surendra et al., 2014). Digestate could be used as a soil conditioner and/or organic fertiliser, however due to the possible presence of pathogens its proper treatment might be required (Surendra et al., 2014).

2.3 Supply network layer

Biomass feedstocks have several peculiarities, such as variable harvesting periods, low energy density, high storage requirements, deterioration during storage, extensive transportation and other (Egieya et al., 2017). On the other hand, waste (manure, agricultural waste, organic waste, sewage sludge) represent the environmental risk, and in some cases significant management issues and the threat to human health (Surendra et al., 2014). Substrates (biomass and waste) also vary based on their dry matter content, biogas yield per fresh matter and methane content of produced biogas. Additionally, local shortages of cheap feedstocks might limit biogas productivity and significantly affects the economics (Budzianowski, 2016), besides the high transportation cost which might represent the highest share of cost (Egieya et al., 2017). It is important to design a biogas plant by considering its supply network. A supply network is a set of facilities connected with distribution links to produce, store and distribute products to customers. Optimising the biogas production through supply network optimisation might help in decision-making process to identify resource efficiency improvements and economic and environmental opportunities. Figure 4 illustrates the biogas supply network which consists of biomass collection, waste acquisition and preparation, anaerobic digestion, treatment of the obtained biogas and digestate, and the transportation and distribution steps. Supply network takes into account storage of biomass, waste, intermediate and final products (except products which cannot be stored), the possibility of selling biomass sources without transforming them to biogas and digestate, and selling untreated digestate. A supply network model helps to identify the potential locations and capacities of the digestion plants, storage facilities, treatment technologies, and all the material and energy flows. Different objectives might be preferred, such as maximal economic profit, overall sustainability profit (Zore et al., 2017) and other. Uncertainties which may result mainly from supply fluctuations and prices present important challenges relating to biogas supply networks. Prices of products and substrates have been identified as critical issues (Egieya et al., 2017).

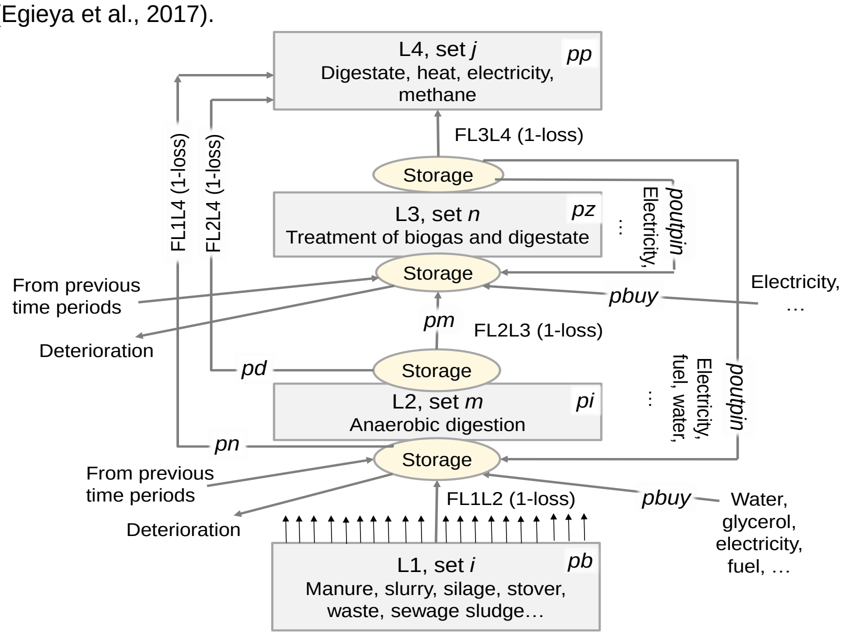

Figure 4: Scheme of a biogas supply network formulation (modified from Egieya et al., 2017)

2.4 Company layer

Based on the relative size, purpose and location biogas plants could be classified as family-scale (cooking, lighting), farm-scale (business opportunities), centralised/joint co-digestion plants (energy production, waste treatment and nutrient recycling), and industrial plants. Such industrial plants where biogas plants could be used for the treatment of industrial waste and waste waters are food processing industries (see Figure 5), beverage industries, industries producing paper and boards, starch and other (Al Seadi et al., 2008).

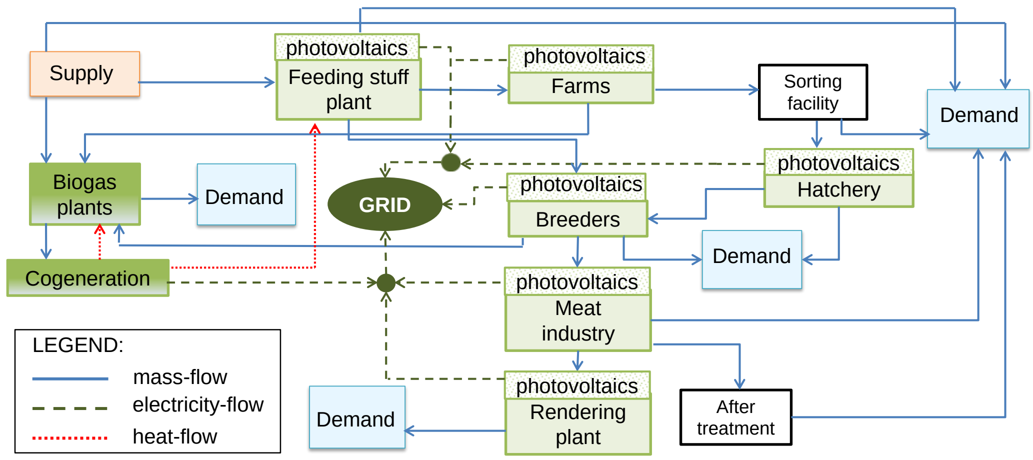

Figure 5: Company supply network including biogas plants (modified from Kiraly et al., 2013)

Biogas plants could be organised in a decentralised or centralised way. Decentralised plants typically receive substrates from one household, farm or company. Centralised plants are typically organised as cooperative companies where different suppliers deliver substrates to the plants (Angelidaki and Ellegaard, 2003). The most important questions at the company layer are related to existence and availability of substrates and possibility to sell or use the products. As the biogas plants might significantly affect the company performance, optimisation of biogas production should be performed together with the other production activities of the company.

2.5 Integrated sustainable company layer

The increasing awareness towards the environment coupled with the environmental legislations and financial incentives push the stakeholders towards considering sustainability issues. This could be achieved through resource efficiency by process integration and by efficient treatment of emissions, waste, polluted waters and effluents (Figure 6).

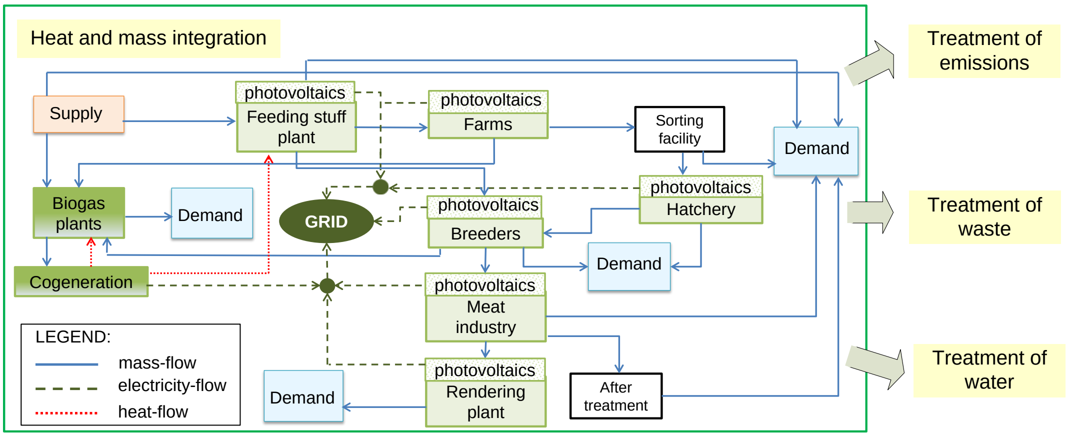

Figure 6: Integrated company layer including Heat and Mass Integration and treatment of emissions, waste and polluted waters

3. Conclusions

In the longer-term sustainable solutions relating to energy requirements, resource use, efficiency, waste management and closing the cycles (“cradle-to-cradle” approach) are required. They have been several concerns related to overexploitation of resources, land and species and degradation of the environment. Several footprints are already in uncertain “region”, at high risk of crossing or have already crossed the planetary boundaries which might lead to non-linear environmental change (Steffen et al., 2015). Such most significant footprints are nitrogen, biodiversity, phosphorus, land and greenhouse gas footprints (Čuček et al., 2015). Among the variety of possible solutions might be anaerobic digestion which offers inherent potential that is still underutilised. For anaerobic digestion many different waste substrates might be used, the process might operate at various scales and there are versatile possible uses of products. For better acceptance and lower cost, further improvements of the process are needed. Crucial issues requiring significant research activities are identified to be the following: i) optimisation of substrates use and their ratios together with influential process parameters, ii) improvements of the quality of digestate and/or product(s) containing nutrients in order to avoid the risk of biological hazards and contamination of with heavy metals, iii) optimisation of biogas supply network to reduce the overall cost, iv) optimisation in “real time” to be able to more appropriately respond to fluctuations in supplies and uncertainties and v) technical improvements (e.g. prevention of unpleasant odours when transporting waste materials, prevention of leakage) in order for technology to be more acceptable to people. Applying the onion structure for optimisation of biogas production can help to improve the sustainability of the process especially due to a complexity of each "layer".

Acknowledgments

The authors acknowledge financial support from the EU project Sustainable Process Integration Laboratory – SPIL funded as project No. CZ.02.1.01/0.0/0.0/15_003/0000456, by Czech Republic Operational Programme Research and Development, Education, Priority 1: Strengthening capacity for quality research and the collaboration agreement with the University of Maribor based on the SPIL project and from Slovenian Research Agency (project L2-7633 and programs P2-0032 and P2-0377).

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