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Review

Integrating electrochemical, biological, physical, and thermochemical process units to expand the applicability of anaerobic digestion

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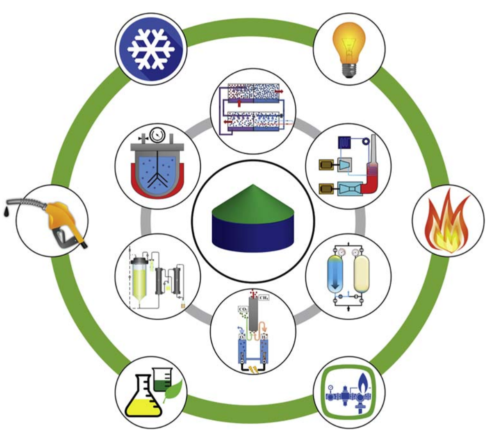
GRAPHICAL ABSTRACT



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ABSTRACT

Anaerobic digestion (AD) is a mature biotechnology-production platform with millions of installations at homes, farms, and industrial/municipal settings. Large-scale industrial, agricultural, and municipal waste-treatment systems may observe novel integration with electrochemical, biological, physical, and thermochemical process units to make AD more attractive. Without governmental subsidies, AD has often only a relatively low economic return or none at all. Diversification of products besides methane in biogas may help to change this. Here, several sections discuss different process units to: 1) upgrade biogas into biomethane; 2) convert carbon dioxide in biogas to more biomethane; 3) generate cooling power from process heat; 4) produce bio-crude oil (bio-oil) from organic matter; and 5) produce a liquid biochemical product from organic matter. This is not meant to be an exhaustive list, but rather a selection of particularly promising process units from a technological view, which are already integrated with AD or close to full-scale integration.

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1. Introduction

Anaerobic digestion (AD) has matured with numerous companies selling a complete system for a plethora of different waste-treatment applications. Currently, AD is one of the most successful resource recovery systems. When designed, built, and operated correctly, the performance of AD cannot be improved much further from what is currently possible. In certain cases, process units, such as micro-wave, ultra-sound, or hydro-thermal technology, can be integrated into the system to, for example, pretreat the biomass feedstock with the overarching goal to improve the biogas yield. Still, one of the main shortcomings of AD is the lack of product diversity, while the main product − biogas − encompasses a relatively low economic value. Here, the technological details for five different process units are discussed that can diversify or change the products from AD: 1) biogas upgrading; 2) power-to-gas (P2G); 3) combined cooling, heat and power (CCHP); 4) hydrothermal liquefaction (HTL); and 5) product extraction systems. These process units span electrochemical, biological, physical, and thermochemical technologies. This is not meant to be an exhaustive list of technological possibilities, and other technologies include: 1) drying and pyrolysis to convert digester sludge into biochar as a soil amendment product; and 2) cleaning and upgrading biogas into liquid fuels by a combined metal catalysis and biodiesel process. Finally, the authors do not have detailed economical data available to give predictions whether the processes would become economical during future application, and believe that a detailed life-cycle and economic analyses study would be necessary to provide meaningful comparisons.

The carbon dioxide in biogas, which may reach up to 50%, has been seen merely as a nuisance, and biogas-upgrading process units wasted this gas to the atmosphere. However, this may be changing rapidly with, for example, P2G technology. P2G utilizes carbon and intermittent electric power to produce methane – a storable gas within the existing natural-gas infrastructure. Thus, P2G increases the output of methane gas for an AD system and turns the biogas into biomethane. Conventional combined heat and power (CHP) systems convert biogas into electric power, heat, and carbon dioxide as end products. In most locations, considerably more heat is produced than what can be consumed, but when absorption cooling is integrated with the CHP, ample volumes of cooling water can be produced from the surplus waste heat as well. Further product diversification is possible by integrating HTL to generate a bio-crude oil (hereafter bio-oil) that can be further upgraded in conventional refineries to a wide variety of end products. Here, the complimentary nature of AD and HTL is envisioned rather than a competing one. The ultimate objective should be to improve the overall conversion of the biomass into the most valuable product portfolio. Finally, the integration of extraction process units with AD is discussed with the overarching goal to produce medium-chain carboxylic acids (MCCAs) as a main product with a much higher value compared to biogas.

2. Biogas upgrading technology to remove carbon dioxide from biogas: biomethane

2.1. Biomethane

Raw biogas from AD comprises mainly of methane (40–75%) and carbon dioxide (15–60%), but also contains low levels of other fermentation byproducts and impurities, including: water vapor, hydrogen sulfide, ammonia, hydrogen, oxygen, nitrogen, siloxanes, and volatile organic compounds (Ryckebosch et al., 2011). Because methane is the primary energy carrier in biogas, the objective of any biogas upgrading technology is the enrichment of methane through the removal of carbon dioxide and these other impurities. The resulting product of biogas upgrading is biomethane or renewable natural gas, which has a higher energy value than biogas, and can be used immediately on-site as a heating fuel, or after compression, injected into the natural gas grid. On the other hand, biogas conditioning is a process often used in conjunction with biogas upgrading, but only requires the removal of the impurities (rather than carbon dioxide).

Biomethane can be pressurized to produce compressed natural gas and, through further cooling, produce liquid natural gas. Both compressed and liquid natural gas can serve as transportation fuel, which may qualify for the renewable fuel standard and gain renewable identification number credits in the U.S. (Patterson et al., 2011a). However, because combustion engines are sensitive to impurities, stricter fuel standards are required compared to biomethane that is intended for grid injection (Sun et al., 2015). Higher purity requirements not only increase operating costs, but also increase the rate of methane slip, which contributes to greater methane emissions and reduced total energy recovery (Bauer et al., 2013; Patterson et al., 2011a; b). However, this off-gas from methane slip should be collected, combusted, and used to heat the digester or for other on-site applications.

2.2. Advantages compared to conventional combined heat and power (CHP)

The application of combined heat and power (CHP) in conjunction with AD has become a conventional approach to harness biogas energy. With CHP, biogas conditioning is often required depending on the quality of the biogas. CHP typically results in a high total energy recovery through: 1) electric power (30–40%); and 2) low-to-medium temperature heat (35–55%) (Lantz, 2012). Electric power is a long-range energy carrier, which can be used on-site or fed to the electric power grid to earn tariffs. Process heat, on the other hand, is a short-ranged energy carrier, and thus needs to be used relatively close to the AD system. Some of the heat can be used on-site to heat the digester or to preheat/pasteurize the influent slurry. However, these particular applications only consume a fraction of the captured process heat (6–44% for single-stage mesophilic systems) (Berglund and Börjesson, 2006; Chevalier and Meunier, 2005). Therefore, when no other local applications are possible, much of the available heat is wasted (Lantz, 2012). When the heat resource is underutilized, it reduces the total energy recovery (Poeschl et al., 2010), and, as several life-cycle assessment studies have shown, considerably undercuts the environmental benefits of the AD system (Poeschl et al., 2012a,b).

Therefore, producing biomethane from biogas rather than electric power and heat with CHP can be advantageous, because all the biomethane can be transported over long distances *via* the natural-gas grid or as a compressed fuel, while only the electrical power can be transported with CHP. In addition, biomethane can be stored in the existing infrastructure of the natural gas grid, which is technically easier than to store electric power or heat. Finally, another advantage of biomethane is that fuel credits can be earned, while this is not the case for CHP.

2.3. Biogas upgrading technology

Biogas upgrading can be accomplished through the application of several technologies, some of which are commercially viable, while others are still being further developed. The most common biogas upgrading technologies are water scrubbing (36% of the market share in 2015 in a group of countries, consisting of Australia, Austria, Brazil, Denmark, France, Finland, Germany, Ireland, South Korea, Norway, Sweden, Switzerland, The Netherlands, and The United Kingdom), followed by amine scrubbing (21%), membrane separation (21%), and pressure-swing adsorption (17%) (Svensson and Baxter, 2015). For water scrubbing, water is used as the solvent to selectively remove carbon dioxide, which has a much higher solubility in water compared to methane. By the same principal, water scrubbing is also capable of removing hydrogen sulfide. Amine scrubbing is a chemical absorption process where the solvent (*e.g.,* methyldiethanolamine, diethanolamine, monoethanolamine) forms a reversible chemical bond with the solute, typically at an elevated temperature (Bauer et al., 2013). The amine