The corporate added value of biomethane[*]

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I. Introduction

Production of biogas and biomethane (namely, renewable natural gas—henceforth, RNG) provides a potential solution to two key challenges humanity faces: the increase of organic waste produced and the imperative need to reduce anthropogenic global greenhouse gas (GHG) emissions. A fundamental concept guiding the production of these gases is the circulating economy, whereby the continuous use and reuse of organic waste generate renewable energy while delivering environmental benefits (Figure 1). In addition, the sustainable accounting of biogas and renewable natural gas (RNG) production via carbon credit may generate value for segments of communities, including companies. However, what are these environmental, social, and economic benefits, and how sensitive are the various processes to technologies and waste streams?

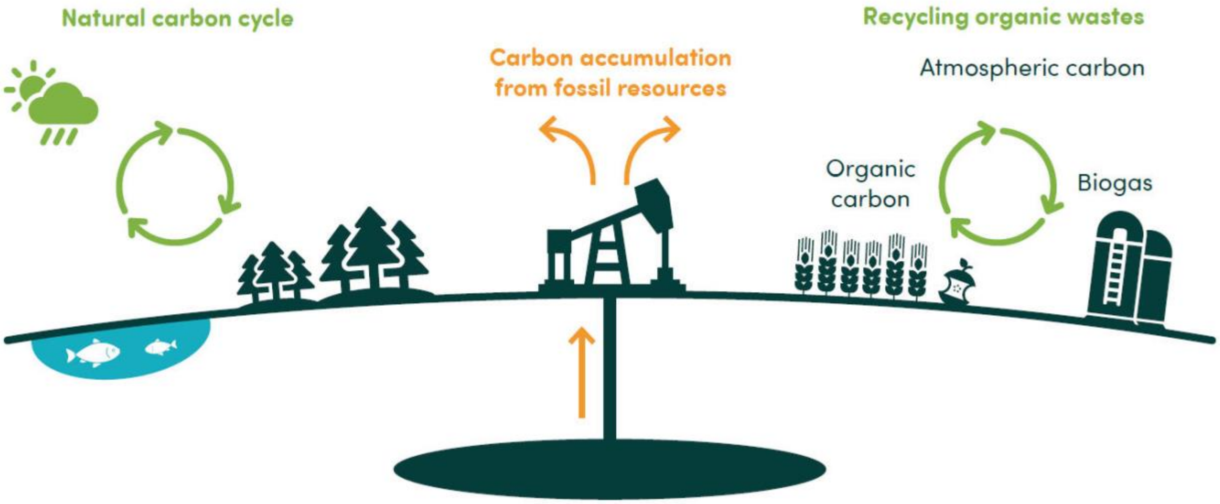

Figure 1. Carbon Circulation

To assess the prospects for "organic growth" of biogas and RNG, we investigate alternative pathways and processes and evaluate the efficacy of RNG to support sustainable energy systems. We use existing literature to quantify the benefits of biogas and biomethane under alternative technological pathways. Furthermore, by deciphering the various technologies, the paper aims to identify the importance of technologies through sustainable accounting and the corporate value these technologies generate. This paper evaluates the potential of alternative technological pathways and various processes in generating added corporate value through sustainable accounting. It shows that developing RNG under specific pathways is an activity that directly benefits society and the environment and creates corporate value. Our analysis suggests that while an anaerobic digester technology to electricity path yields a levelized cost of electricity (LCOE) of $10.03 per MWh, when we introduce environmental benefit into the accounting system, the LCOE drops to $2.72 per MWh: social accounting reduced the LCOE to the level of landfills, which is $2.50 per MWh. Recycling and reusing waste generate significant value, that if monetized, yields much value to companies.

GHGs warm the Earth by absorbing energy and slowing the rate at which energy escapes to space. US EPA measures the GHG emission potential through Global Warming Potential (GWP), measuring how much energy the emission of 1 ton of a gas will absorb over 100 years. For example, US EPA estimated methane to have a GWP of 28 to 36, which led to the social cost of methane fluctuating between $540 to $3,200 per metric ton.

Accordingly, introducing negative environmental externalities and adjusting companies' values modifies conventional accounting and influences values and behavior, potentially directing the corporate world's attention toward factors beyond financial performance. Social accounting may provide feedback on companies' social impact, thus identifying organizations' social value and nonfinancial information. Such an accounting system should be based on accepted accounting principles, seeking to emphasize corporate accountability. However, we should address credibility issues, and the system needs to agree on a reliable mechanism to price pollution.

In what follows, we first survey the literature, from the state of existing technologies to the use of waste streams, products produced using food waste, and the economics of the various processes (section II). Section III builds on the literature review and calculates the economic viability of key technologies used to bridge between organic waste and RNG. Next, section IV expands the discussion and introduces social accounting while recalculating the viability of the various technologies and shows that social accounting can make a big difference to the companies' values, likely leading to accountability. The challenge is in its implementation. Finally, we discuss challenges and opportunities in section V, with concluding remarks offered in section VI.

II. The current state of the industry

There is a great need to create economically viable and environmentally sustainable product recovery organic waste-based supply chains, including food and yard waste and other biodegradable materials such as food-soiled paper. This waste stream is 30% of the United States municipal solid waste and 14% of its methane emissions (US EPA 2021). To this end, there is a need for more research to achieve cost-efficient co-products. In addition, there is also a need for studies regarding centralized or small-scale but efficient production facilities. However, there is also immense knowledge of the alternative technologies and some understanding of the challenges these technologies face.

Some of the organic waste reutilization for energy technologies are mature technologies. These commercially available systems of converting organic biodegradable waste to energy include anaerobic digestion (AD), direct combustion in stoker boilers, low percentage cofiring, municipal solid waste incineration, and combined heat and power. Others, including biomass gasification and pyrolysis, are only now beginning their respective development phase. In contrast, integrated gasification combined cycle, biorefineries, and biohydrogen are in the R&D phases. We dwell on these various technologies through the existing literature, discuss the importance of waste streams, and identify research gaps.

2.1 Technologies

Next, we offer an in-depth discussion of the alternative technologies the use waste as an input, starting with anaerobic digestion (AD).

Anaerobic digestion: There are several ways to produce RNG, where the various paths depending on the feedstock supplied. One option is the AD of the biodegradable organic portion of municipal solid waste (MSW). This technology can effectively process various organic waste streams to produce biogas, nutrient-rich solid digestate as a soil amendment, and liquid digestate typically used as an organic fertilizer. AD extracts the benefits from organic waste and positions this technology as a valuable resource for energy generation, nutrient recovery as fertilizer, compost feedstock, and reducing water consumption.

AD is a biochemical treatment process that stabilizes a myriad of organic wastes, from complex lignocellulosic materials to easily degradable food wastes (see references below). At the same time, the AD process produces renewable energy, recovering fibers and nutrients for soil amendment and offsetting GHG emissions. AD technology can effectively process various organic waste streams to produce biogas, nutrient-rich solid digestate as a soil amendment, and liquid digestate typically used as an organic fertilizer. Fagerström et al. (2018) highlight the diversity of benefits from anaerobic digestion and biogas systems. Sustainable biogas systems include waste treatment, environment protection, and conversion of low-value material to higher-value material to produce electricity, heat, and biofuel. They introduce the biorefineries-based biogas plant and its linearity to the circular economy and the multiple functions of biogas in the circular economy. The authors conclude that products from bio-based resources will lead to a bioeconomy. Because AD systems are robust and flexible technology, they can treat a wide variety of organic waste ranging from soluble cheese whey to insoluble concentrated fats, oils, and grease (FOG).

Food waste generators include businesses and households, institutions, supermarkets, farms, and food processors. These stakeholders are the source of the MSW. Food waste is the primary and most biodegradable component of MSW, and food waste is the primary source of biomethane. AD can convert food waste and any organic matter into biogas. The biomethane portion of biogas can then be converted into a usable form of energy as it is combustible. There are mainly three types of AD systems in the United States (Labatut & Pronto, 2018):

(1) Stand-alone digestion, processing food wastes only
(2) Farm-based co-digestion, processing animal manure (swine, poultry, and dairy) with food wastes
(3) Wastewater treatment plant (WWTP)-based co-digestion systems, processing waste activated sludge (WAS) with food wastes.

However, for a successful AD project, detailed and current data about the amount of available organic waste, with its components and seasonal variability, is critical. In addition, the properties of the organic feedstock will directly influence the performance and outputs of the AD system. Therefore, both feedstock assessment and feedstock preparation are essential for achieving steady-state operating conditions. In the United States, 60 million tons, or 31% of the food waste, originates at the retail and consumer levels. In contrast, the food processing industries contribute more than 35 million tons of food waste (Labatut & Pronto, 2018). If the trash does not change its state of matter, the methane produced is mainly dependent on the biodegradability of the subject. In the United States, over 40% of the food produced ends up in a landfill without ever reaching a table (Labatut & Pronto, 2018).

A critical consideration comes with the feedstock preparation and handling, as there are significant economies of scale. For example, the capital costs for preparation can be 6%-20% of the total investment for a plant that uses 550/tons/day and above. Thus, the capital costs fall from around $29,100/tons/day with systems using 90 tons a day to $8,700/tons/day with a plant that employs 800 tons a day (Ghose & Franchetti, 2018).

Decisions on environmental and economic matters involve many stakeholders throughout the supply chain of organic waste, including food waste generators, AD facility operators, end-product marketers, and consumers. Although AD technology is considered mature, contaminated feedstock and poor process stability can result in inefficient performance and failures. In addition, stand-alone food waste digesters are more susceptible to instability if not monitored and managed carefully. Therefore, efficient control of critical operating parameters including ensuring feedstock quality and process monitoring is essential for the successful performance of AD systems and pitfalls for the various AD pathways identified.

The AD process results in digestate, i.e., the undigested portion of the feedstock. The digestate can be centrifuged and filtered to separate bio-solids serving as an efficient feedstock for composting and the liquid portion utilized as fertilizer or disposed of, depending on the season when it is generated.

State-of-the-art ADs can capture up to 99.85% of the biogas. Biogas generation occurs from the natural breakdown of organic substances in anaerobic conditions. Biogas generally contains impurities, which are removed before the gas is used for energy. These impurities may include moisture, ammonia, and sulfur if food waste is the feedstock.

Biogas can be utilized as follows:

A. COMBUSTED IN:

- Boilers to generate heat.
- Internal or external combustion engines to produce electricity.
- Combined heat and power (CHP) plants to produce both heat and electricity; and
- Tri-generation systems to provide cooling via absorption chillers in addition to heat and electricity.

B. UPGRADED INTO BIOMETHANE:

- To be used as vehicle fuel in gas-powered vehicles in the form of compressed natural gas (CNG).
- To be used in place of natural gas in industrial, commercial and domestic uses; and

- Carbon dioxide may be extracted for commercial use, for example as a feedstock in greenhouses.

C. PROCESSED INTO HIGHER VALUE PRODUCTS SUCH AS BIOPLASTICS OR BIO-CHEMICALS.

The generated biogas can either be used directly for power generation after removal of the impurities (i.e. moisture, H_2S, ammonia) or upgraded to pipeline quality gas (RNG). Biomethane is a significant component of the biogas, ranging from 50% to 65% by volume, based on the feedstock characteristics and process conditions. Pipeline quality gas can be produced by the removal of CO_2 content and impurities in biogas. The pipeline quality gas, RNG, is a product that contains 95-98% methane. Biogas upgrading is achieved through available state-of-the-art technologies to methane-rich, pipeline-quality RNG.

Biogas has between 30% and 40% less methane than fossil fuel-derived natural gas, and therefore a proportionally lower heating value. However, methane concentration in the biogas produced by some operations can be as high as 70%. The highest methane concentration and production of biogas are normally obtained via AD systems. The most widely used energy generation technologies suited for pairing with an anaerobic co-digestion facility to convert the methane gas produced to heat or electricity currently include combined heat and power (CHP), reciprocating engines, gas turbines, microturbines, and fuel cells. Reciprocating engines have good operational efficiency and are cost-competitive but have low fuel flexibility, high operating and maintenance costs, and high emissions. In addition, the price of the fuel cells that have been operated with biogas is still very high. There has recently been increased interest in the option of combining AD systems with solid oxide fuel cells (SOFCs) due to their relatively high operating temperature, which makes them more robust to fuel impurities.

The performance of an anaerobic digestion system is primarily evaluated based on the efficiency of substrate stabilization (or treatment) and methane production (or energy output). The substrate stabilization efficiency is the extent to which the treatment of organic matter has been accomplished. The higher the methane production, the more usable energy is generated. Food wastes with high moisture content (i.e., low VS, TS), such as green leafy vegetable or whey, may have methane yields of up to 10 times lower than those observed for high-solid content food wastes, such as grains, cereals, fats, and used oils. Biogas, methane yields, and the organic matter removal efficiency are significantly affected by the OLR (Organic Loading Rate). In general, studies show that as the OLR increases (or the HRT (Hydraulic Retention Time) is decreased), the biogas/biomethane production increases until inhibition ensues due to substrate overloading. Poor process stability leading to low system performance is still frequently observed in full-scale plants worldwide. Many of these problems occur because of inadequate operational management or lack of process control. Stand-alone food waste anaerobic digesters are more susceptible to instability than, for example, manure- or WAS-based anaerobic digesters (Labatut & Pronto, 2018).

In the United States, most anaerobic digesters treat food waste in conjunction with other substrates, mainly in farm-based operations. In this practice, known as anaerobic co-digestion (ACOD), food wastes are co-digested with animal manures as a primary substrate in terms of proportional influent mass. Co-digesting recalcitrant manure with easily degradable food wastes in farm-based digesters can improve the economic viability of the farm operation: first, by increasing biomethane yields, which can then be converted to electricity that can be used for facility operations and sold to the utility company, and second, by receiving additional income in the form of tipping fees for the imported food waste (Labatut & Pronto, 2018). In addition, co-digesting food waste with an appropriate primary substrate may be necessary to enhance process stability and performance of organic matter biodegradation, leading to an increase in the plant's energy output.

When reviewing the upgrading of biogas to biomethane (RNG), Zhao et al. (2010) focus on existing technical solutions for scrubbing CO2 and H2S. First, Zhao et al. evaluated the existing biogas purification technologies, including water and polyethylene glycol scrubbing, chemical absorption, pressure swing adsorption, membrane, bio-filter, and cryogenic separation. Then, they introduce the testing technology called absorption tower technology and the preliminary trials of sodium hydroxide and diethanolamine systems. From the additional revenue generated, biogas purification technologies can improve the economic feasibility of anaerobic digestion with relatively low electricity prices because of cheap hydroelectric power.

On the other hand, Zamalloa et al. (2011) propose an alternative approach via the preconcentration of algae solution to decrease the cost and energy required for harvesting and use this solution in a high-rate anaerobic digester to produce biogas, biogas that can be upgraded and converted to electricity and thermal energy. Zamalloa et al. offered a comprehensive technological and economic assessment that is then applied to estimate the cost of energy production using microalgae as feedstock.

Hublin et al. (2012) investigated the enhancement of biogas production from co-digestion of whey and cow manure in a series of batch experiments. They aim to optimize the anaerobic co-digestion process by performing different pH measurements, whey and cow manure ratios, and different experiment days. The result indicates that the biogas production (6.6 %), methane content (79.4%) in a biogas mixture, and removal efficiencies for total solids (16%) are achieved at optimum process conditions under the temperature of 55^{o} C, 10% v/v of whey, and 5 NaHCO3. Furthermore, the paper shows that whey is efficiently degraded to biogas in a one-stage batch process when co-digested with cow manure. However, separating the operations into a two-stage process is preferable.

Using survey data, Cowley and Brorsen (2018) estimate methane production and cost functions for anaerobic digesters for US dairy and swine operations. They consider variables including farm size, digester inputs, digester design parameters, and construction materials affecting the productivity and profitability of an anaerobic digester. They find that economies of scope are evident for plug flow and complete mix anaerobic digesters that are more economically feasible on dairy farms than swine farms. Economic feasibility can be reached by marketing co-products such as electricity and animal bedding on dairy farms. At the same time, government support is needed to achieve positive net present values for swine farms. To this end, Astill et al. (2016) examined the economic feasibility of a set of dairy waste management systems composed of two groups mitigating air and water pollution, including an AD system with animal waste input, and compressed natural gas or combined heat and power output and a filtration system with fiber separation, nutrient separation, and water recovery. Their work concludes that scenarios using co-digestion can contribute to a nutrient application without nutrient separation technology. Economic feasibility is accessed by calculating the net present value (NPV), where NPV is optimized for AD with compressed natural gas scenarios. Estimated NPV for AD with compressed natural gas and environmental credits is $1.8 million and $39.7 million for dairies with 1600 and 15,000 wet cow equivalents. The addition of co-digestion contributes $4.8 million and $47.3 million for such firm sizes.

Caposciutti et al. (2020) analyze an anaerobic digestion plant's mass and energy fluxes as a function of the biogas percentage sent to the upgrading system with the amount of biogas production in a numerical model. While using different scenarios of the bio-methane output, the digesters' mass and energy balance, cogeneration unit, upgrading system, and auxiliary boiler are estimated. The analysis suggests that the plant's energy balance depends on bio-methane production, and the excess of the bio-methane output makes the plant dependent on external energy sources. Therefore, the optimal level of the bio-methane output is feasible to minimize carbon dioxide emissions with higher biomethane subsides as an encouragement to reduce savings from carbon dioxide.

Molino et al. (2013) show the feasibility of integrating an anaerobic digestion plant with a polymeric membrane purification system for conditioned biomethane production. The whole process is split into three stages: hydrolysis or liquefaction, organic acids transformation by bacteria, and biomethane generation. The simulation results indicate that the biomethane produced by cascade configuration has the Wobbe index within the range of 46-51; thus, it is possible to apply it in the natural gas gird. Purification for high qualify bio-methane is necessary to remove water, sulfur compounds, halogenated organic molecules, carbon dioxide, oxygen, and metals. Economic feasibility is also raised in European standards.

Abatzoglou and Boivin (2009) study the scientific and technical purification process of biogas produced from fermentation and combustion. Two purification methods are reviewed, including physicochemical phenomena and biological processes. Reviews of physicochemical and biological biogas purification methods and techniques are used to remove Sulfur-containing contaminants such as H2S. Physicochemical methods with chemical adsorption and absorption processes are economically feasible in industry, while biological methods are intensively needed. They point out that the eventual success of a newly proposed technique comes from a combination of better Sulfur-capture efficiency, low media, and operating costs, energy prices, and socio-economic policies.

The use of either biogas or the upgraded pipeline-quality RNG to generate electricity has numerous benefits. Evangelisti et al. (2014) used life cycle assessment (LCA) to compare the environmental impacts of AD with energy and organic fertilizer production against two approaches: incineration with energy production by CHP, and landfill with electricity production. The inventory data was obtained from the Greater London area in the UK. Two key issues that affect the development and deployment of future AD plants are maximizing the electricity produced by the CHP unit from biogas and defining the future energy scenario embedded in the AD plant. The former is related to technology development. The latter depends on macro-level national and European developments to indicate the importance of a holistic approach for waste management treatments in the UK.

The direct environmental impact of AD and economic value generated, i.e., sustainable accounting, is clear. Hermanowicz et al. (2011) apply life cycle analysis (LCA) on environmental impacts of anaerobic digestion and electricity generation from biogas in organic solid waste management to determine its potential in biogas utilization while reducing the need for composting. LCA results in terms of single score and midpoint characterization are presented, which indicates that an incremental approach can assess the environmental impact of AD and biogas facilities. This approach provides more direct modeling, a better-defined system, and is less demanding from input data.

Stillwell et al. (2010) use data from the US Environmental Protection Agency to analyze the potential for energy recovery from wastewater plants via AD with biogas utilization and biosolids incineration with electricity generation. Their results indicate that anaerobic digestion can save 628 to 4,940 million kWh annually in the entire country. In Texas, the most significant energy-produced state in the US, AD could save 40.2 to 460 million kWh annually, and biosolids incineration could save 51.9 to 1,030 million kWh annually. Those direct calculations illustrate the interrelationship between energy and water, and the organic content of wastewater can encourage energy recovery operations.

The two main barriers to the widespread adoption of AD are the lack of policy directives and funding resources for securing uncontaminated organic waste and funding for AD facility Capex. A few of the more notable economic initiatives include no taxes or subsidies on biogas, government funding support for 60%-80% of agricultural biogas plant capital needs, enforcement of renewable portfolio standards, and creation of a feed-in tariff. Process instability is the leading cause of failure in operational systems, which is prevented by robust process monitoring and control and careful microbial management. Subsequent ability to adjust system control to remedy or prevent an impending failure is a necessary feature.

Other forms that can reutilize waste beyond AD, include landfill gas (LFG) and as mentioned above, the anaerobic digester gas from wastewater treatment facilities (WWTF). Although all gases generated using these technologies are used interchangeably and called biogas because their primary constituents are CH4 and CO2, there are differences among the gases via varying impurities; variation that are the outcome of the waste decomposition, location, and feedstocks (see also section 2.2). However, if we remove all the contaminants and CO2 content, these gases' biomethane content is RNG.

Landfill Gas (LFG): There is a growing interest in upgrading traditional landfills with gas recovery facilities. Landfills are the most used method to dispose of solid waste globally, and landfill gas recovery technology is becoming more economically viable (Zhang et al., 2007). In the United States, there are about 3,581 municipal solid waste landfills, which are the third-largest source of human-related methane emission, accounting for 16.4% of total methane emission in 2012 (Lamb, 2012). In the past, on average, about 872.3 Gg landfill methane was produced annually, which is equivalent to 43.14 gigawatt-hours (GWh) of electricity, accounting for 0.1% of total electricity generation (Bolan et al., 2012). However, we observe a 27% decrease in the net methane emission from landfills from 1990 to 2011, where landfills with methane recovery almost doubled from 1999 to 2010, producing approximately 14 TWh of electricity (US EPA, 2011).

The landfill's gas is a mixture of methane (45-60%), carbon dioxide (40-55%), and traces of other components that give landfill gas its characteristic smells.[5] In addition, trace amounts of non-methane organic compounds and volatile organic compounds may result from the decomposition of byproducts or the evaporation of biodegradable solid wastes. The most important impurities present in the landfill gas are siloxanes whose removal is costly. Landfill also experience costly leachate treatment and disposal problems

In practice, the moisture content of the waste compound, the temperature inside the reactor, the size of disposed waste, and airflows can affect the degradation process in landfills. For example, extra water leads to a stagnant saturated zone in the waste that speeds up the first two steps of biodegradation while limiting methanogens (Hans Oonk, 2010).

Landfilling is a dominant method of waste disposal, and, as with AD, the environmental impacts of landfills with gas recovery facilities depend on proper management (Bolan et al., 2012). Operating landfill in the aerobic environment have merits like increased settlements, decreased metal mobility, lower methane control costs, and reduced environmental liability (Kumar et al., 2011).

LFG is a natural byproduct of the decomposition of organic material in landfills. The organic waste gets mixed with other waste streams disposed into landfills. When the decomposition of the organic material occurs in the landfill cells, landfill gas gets contaminated by siloxanes, silanes, and silanols. However, the most commonly occurring VOSCs are siloxane compounds. Siloxane levels vary significantly from one landfill to another, while there seems to be a relationship to waste age. Landfills with older average waste ages generally have lower siloxane levels, which may result from the increased use of siloxane in recent years.

Wastewater Treatment Facility (WWTF) Digester Gas: Wastewater treatment facilities emit CH_4, CO2, and N_2O during organic sludge degradation by aerobic and anaerobic bacteria.[6] If a facility utilizes AD only, the gas is called digester gas. Like landfills, the widespread use of siloxanes in personal care products, i.e., shampoos, deodorants, results in siloxanes found in digester gas generated at WWTF in high amounts.

Stillwell et al. (2010) use data from the US Environmental Protection Agency to analyze the potential for energy recovery from wastewater plants via AD with biogas utilization and biosolids incineration with electricity generation. Their results indicate that anaerobic digestion can save 628 to 4,940 million kWh annually in the entire country. In Texas, the most significant energy-producing state in the US, AD could save 40.2 to 460 million kWh annually, and biosolids incineration could save 51.9 to 1,030 million kWh annually. Those direct calculations

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[5] Data available at *https://www.epa.gov/lmop/basic-information-about-landfill-gas*

[6] Information available at https://css.umich.edu/sites/default/files/Wastewater%20Treatment_CSS04-14_e2021.pdf

illustrate the interrelationship between energy and water, and the organic content of wastewater can encourage energy recovery operations.

Combustion: A commercially viable technology is less appealing from both an economic and environmental perspective. Oreopoulou and Russ (2007) discuss combustion technology used in the composition of agricultural and food waste is covered in the final chapter. And Hochman et al. (2015) evaluated the benefits of converting food waste and manure to biogas and fertilizer by focusing on four waste treatment technologies: direct combustion, landfilling, composting, and anaerobic digestion. Their calculation indicates that anaerobic digestion with gas collection has the highest technological productivity. In terms of economic feasibility, the landfill to gas method has the least cost of waste treatment. As a comparison, direct combustion is the least efficient of all four waste-to-energy technologies. A similar analysis was performed by Bernstad and Jansen (2012), who reviewed 25 comparative cycle assessments (LCAs) addressing food waste treatment, including landfill, thermal treatment (including direct combustion), compost, and anaerobic digestion.

Gasification and pyrolysis of organic waste, different than AD, are suitable pathways to converting low moisture food waste into biofuels or desired chemicals (Guran, 2018). Gasification is sufficient for converting low moisture food waste into syngas. Syngas can be used as an intermediate in creating synthetic natural gas or methane, however more GHG based LCA assessment is needed. Pyrolysis seems to be able to convert viable feedstock into bio-oil and biochar. Increased temperatures will lead to more bio-oil being produced, which can then be upgraded to liquid biofuels. Bio-oil is highly dependent upon the feedstock, and conversion parameters. Substances that can serve as feedstock in other industries can be derived from pyrolysis oil. Biochar can be used in different sectors such as flavoring and serve as a water cleaning medium. Biochar is also considered for soil remediation and carbon capture and storage material (Guran 2018).

Gasification: Gasification is a thermochemical conversion process in which carbon- and hydrogen-containing substances, such as biomass and municipal solid waste, are partially oxidized at high temperatures (800-1100¬∞C) in the presence of a gasifying agent (air, steam, and oxygen) and converted into gaseous products.

The product gas, called syngas, contains hydrogen, carbon monoxide and small amounts of carbon dioxide, water, and hydrocarbons, i.e, CH_4 and C_2H_6. To increase hydrogen production from biomass gasification is effective (Guran, 2018). However, syngas needs to be cleaned following gasification. Syngas is best used as fuel for stationary power and heat generation or catalytic conversion to manufacture a range of liquid fuels, chemical intermediates, and end products.

Tar formation from biomass gasification can lead to corrosion, fouling, and blocking. Therefore, to reduce the tar, the biomass gasification process should be optimized. Cyclones, ceramic and textile bag filters, electrostatic precipitators, scrubbers, and rotating particle separators are efficient gas cleaning systems to remove dust, particles, and tars from syngas (Guran, 2018).

There are three gasifier designs (Guran, 2018):

- fixed bed,
- fluidized bed, and
- entrained suspension bed gasifiers.

Fluidized bed gasifiers achieve more efficient mass and heat transfer due to uniform temperature distribution. Before gasification, feedstock needs to be processed to the proper particle size. Gasification adds value to low or negative value feedstocks making them into marketable fuels or products.

Heyne et al. (2013) perform an exergy-based comparison of the two gasification technologies. They use a simplified gasification reactor model, which compares two technologies on a common basis without possible bias due to model regression on reactor data. The significant parameters investigated are the delivery pressure and the air-to-fuel ratio for gasification with the H2/CO ratio in the product gas. The calculations show no significant difference in performance between the technologies, but the challenge identified for process design is efficient heat recovery and cogeneration of electricity. Furthermore, direct gasification is penalized by incomplete carbon conversion in contrast to indirect gasification. Therefore, they conclude that neither direct nor indirect gasification can be identified as intrinsically superior for Bio-SNG production based on the presented calculations.

Pyrolysis: The pyrolysis process involves the thermal degradation of materials in the absence of an oxidizing agent, causing irreversible rupture of polymer structures into smaller molecules leading to the formation of solid (char), liquid (bio-oils), and non-condensable gaseous products (carbon monoxide, carbon dioxide, hydrogen gas, methane, and ethane). Pyrolysis is influenced by reactor design, operating parameters, temperature, heating rate, feeding rate, particle size, and residence times. Slow pyrolysis leads to more char, while fast/flash pyrolysis leads to more liquid. As a result, pyrolysis produces lower amounts of gaseous products compared to gasification or combustion, potentially eliminating the need for a gas cleaning system.

Salman et al. (2017) present a new process of coupling pyrolysis and anaerobic digestion from green waste that produces more biomethane and stand-alone processes. During the process, the biochar obtained from pyrolysis was added to a digester to boost the reaction to increase the biomethane content and stabilize the development of microbial communities. Their modeling and simulations show an around 1.2-fold increase of the biomethane volume with an overall process efficiency of 67% better than a stand-alone anaerobic digestion system. Furthermore, the annual revenue for this new biorefinery system is compared with both stand-alone systems. The economic analysis is also conducted by direct calculations and sensitivity analysis from the effect of different parameters on net annual profit, indicating the integrated process's feasibility.

Görling et al. (2013) propose a poly-generation plant producing biomethane, biochar, and heat via fast pyrolysis of biomass by simulation with the energy and material flows for the fuel synthesis. Their calculations result in 15.5 MW and 3.7 MW of the production of bio-methane and biochar when the total inputs are 23 MW raw biomass and 1.39 MW electricity, which indicates the higher overall energy efficiency for the fast pyrolysis plant than for the gasification production route. The first-step result makes it a competitive technology for biomethane production in small-scale applications, while further research on integration and optimization is required for economic feasibility.

Wright et al. (2010) explore two scenarios of the cost of naphtha and diesel range fuels from corn stover by pyrolysis and bio-oil upgrading. The first one is based on hydrogen production from bio-oil that diverts a portion of its bio-oil to upgrade hydrogen generation. Another is based on purchasing merchant hydrogen that employs hydrogen from remote sources. Their model indicates liquid fuel production rates of 134 and 220 million liters per year for hydrogen production and purchase scenarios. Capital costs and fuel product values are also estimated with remaining research on the effect of feedstock properties and process conditions on the ultimate yield of fuel from bio-oil.

Opatokun et al. (2017) evaluate the environmental performance of industrial anaerobic digestion, pyrolysis, and the integrated system on organic waste using life cycle assessment. The integrated system shows immediate environmental benefits to anaerobic digestion with significant benefits in climate change with more energy generation and production of biochar and bio-oil. Their work investigates that all three organic waste management treatments are more environmentally friendly than the conventional landfill option. The economic analysis reveals the integrated system provides similar overall benefits and impacts with anaerobic digestion.

Edenhofer et al. (2011) introduce an assessment of the literature on the contribution of six renewable energy sources to climate change mitigation, including scientific, technological, environmental, economic, and social aspects. Greenhouse gas emissions resulting from the increasing demand for energy and associated services have contributed significantly to the historical increase in atmospheric GHG concentrations. Therefore, renewable energy (RE) becomes a good option for lowering GHG emissions while still satisfying the global demand for energy services, which comprises a heterogeneous class of technologies, including bioenergy, direct solar energy, geothermal energy, hydropower, ocean energy, and wind energy. To estimate the economic benefits from bioenergy, they present the global and regional status of markets and industry deployment for certain technologies such as combustion, fermentation, gasification, pyrolysis, and anaerobic digestion. Mitigation potentials with costs and RE policies with implementation and finance are also addressed.

Many factors contribute to the efficacy of an economically feasible WTE system, such as the waste quantity, the generation location, and the feedstock characteristics: moisture content, biodegradable organic matter, calorific, heating value, fats and oils, sugars, carbohydrate, transportability, particle size, periodic variations, and potential contamination. For example, AD and fermentation are suited for wet waste feedstock, while gasification and pyrolysis are suited for dry waste feedstock. Source separated food waste is the most desirable as it requires minimal processing at the WTE plant. Food WTE plants should have a modest impact on operations, and the food waste should be sampled to see whether it contains contaminants.

2.2 Waste streams

Waste composition varies widely across food supply chains, making standardizing food waste fermentation to ethanol difficult. There have been some promising results with using food waste to produce ethanol, but higher alcohols need more research. Understanding waste composition and generation quantities would facilitate a standard production process. Hegde and Trabold (2018) recommend mapping food waste resource flows in a particular region to estimate the share of food waste available for alcohol production.

Food waste can be classified into four major groups by source generation: residential, institutional, commercial, and industrial waste. Commercial (agricultural waste, supermarket waste) and industrial (food processing industry) food waste can also be classified as pre- and post-consumption food waste. Residential and institutional (cafeteria, hospital) wastes are post-consumer food waste. Mixed food waste sources from post-consumer groups are characterized by high moisture content (60%–90%), high organic content (more than 95% of dry matter), high salt content, and rich nutrition, which are valuable for recycling and valorization. However, post-consumer food waste is much harder to convert to energy due to its mixed composition (Guran, 2018).

The amount of food waste, globally, is significant. For example, the USA was estimated to have produced 1078.5 million tons of crops in 2015. In 2016, the US produced 26.4 million tons of fruit, 39.9 million tons of vegetables, and 44.1 million tons of meats. In 2011, the USA had a farm-to-fork wastage of 22% of total meat production, 38% grain products, and 52% vegetables. In 2017, the annual electricity consumption of the USA was 3820 TWh. At the high end of conversion efficiency, biogas production from animal manure could produce 108.8 TWh, around 2.85% of the USA’s annual energy consumption.

On the other hand, according to a World Bank report from 2011, agricultural lands in Latin America and the Caribbean region amount to around 37% of the total land. About 65% of the total tropical fruit production in the world comes from these countries. As production capacity increases in these countries, it is expected that tropical fruit production will increase. Agricultural and meat waste could serve as a significant source of bioenergy feedstock. While using Eurostat, the EU-28 in 2013 yielded 489.7 million tons of grains, 85.3 million tons of vegetables, and 30.2 million tons of fruits. Meat production was around 29.9 million tons, with 1.4 million tons of manure. In 2015, 14 European countries produced 90% of Europe’s biogas, with Germany leading them. Germany generated 64 TWh in 2015, with 43% of it coming from agricultural and animal waste on-site. Germany valorized more than 55 TWh in combined heat and power plants with 57% electricity generation. Biogas production in the EU is heterogeneous to volumes, market and technology maturity, and potential growth.

Other examples include Iran in 2016, which produced around 58.95 million tons of crops, with wheat being the largest, although this number is likely higher due to data limitations. Khuzestan, in 2016, produced 7.61 million tons of waste, corresponding with 12.79 million tons of crops. The second and third largest waste-producing regions, Fars & Golestan, in 2016, produced 4.201 and 3.447 million tons of waste. The Razavi Khorasan and South Khorasan provinces had 5.35 million tons of manure and 0.2 million tons of rumen in 2016. The Sistan and

Baluchestan provinces produced 8.63 million tons of slaughterhouse blood in 2016. There is much potential for using this waste as feedstock for bioenergy production. In 2016, Australia was the fourth-largest wheat exporter globally and was the world’s largest beef exporter, with 15% of total global beef exports.

In 2013, Australia’s meat production constituted 89% of total agricultural production. Combined agricultural production in 2013 was 683.8 million tons. While in 2015, bioenergy-from-waste plants produced 0.9% of the annual electricity generation (7113.1 GWh/year). In 2012, India produced 260 million tons of cereal, and in 2014, India made 4% and 14.7% of total global chicken and cattle meats. India has much potential for WtE plants. It can use waste produced from its agricultural output. From China’s statistical yearbook of 2015, the total yield of farm products was 621.44 million tons. China is the world’s largest electricity consumer, with 5638 TWh in 2014. China produced 13.24 billion cubic meters of biogas from processing waste feedstocks. China has much potential to improve energy production if they manage their waste better. In the sub-Saharan Africa region in 2013 produced 143.4 million metric tons of cereal. Countries in the SSA have great potential to use WtE plants to solve the shortage of electricity in the region. 81% of the population in this region burn agricultural residues for energy, contributing significantly to GHG emissions. Adopting these technologies would be beneficial from this point of view. There is excellent availability of food waste feedstocks—we need to figure out how to use them.

Food waste conversion to energy varies by feedstock and generally goes through two pathways: biochemical/chemical or thermochemical. Thermochemical conversion includes four pathways: combustion, gasification, pyrolysis, and hydrothermal liquefaction. Combustion is an exothermic reaction that uses oxygen and fuel and produces carbon dioxide, water, and heat. Unfortunately, mixed food waste combustion is not viable due to the high moisture content, making this process energy inefficient.

Most meat rendering industry by-products are incinerated, providing no value to those facilities. Gasification of the waste creates various components such as hydrogen, carbon monoxide, methane, ethane, carbon dioxide, ethylene, and acetylene, whose energy density is estimated to reach 400 MJ/m3 for oxygen-fired gasification. However, tar formation became an issue. Meat and bone meal materials can be effective feedstock for syngas production. Two-stage gasification increased the yield of hydrogen gas from 7.3% to 22.3% by volume and reduced tar. If performed with steam, the yield by volume rises from 36.2% to 49.2% (Guran, 2018).

It has been estimated that the US poultry industry must address the challenge of 650,000 tons of broiler and 195,100 tons of turkey carcasses yearly. A steady-state simulation model found that H2 production increased with temperature up to 600º C, and CO production increased with a temperature above 600º C. Poultry waste should be gasified with charcoal or high caloric substances. Poultry feather and bone pyrolysis (at 450–600° C) produced biochar and bio-oils with lower heating values (LHV) of 23 and 28 MJ/kg, respectively (Guran, 2018). An optimized pyrolysis process can benefit the use of poultry waste. Pyrolysis of dissolved air flotation (DAF) skimming from a poultry operation with solvent extraction to reduce fatty acids can result in bio-oil containing unsaturated fatty acids. These acids can be esterified into biodiesel and fatty nitriles, which could be a feedstock to produce bio-based surfactants.

The global per capita supply of seafood in 2014 was estimated to be 20 kg. Around 50% of fish and 60-70% of shellfish by mass are nonedible and, therefore, waste (Guran, 2018). Total US fish processing waste weight adds up to 1 million metric tons a year. Nonedible parts of seafood include valuable bioactive components, such as collagen, gelatin, lipid, protein, protein hydrolysate, cartilage, calcium, chitin, chitosan pigments, enzymes, glucosamine. The gasification of red salmon by-products at 700°C resulted in syngas with a 0.35 H_2:CO ratio (Guran, 2018). Gasification becomes more economical if the oil content from the fishbones is extracted before the gasification converts the fishbones into fish oil or biodiesel production.

Pyrolysis of waste fish fats at around 500º C can result in yields from 54-72% liquid. The oils can be used as forms of renewable energy, with some requiring upgrading after the process. Char produced by pyrolysis of fishbone at 500°C removed enough fluoride in 1 h to meet the World Health Organization standard of 1.5 mg/L for starting fluoride concentration of up to 10 mg/L. 500°C is the optimal pyrolysis condition for the fishbone charring, and that fishbone char is a viable technology to simultaneously remove fluoride and arsenic contaminants (Guran, 2018).

Over 78,000 tons of pecan shells and 266,000 tons of walnut shells are generated from US-produced nuts. Waste from olive oil, wine, jams and preserves, fruit juice manufacturing pulp, and wastes can be valuable sources of energy and raw chemical feedstock for thermochemical conversion technologies. Vacuum pyrolysis of cashew nut shells at lower temperatures resulted in a 40% oil yield that indicated fuel-like properties. When almond shells and potato skins were co-pyrolyzed with high-density polyethylene, the properties of the oil yield resembled fossil diesel in terms of H:C ratio and heating values. Studies of catalytic pyrolysis of cotton cocoon shells, olive husk, and tea factory waste concluded that total hydrogen-rich gaseous products increased with increasing pyrolysis temperature. Na_2CO_3, K_2CO_3, and $ZnCl_2$ were used as catalysts. The gasification of walnut shells yielded promising results, with one study reporting that temperature had a significant effect on the total syngas yield, and H_2 content increased with increasing temperature (Guran, 2018).

Approximately 100 million tons of rice husk yearly are produced, going to waste. Slow pyrolysis of rice husks in a fixed-bed reactor resulted in gaseous yields of CO, CO_2, H_2, CH_4, and C_2H_2, and lower concentrations of propane, propane, butane and butene were also observed (Guran, 2018). The highest calorific value of the gas was reported to be 15.60 MJ/m^3, although fast pyrolysis of rice husks yielded higher amounts of bio-oil, up to 60%. Catalytic pyrolysis of rice husks resulted in gaseous yields with higher H_2 content than a non-catalytic process. Moderate temperatures of corncob pyrolysis provided the maximum oil yields, whereas higher temperatures favored cracking reactions, resulting in higher gas yields.

How do the various technologies compare? Postconsumer food waste is characterized by heterogeneous chemical characteristics, including carbohydrates, lipids, amino acids, phosphates, vitamins, and carbon but also containing other substances, and it may also have a higher moisture content (Guran, 2018). Low moisture postconsumer food waste may be suitable for feedstock in gasification and pyrolysis. Mixed food content with a moisture content of 45% or more should use a steam gasification approach which would recover the energy used to evaporate moisture. Hydrogen content increases with increasing steam to biomass ratio. Syngas adjustment can be achieved by the reverse water gas shift reaction to result in a H2:CO molar ratio close to 2.15, which is desirable as feedstock for Fisher-Tropsch synthesis to produce liquid fuels and chemicals.

Understanding the catalytic effect of char on the overall efficiency of gasification is essential. In addition, research on the gasification and co-gasification of wood with mixed food waste with moisture levels of 54%, 66%, and 83% concluded that food waste gasification and co-gasification could provide viable valorization pathways (Guran, 2018).

Vandermeersch et al. (2014) analyze the environmental performance of two food waste valorization scenarios from a retail sector company in Belgium via exergy analysis, energetic life cycle assessment (ELCA), and a traditional LCA. Two scenarios are discussed. In scenario 1, food waste is valorized in AD, producing electricity, heat, digestate, and packaging material as fuel for the cement industry. In scenario 2, some of the waste is valorized to create an animal feed, while others are valorized in AD. The results show that scenario 2 is 10% more efficient than scenario 1 in exergy analysis with lower environmental impacts in terms of ELCA and LCA due to the avoided products from the traditional supply chain with lower exergy loss. In addition, food waste with lower water content is another reason for higher efficiency in scenario 2.

Vergara and Silver (2019) use micrometeorological methods to measure greenhouse gas, including emissions from green waste and manure compositions. They measure oxygen moisture and temperature inside the composting pile and analyze the chemical and physical characteristics of the feedstock. The result indicates that managing composting piles to minimize methanogenesis while maintaining sufficient oxygen concentrations can reduce emissions to contribute to the climate mitigation benefit. Environmental conditions, including temperature, moisture, and oxygen level, are significant variables affecting the efficiency of the biomethane production process. In addition, biogeochemical characteristics and reaction time are also crucial to the amount of greenhouse gas emissions. Thus, this paper highlights the potential to minimize greenhouse gas emissions from commercial-scale composting.

Schott et al. (2016) present a review of existing LCAs on organic waste management with two primary objectives. One is to do an analytical study of previously performed LCAs of different treatment/disposal alternatives for organic waste about global warming potential. The other is to identify the key factors decisive for the modeled net emissions of greenhouse gases from different treatment alternatives of food waste. Several criteria are constructed to identify relevant comparative LCAs. The systematic investigation illustrates some comparisons between other treatment options, which explains the significant differences in global warming results from different assumptions made about the background system rather than differences in input data of emissions. In addition, this paper highlights the significance of identifying induced and displaced marginal products in the modeling of system expansion. To reveal the valid results, the transparency with sensitivity analyses related to assumptions made in the model is a key for global warming potential analysis.

We also survey the various systems' finances and present detailed estimates of all costs needed to complete project implementation, operation, and the revenues from the project. The literature suggests that the Levelized Cost of Electricity (LCOE), the price of electricity for a production process, varies by the technology type, energy resource, and efficiency. The capital expenditure or total investment cost depends on the technology and sophistication. The total investment consists of equipment (prime mover and the fuel conversion system), fuel handling and preparation machinery, engineering and construction costs, and planning. Guided by the literature, the cost of biomass power generation technologies suggests the feedstock conversion technology and feedstock preparation and handling machinery accounts for between 62% and 77% of the capital costs for biomass power generation technologies.

2.3 Products and processes

Ethanol is the most used fuel alcohol, oxygenating blending component for gasoline. However, advanced biofuels use renewable raw materials as feedstocks, and they are expected to reduce emissions by 50% or greater. In addition, food waste is generated in large quantities, making it a good candidate for advanced biofuel production, and diverting it from landfills is beneficial for the environment (Hegde & Trabold, 2018).

Although we can produce hydrogen from various feedstocks, most of the hydrogen production is from steam reforming methane in natural gas. We can also produce hydrogen from water electrolysis, but that is not economically viable (Hochman et al., 2021). Fermentative hydrogen production is an alternative to derive energy from a heterogeneous mix of organic waste materials like food waste. Food waste provides a rich nutrient source for microbes and can be converted through biodegradation pathways. Producing fuels from food waste will help meet future energy demand and reduce waste from the food sector. In addition, food waste is a cheaper alternative to other potential feedstocks, including corn, lignocellulosic biomass, and molasses which are considered following food-to-fuel pathway.

Hydrogen production can be efficient due to using different food waste, and it only produces water when combusted. There exist three mechanisms for biohydrogen production:

1. photolysis of water by algae,
2. dark fermentation during the acidogenic phase of anaerobic digestion (hybrid biogas and biohydrogen), and
3. two-stage dark/photo fermentation.

Biohydrogen production is an alternative to natural gas since many bacteria can produce hydrogen through fermentation with many different organic feedstocks. However, the lack of standardization for hydrogen production and uncertainty in yields makes it difficult to commercialize hydrogen production this way. Thus, renewable natural gas is yet another path to generate hydrogen.

Transportation and storage costs of all these different materials are high. Cost is the real challenge to hydrogen usage, although research is being done to reduce costs. Food waste is decentralized, and transportation routes would need to bring it to central plants to utilize the product to its best.

Properties of the **pyrolysis** products from postconsumer food waste depend on the feedstock composition and reaction conditions. Carbohydrates produced furan- and sugar-based derivatives, whereas pyrolysis of proteins resulted mainly in hydrocarbon-based products in the aromatic form. The pyrolysis of lipids produced high amounts of acids and low concentrations of hydrocarbon and alkene products. Substances that can serve as feedstocks for other industries can be isolated from the pyrolysis oil and recycled. Microwave-assisted pyrolysis of coffee hulls resulted in higher oil yields compared to conventional pyrolysis. The presence of metal salts negatively impacted oil yield and enhanced gas yield, whereas chloride salts provided the opposite effect. Pyrolysis of postconsumer fats and oils, such as waste cooking oil with animal fat content, resulted in triacylglycerols decomposed into fatty acids. Unsaturated fatty acids decomposed into hydrocarbons at temperatures up to 390°C (Guran, 2018).

Thermochemical conversion of food waste is an emerging research area that needs further research into gasification and pyrolysis pathways. It is essential to consider coupling specific feedstocks with a suitable conversion technology and optimizing process conditions for successful commercialization. If gasification is performed, the generated syngas H2:CO ratio is essential to converting syngas catalytically into clean fuels and chemicals (Guran, 2018). Further research is also needed to achieve the required H2:CO ratios for downstream conversion to fuels or chemicals. Similarly, pyrolysis oil and biochar yield properties for any specific feedstock still need further research for improvement and successful scale-up.

Biogas is a gaseous product produced from anaerobic digestion, comprised of 50-70% methane, 30-50% carbon dioxide, and trace elements made from various waste sources. Biogas can be used for heat or electricity, converted to pure methane, which is comparable to natural gas used in pipelines or transportation fuel and can also be a source of hydrogen for fuel cells. The biomethane production potential in the US is around 7.9 million tons a year or 420 billion cubic feet (Table 1), accounting for 5% of natural gas use in the electric power sector and 56% in the transportation sector as of 2013.

TECHNOLOGY	SOURCE	BIOMETHANE POTENTIAL (METRIC TON PER YEAR)
LANDFILLS*		2,454,974
ANAEROBIC DIGESTOR	Wastewater	2,339,339
	Animal manure	1,905,253
	Food waste	1,157,883
TOTAL		7,857,449

*Includes candidates landfills only as defined by the EPA's Landfill Methane Outreach Program

The states that can produce 200 thousand or more tons per year of biogas from select sources are California, Texas, North Carolina, Illinois, Ohio, Florida, New York, Iowa, Pennsylvania, Georgia, and Missouri. However, if lignocellulosic biomass generation is used, the methane generation potential is much higher. Future estimates reach 4.2 trillion cubic feet per year, accounting for the entire transportation sector and 46% of electrical power derived from natural gas.

Sun et al. (Sun et al., 2015) review the state-of-the-art biogas cleaning and upgrading technologies regarding product purity, methane recovery, upgrading efficiency, and investment and operating costs. The calculated results, including energy efficiency, cost of biogas upgrading, and biogas purification of comparisons between the technical features of upgrading technologies, the specific requirements for different gas utilizations, and the appropriate investment and operating costs, are determined. Another contribution of this paper is that it investigates the possibility of integrating carbon dioxide utilization into biogas upgrading and explore its potential utilization after separation.

Hydrocarbon liquid fuel production from natural gas or biomethane has the potential to replace much petroleum-based liquid fuel usage in the US while concurrently valorizing a wasted resource and mitigating climate change dangers exacerbated by vented and flared natural gas. With economically efficient systems biology tools (genomics, transcriptomics, and metabolomics), the ability to create methanotrophic bacteria for fuel production is more accessible. Production of microbial lipids and hydrocarbon fuels from methanotrophs requires a robust strain with a stable phenotype for rapid growth and lipid production.

Fei et al. (2014) argue that it is likely that the stable overexpression of pMMO will be significant in the future. Still, additional improvements in carbon flux will be needed to increase yields. Constructing de novo fatty acid synthesis pathways is making the production of liquid fuels viable. However, standard methods for metabolic engineering interrupt several metabolic networks and important metabolites, such as ATP/ADP, NAD+/NADH, NADP+/NADPH, and Acyl-CoA. Therefore, a thorough understanding of the central metabolism of methanotrophs is needed. In addition, some methanotrophs are capable of growing chemolithoautotrophically with carbon dioxide as a source of carbon. For example, Methylacidiphilum fumariolicum strain can use the Calvin–Benson–Bassham (CBB) cycle for carbon dioxide fixation, using methane as an energy source. Cultivating this strain using methane and carbon dioxide could improve the yield, resulting in lower production costs of liquid fuels. Lowering production costs can be extra valuable if biogas is the source of methane, as carbon dioxide is a significant component.

The shortage of liquid fuel production is estimated to increase in the following decades. Natural gas is an explosive mixture of several hydrocarbon gases that often contain about 80–95% (v/v) methane mixed with heavier alkanes like ethane, propane, butane, and pentane. Most natural gas is drawn from wells or extracted in conjunction with crude oil production. Undesired natural gas from oil extraction is usually injected back to the reservoir. CNG is considered a cleaner alternative for vehicles than fossil-based diesel. However, only a very small amount is used worldwide as of 2014, despite the recent abundance of natural gas. Although feedstock supply is of concern, a potential solution to this situation is to explore converting natural gas to liquid transportation fuels. Natural gas production of 5 quadrillion BTU of fossil fuel energy, around 5% of the annual output, is flared or vented emitting GHGs as of 2013. The wasted gas is equivalent to 27% of US electricity production, but pipeline and facility development has not kept pace with output as there is no incentive to do so.

Shale gas production, depletion of liquid petroleum, and volatility of crude oil have made natural gas a popular and upcoming choice of feedstock for producing liquid fuels. Fischer–Tropsch (FT) technology has gained interest for the conversion of natural to liquid products. The FT process needs a large scale for successful commercialization due mainly to production facilities and sustainable gas supply requirements. In addition, there is limited energy efficiency, and conventional FT technology can only achieve carbon conversion efficiency (CCE) from 25 to 50%.

Biological methane conversion targeting valuable compounds like liquid fuels is being debated within the scientific community. Methanotrophic bacteria are aerobic microorganisms that can oxidize methane as energy and carbon sources, producing lipids that can be used as a fuel precursor in a hydrotreating process. A Bio-gas-to-liquid (GTL) could compete with traditional chemical processes being more economical and efficient if appropriately designed. The products derived from methane bioconversion processes depend on the type of bacterium used and the metabolic pathways. Earlier on, many studies focused on producing biopolymers, vitamins, anti-biotics, single-cell protein (SCP), and carboxylic acids. Little research has been done on using these bacteria to produce liquid fuel due to a robust, suitable production strain not being identified.

Downstream processing of lipids for renewable biodiesel production requires a catalytic upgrading process involving hydrotreating followed by catalytic cracking and then isomerization of the fatty acyl chains. Renewable diesel blends from this process can be created in existing refineries with petro-diesel as a feedstock in co-processing. It can also be used in existing infrastructure (pipelines, cars) and has a higher energy content than petro and biodiesel.

Aerobic methanotrophs, bacteria that use methane as the sole carbon source for growth and require oxygen, are separated into different groups. Group 1, Gammmaproteobacteria, use the RuMP cycle, group 2, Alphaproteobacteria, use the serine cycle, and Verrucomicrobia, which use the Calvin Benson Bassham cycle. For a variety of biological reasons beyond the scope of this review, methanotrophic bacteria are among a small subset of microorganisms capable of accumulating lipids suitable for liquid fuel, and they are the only ones that use methane as a source of carbon.

The vast volumes of burning transportation fuels, which account for around 50% of the world's energy consumption, show that we can significantly expand the use of liquid fuels from biomass. Lipids produced from methanotrophic bacteria could be used as a fuel precursor in the production of liquid fuel. However, the phospholipid concentration could cause problems, leading to a need to pay attention to the lipid composition of the feedstock. An economically viable process will likely depend on engineered strains with higher lipid levels. Considering the theoretical ethanol yield (0.51g/g), butanol yield (0.41 g/g), and lipid yield (0.35 g/g) on glucose, a 35% lipid content is the minimum target needed to compete with the efficiency of glucose for different biofuel production. It will be necessary to optimize culture and growth conditions to improve lipid productivity.

Metabolic pathway engineering will be critical for using methanotrophic bacteria at an industrial level. Currently, the slow growth rate and lower production levels limit these bacteria from being used. Genetic tools for manipulating methanotrophs are also limited, although there is potential to develop these tools. Lipid production with good biomass productivity from this process will be challenged by methanotroph cultivation and the extraction and upgrading of microbial lipids.

To achieve a high product yield, an optimal production medium with the proper nutrient components is necessary. The impact of medium design on the strain's growth, the feasibility of scale-up, target variable for improvement, and commercial viability of the medium must all be considered in this process. The copper level found in the medium is one key element that must be considered when encouraging growth. Medium optimization should be researched in an integrated bioprocessing framework, considering the improvement of metabolic production yield, reducing pretreatment cost, and reducing not-required chemicals in the upstream process.

To maximizes the yield of desired products, growing conditions must be standardized. The most critical physical variables that affect cultures of methanotrophs are pH, temperature, dissolved oxygen gas concentration, the ratio of methane and oxygen gas, and the time of cultivation. pH level is vital for optimal activity as it affects the physiological behavior of methanotrophs. The cultivation temperature is also crucial as it affects cell growth, carbon source utilization, lipid production, and the solubility of methane in the culture. Finally, the time of cultivation can also affect the yield of desired products and should be optimized.

A significant challenge to improving production yields is the mass transfer of methane from a gas to the liquid medium and then into the cells. This mass transfer significantly affects the product produced in the Bio-GTL process. There has been much focus on designing a bioreactor that improves mass transfer as a result. There is no singular optimal bioreactor design, but key factors are high mass transfer rates, low operation and maintenance costs, and easy scale-up. Continuously stirred reactors are the most widely used, and a strategy for improving mass transfer has been to increase the speed. However, this strategy has a significant power demand, making the process less economically viable when producing low-cost products.

Few studies have been done on the development of bioprocess technologies for fuel production from methanotrophs. During cultivation, lipid production from methanotrophs could be regulated by oxygen gas concentration, nitrogen source, and phosphate source. We can achieve a high lipid yield by limiting conditions in a two-stage fed-batch culture. In addition, methane and oxygen gas sensors are necessary for the cultivation process. The use of methane and oxygen, with flow and pressure sensors, can optimize the conditions for the growth and production of lipids.

The lipid extraction process is vital for improving lipid yields. We should strive to improve the effectiveness of the extraction process concerning the distribution of fuel precursor lipids at each step in the process. Supercritical fluid extraction has been looked at but can only capture about 60% compared with the standard procedure and concerns its economic viability. Emphasis should be placed on a wet extraction system, as dry extraction systems are very costly, and dry systems are the most used. Considerations should be given to up and downstream processing when designing this extraction system.

A hydrotreating process will occur after biomass extraction occurs from the methanotrophs, which reduces contaminant levels. The reactions mainly involved depending on the feedstocks and catalysts. A potential challenge in the hydrotreating process comes from the many phospholipids that break down the process. Developing a process that converts these lipids to fuel range hydrocarbons is critical for a Bio-GTL process.

A significantly overlooked source of biomass is from agriculture and livestock wastes. Shirzad et al. (2019) studied electricity generation and GHG emission reduction potentials through AD in Iran in 2016. In 2016, these wastes showed a potential for generating 2848.26 Megawatts (MW). The LCA showed potential for avoiding a minimum of 10,693.5 thousand tons of carbon dioxide equivalent per year. In the case of Iran, this would amount to a 1.5% reduction in annual GHG emissions. If considering a short-term horizon for generating electricity from different agriculture and livestock wastes, the reduction rate could achieve 24,153 thousand tons of CO2eq/yr, a 3.39% reduction in Iran's annual GHG emissions (Shirzad et al., 2019).

Global demand for electricity projections shows electricity demand growing 40% by 2040 for energy consumption, while energy demand is expected to grow 65% from 2014-2040. Renewable energy resources could minimize the drawbacks of using fossil fuels as a source of electricity. In addition, with the rising population, the need for more intensive agricultural and animal farming practices has become more prevalent. There is a large amount of waste, however, with an annual global residue-to-food ratio of up to 40-50% for root crops, fruits, and vegetables; 35% for fish; 30% for cereals; and 20% for oilseeds, meat, and dairy products (Shirzad et al., 2019). This waste and waste from livestock farming and slaughterhouses can be used as a source of renewable energy that could be integrated with other sources to phase out fossil fuel reliance.

According to the model, manure, blood, and rumen content could respectively yield 6524.91, 1510.08, and 78.02 million cubic meters of biogas in Iran, with a total of 8113.01 million cubic meters (Shirzad et al., 2019). The total biogas production potential from cows was the highest. Electricity from livestock/slaughterhouse wastes (19.951 TWh) could account for 8.78% of Iran's electricity consumption. The total biogas production capacity from agriculture is around 2208.22 million cubic meters. Wheat, sorghum, and barley had the highest potential for biogas production in 2016. The conversion of biogas to electricity could lead to 570.72 MW in Iran in 2016, representing 2.2% of Iran's electricity consumption in 2016. The results from this study show that, overall, agriculture and livestock/slaughterhouse waste could provide 10.98% of Iran's total electricity consumption in 2016.

Challenges still arise when thinking about using these technologies. For example, efficient waste collection and supply chains are crucial for making this cost-effective. Also, the short and long-term realization of generating electricity can significantly affect GHG emission reduction.

2.4 The Economics

AD systems have been the most successful and can deal with liquid, wet, and high moisture content organic waste. ***However, capital cost and infrastructure investment*** are a key barrier for AD and similar systems, and they are only viable financially at a large scale for the time being. AD facilities vary, but the capital cost for available facilities is $500 (US 2007) per metric ton of installed annual capacity. Shared infrastructure is a an option for an AD located at farms or other feasible locations such as landfills, For conventional combustion/WtE, the average capital cost for a 50,000 metric ton per year capacity is $1,200 per ton of installed capacity (Ghose & Franchetti, 2018). Gasification and pyrolysis are in their early stages, but an estimate of a gasification plant by Enerkem shows it to be $1,400 per metric ton of installed annual capacity (Ghose & Franchetti, 2018). Mixed waste processing facilities have little available data. Still, a study showed that for a 300,000 ton per year facility, the capital costs would be about $200 per ton of installed capacity (Ghose & Franchetti, 2018). However, the upgrading of the biogas to biomethane and the purifying process is a challenge, especially for biogas from landfills and wastewater treatment plants as noted above—especially with the increase of siloxane in existing waste streams.

Operation and maintenance costs refer to the fixed and variable costs for operating and maintaining a plant. The O&M cost for biomass power plants typically ranges from 1% to 6% of the initial capital expenditure, and a reasonable estimate for AD plants is $90 per metric ton. Combustion/WTE plants are around $115 per metric ton (Ghose & Franchetti, 2018). There is still little data for gasification and pyrolysis, but $40 per metric ton should be added to the typical operation cost for WTE (Ghose & Franchetti, 2018). For MWPF, net operating costs per ton, after recyclable sales, fall into the $30-$50 range (Ghose & Franchetti, 2018).

Hauling costs should be estimated by calculating the distance (in miles) between each generator and its assigned disposal facility, then calculating the number of truckloads of food waste produced by each generator in each week, based on generator-specific estimates of weekly food waste tonnage and an assumed 20-tonne capacity of long-haul collection trucks. The calculation then multiplies the number of truckloads of food waste by the distance and the estimated $4 per mile cost (Ghose & Franchetti, 2018).

Operating revenue comes from tipping fees and energy and by-product sales. The national average landfill tipping fee in 2013 was $50.60 per ton (Ghose & Franchetti, 2018). The total potential revenue from tipping fees can be calculated as the estimated annual tonnage of food waste from each generator, multiplied by the tipping fee at their assigned disposal landfill facility. The quantity and commodity value of the energy products would depend on the food waste feedstock quantities and the specifics of the WtE conversion technology. AD plants generate revenue from the sale of electricity or gas if it is upgraded. A very efficient wet AD may generate up to 260 kWh of electricity per metric ton of feedstock and sell 210kWh after internal usage (dry AD generates around 20% less gas)—Ghose & Franchetti, 2018.

Feedstock availability, processing costs, and political support primarily affect the future of alternative diesel fuels. Techno-economic analysis requires a detailed process flow diagram, rigid materials, energy balance calculations, capital, and project cost estimations. With methane as a carbon source for diesel production from methanotrophs, raw materials costs range from \$0.7-\$10.8/gal (Fei et al., 2014). Petroleum-derived diesel is sold at \$4/gal in the US, so if costs from the methanotrophic process are held below \$2.3/gal, it could compete with petroleum-derived diesel (Fei et al., 2014). With the amount of diesel gas produced in 2012, a Bio-GTL process could produce up to 60% of its demand annually. This analysis so far is minimal and has a high degree of uncertainty. Proper techno-economics should be performed to obtain more specific results. Low cost and increased availability of natural gas suggest plentiful potential methanotroph-derived liquid fuels. This process can be economically viable and sustainable if competitive with algae-based or sugar-based pathways.

III The economic analysis

To visualize the economic feasibility of technologies of generating renewable energy, we present the calculation of net present value (NPV) and Levelized Cost of Energy (LCOE) for methane production and pollutions.

First, we need to translate units of natural gas and electricity for the created social accounting matrix. In our calculation, we use megawatt per hour (MWh) and metric ton for inputs and outputs under all technologies. Therefore, we will transfer numbers into either MWh or metric ton if needed whenever we have numbers from reliable resources, and the translation is based on the sheet of approximate conversion factors from BP Inc.[7] For natural gas price in the US, the energy unit MWh is often used, and we find its price released on 08/31/2021 from EIA,[8] \$4.14 per 1000 cubic feet, which is the latest natural gas price in June 2021. It is equivalent to \$197.14 per metric ton liquefied natural gas (LNG), where 1 billion cubic feet of natural gas equals 0.021 million metric tons liquefied natural gas. For electricity price in the US, the usual unit is cents/kWh, and we find the data for 2019 released on 11/02/2020 from EIA[9] and the average retail price overall is 10.54 cents/kWh, which is equivalent to 105.4 \$/MWh. For global variables, we have the maximum annual capacity, capital cost, operations & maintenance cost, tipping fees, interest rates, inflation rate, degradation rate, the lifetime of power plants, and unit price of the social cost of CH_4 and CO_2. And the values of those variables may vary depending on different types of technology, including anaerobic digestion, fermentation, gasification, pyrolysis, combustion, and mixed waste. While upgrading to electricity from the energy outputs, capital and operations & maintenance costs differ for the four technologies: gas turbines, microturbines, reciprocating engines, and fuel cells.[10]

Two terms define the **net present value** (*NPV*): the current discounted value of costs and the present discounted value of revenues. B_t is the undiscounted revenues benefits of some projects during year t, and we let C_t be the undiscounted costs of the same project during year t. One can calculate the *NPV* based on the following equations.

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[7] Approximate conversion factors, Statistical Review of World Energy. https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2021-approximate-conversion-factors.pdf

[8] The United States Natural Gas Industrial Price, Independent Statistical & Analysis – US Energy Information Administration. https://www.eia.gov/dnav/ng/hist/n3035us3m.htm

[9] State Electricity Profiles, Independent Statistical & Analysis – US Energy Information Administration. https://www.eia.gov/electricity/state/

[10] Combined Heat and Power Basics, Advance manufacturing. Office of Energy Efficiency & Renewable Energy. https://www.energy.gov/eere/amo/combined-heat-and-power-basics

$$\text{Present discounted benefits } = PDB = \sum_{t=0}^{T} \frac{B_t}{(1+r)^t}$$

$$\text{Present discounted costs } = PDC = \sum_{t=0}^{T} \frac{C_t}{(1+r)^t}$$

$$\text{Net present value } = NPV = \sum_{t=0}^{T} \frac{(B_t - C_t)}{(1+r)^t}$$

In those equations, T is the time horizon for the project, and r is the real discount rate. If the *NPV* of a project is positive, the project can be said to be feasible in present discounted value terms. If one is evaluating multiple alternatives, one would generally want to choose the option with the highest *NPV*. In some cases, one may be interested in the *NPV* of a project as of some year before T. Then, one can call it the cumulative *NPV* as of year $X < T$, which can be defined as follows.

$$\text{Cumulative } NPV = \sum_{t=0}^{X} \frac{(B_t - C_t)}{(1+r)^t}$$

The total cost of a system divided by the total amount of energy it produces is called **Levelized Cost of Energy** ($LCOE$),[11] and its equation is as follows by the formal definition.

$$LCOE = \frac{NPV\ of\ Total\ Costs\ Over\ Lifetime}{NPV\ of\ Electricity\ Energy\ Produced\ Over\ Lifetime}$$

Define π_t the inflation rate at year t and $(1 + d_t) = (1 + \pi_t)(1 + r)$ be the discount rate at the current year. All energy systems degrade over time, and the degradation will be denoted as δ with the power output for year n as $Q_n = Q_0 * (1 - \delta)^n$, where Q_n is the amount of power produced that year and Q_0 is the amount of power produced in the first year. Therefore, the total power produced over the system lifetime is $\sum_{t=1}^{n} Q_0 * (1 - \delta)^t$. Thus, the *LCOE* equation becomes

$$LCOE = \frac{\sum_{t=1}^{n} \left[\frac{C_t * (1 + \pi_t)^t}{(1 + d_t)^t}\right]}{\sum_{t=1}^{n} \left[\frac{Q_0 * (1 - \delta)^t * (1 + \pi_t)^t}{(1 + d_t)^t}\right]}$$

Among all the papers and notes on renewable energy we have reviewed, we can find useful data to calculate *NPV* and *LCOE* by technologies including anaerobic digestion (AD) and

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[11] Levelized Cost of Electricity. https://www.pveducation.org/pvcdrom/levelized-cost-of-electricity

landfill gas (LFG). For example, values of global variables methane production by anaerobic digestion are as follows.

Table 3. The economics of alternative technologies

Methane Production		**AD**	
Variable	*Unit*	*Value*	
Maximum Annual Capacity	metric ton	50000	
Tipping Fees	$/metric ton	50	
LNG Price	$/metric ton	197.14	
Average Electricity Price	$/MWh	104.20	
Unit of Social Cost of Methane	$/metric ton	540 - 3200	
The lifetime of Power Plants	year	30	

The AD process uses 25,555 MWh municipal solid waste, 1,753 MWh heat, and 1,485 MWh power to generate 15,750 MWh biomethane. In this process, 15,750 MWh biomethane equivalent to 989.10 metric ton liquefied biomethane is produced, therefore, the capital cost is $494,550, operations & maintenance cost is $89,019. The tipping fees of produced biomethane is $49,455 with direct revenue $194,991.17. So, the net profit is then $155,427.17. By calculating the present values for the entire 30 years with the same initial inflation rate, discount rate, and degradation rate, the system will gain net profits since year 4 from the cumulative *NPV* with total net present value of revenue $5,874,950 and its ***LCOE* is 10.03 $/MWh**. The analysis suggests AD breaks-even on year 4 and starts making positive profits thereafter.

Using similar assumptions, an LFG system will gain net profits since year 14 from the cumulative NPV with total net present value of revenue $9,178,528 and its ***LCOE* is 2.94 $/MWh**. Howbeit, the cost estimates are a lower-bound, given the need to purify the biogas when upgrading it to biomethane and eradicate it from impurities such as siloxane.

IV Incorporating renewable energy alternatives in the Social and Environmental Accounting (SEA) frameworks of businesses outside of the energy sector

Social and environmental accounting generally relates to preparing and collecting information to educate stakeholders both within and outside the organization about its impact on the societies and environments. It represents the ventures that directly impact the environment, society, and a firm’s economic performance. This accounting practice is used to justify firms’ existence, and it helps firms be more accountable to society and the environment. Social and environmental accounting considers the values and costs of these different impacts on society and the environment. It quantifies them so that a more comprehensive understanding of a firm’s business practices is produced.

There are three critical dimensions involved in this accounting practice:

1. Environmental Factors

2. Social Factors
3. Economic Factors

The above dimensions are broken down further into the following:

Table 4. Factors affecting social and environmental accounting

Environmental	**Social**	**Economic**
Energy	Community Investment	Accountability/ Transparency
Water	Working Conditions	Corporate Governance
Greenhouse Gases	Fair Trade	Stakeholder Value
Emissions	Public Policy	Economic Performance
Waste (Hazardous & Non-Hazardous)	Diversity	Financial Performance
Recycling	Safety	
Packaging	Anticorruption	

Not all these considerations are essential to this investigation, but this shows the depth of social and environmental accounting. For simplicity and brevity, our study is mostly focused on the environmental and economic factors of this accounting practice.

We are incorporating this practice to help show the value and costs generated by these different technologies that produce biomethane from biogas. We will provide the costs and benefits of these other streams to biomethane both with and without this practice. When considering the social and environmental costs, the analysis presents a different picture. The value generated from the carbon and methane emission reductions, which are a direct result of these technological processes, can offset a good amount of the costs of these different technological streams. Of course, these technologies become even more attractive with scale than large-scale plants that are analyzed with standard financial accounting.

Generally, social and environmental accounting (SEA) relates to the preparation and collection of information to educate stakeholders both within and outside the organization about its impact on the societies and environments it operates in (Deegan, 2016). There are many ways to create social and environmental accounts, some more imaginative than others.

The Climate Disclosure Standards Board (CDSB) is a relatively mainstream international organization working on SEA. It is unlikely to call for very forceful regulations. Still, it can convert more conservative, neo-liberal interests over the need for standardized environmental accounting and disclosure, for example, in annual reports. The CDSB describes itself as an "international consortium of business and environmental NGOs … committed to advancing and aligning the global mainstream corporate reporting model to equate natural capital with financial capital. It is composed of The Climate Registry, the Carbon Disclosure Project (CDP), the Coalition for Environmentally Responsible Economies (Ceres), The Climate Group, International Emissions Trading Association (IETA), World Economic Forum (WEF), and the

World Resources Institute (WRI). The CDSB focuses on reporting carbon data from an investment perspective that would allow companies to be more efficient, create more value, and assist policymakers in regulating carbon emissions. They frame the benefits they propose in terms of market outcomes. The work of the CDSB board has been focused so far on creating a climate change reporting framework.

In addition to a complete corporate planning and reporting checklist, the CDSB "guidance for climate-related disclosures" prioritizes environmental risks associated with those assets that stockholders directly own.12 While the CDSB's division of impacts hints at a life cycle analysis, it potentially suggests a lower degree of corporate responsibility for the emissions of entities where the company in question has no direct relationship.

The CDSB observes that "electricity and heat production are among the largest contributor to GHG emissions. Electricity generation will need to expand and switch to renewable sources of decarbonization." Energy vendors would typically emit "Scope 2" emissions under the CDSB guidelines, which means the reporting company has a lower level of direct accountability. In addition, no matter where they arise in the supply chain, GHG emissions in metric tons is difficult for stakeholders to understand and compare—a fact explicitly recognized in the CDSB guidance document.

We believe that it would be better to calculate and distribute standardized measures of the money cost of a given unit of energy that already incorporates the GHG impacts associated with its generation method. Power from renewable sources would look cheaper under such a measure than today. If we include a standardized measure of money unit for a given energy unit into a parallel, sustainability-oriented "set of books," project selection and profitability reports could proceed in the usual manner, using either traditional or climate-friendly energy costs, as desired. Actual choices would remain in the hands of managers who would respond (at least in most cases) to conventional profit measures. Still, the only thing the government would need to do to induce companies to use the correct set of books would be to implement a carbon tax equal to the economist's per-ton cost of CO2 equivalent incorporated into our preferred cost of energy.

One challenge with this approach is that it addresses only the carbon footprint of purchased energy and not other processes over which manufacturing corporations have direct control. A second challenge is that it would require utilities to report and companies to use the precise breakdown of the ultimate feedstock used for the kWH supplied in a given period (e.g., fossil fuels, organic waste, wind, hydro). However, given the close correspondence between energy use and GHG emission liability for many companies (and households, for that matter), this approach is simple to understand and could eventually be enforced.

We recommend the Levelized Cost of Energy for this purpose (see the formula in section III above), which includes the usual resource costs of electricity production, including plant and equipment, labor, and operating expenses. This social cost of carbon is easily added and will increase the cost of fossil fuel electricity relative to alternative feedstocks. Therefore, following our idea of "parallel accounting," we re-do the calculations of NPV and LCOE by introducing

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[12] See https://www.cdsb.net/sites/default/files/climateguidancedoublepage.pdf

social accounting of biomethane for the examples we showed in Section III. To this end, we consider two additional variables: the unit social cost of biomethane and biomethane intensity.[13] The unit value of social cost of biomethane is found to be 540 – 3200 $/metric ton, and the value of biomethane intensity is ranged from 1% to 20% and then the averaged value of intensity is applied.

In the AD process, the average social cost of biomethane is $56,081.97 – 332,337.60 with 989.10 metric ton liquefied biomethane produced. By applying the minimum value of the average social cost, the cost of energy produced from operations and maintenance drops by potential value added from the social cost, $89,019.00 - $56,081.97 = $32,937.03; the profit of energy produced from tipping fees and methane revenues increase by potential value added from the social cost, $155,427.17 + $56,081.97 = $211,509.14. By calculating the present values for the entire 30 years with the same initial inflation rate, discount rate, and degradation rate, **the system will gain net profits since year 3 (1 year ahead) from the cumulative *NPV* with total net present value of profits $8,173,224 (39% more) and its new *LCOE* is 2.72 $/MWh which is 73% cheaper.**

VII. Challenges and opportunities

Barriers to the adoption of these technologies include high costs of commercially available large-scale WTE systems, marginal or insufficient returns, requirements for staffing these plants, and distractions from the focus of business depending on where these plants are and if they are integrated with things such as farms. Ideas to move past these barriers include motivating generators of waste like homes and business to separate their waste either through penalty or incentive; haulers must have monetary incentive to take waste to these plants over landfills, and there must be available infrastructure in place to process the material, while also setting an optimal tipping fee. Transportation costs play a big role in these systems, and inefficient systems can make these ventures cost inefficient. Integrating organic waste pickup with existing waste/recycling routes can save a lot of costs, as well as locating AD plants near large urban centers to reduce transportation fees. Another viable synergistic option is to co-locate the AD with an ethanol plant. A typical ethanol plant producing 50 million gallons of ethanol a year will produce around 150k metric tons of carbon dioxide. Integrated ethanol fermentation and anaerobic digestion plants can convert the high chemical oxygen demand from stillage into energy rich biogas. Ethanol plants need between 20–30 MWh of energy to run and co-locating an anaerobic digester to produce energy can offer significant economic benefits.

A sustained, available supply of waste poses a problem as large scale WTE plants need to create a large set of contracts with multiple points of waste generation. Solutions include incentivizing sorting food waste at homes and businesses, having municipalities encourage local generators to sign long term contracts with project developers or haulers, and enforcing landfill diversion policies. Contamination such as packaging material increases pre- and post-processing costs, hurting profitability considerably. Postconsumer food waste is usually riddled with contaminants, and most existing AD systems are reluctant to take this waste, although some efforts are being made at local levels to facilitate source separated food waste for AD plants.

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[13] See https://www.aga.org/about/investor-relations/natural-gas-sustainability-initiative-ngsi

Solutions include education and incentives to households to separate their waste to develop interest from WTE plants, and businesses and innovators can use or create biodegradable packaging that is fit for WTE plants.

Scale and size for food WTE systems depend on a multitude of factors including

- Type of conversion technology
- Availability, transportability, and handling capacity of waste feedstock
- Energy, fuel, and by-products handling and marketing capability
- Fixed and variable cost of system components
- Economic feasibility for a site-specific project, which would be subject to local factors like land, capital, labor, feedstock, and energy costs
- regulatory and permitting considerations
- Equipment:
  - Material handling and feeding equipment (grinders and pulpers, feed pumps, augers),
  - mixing equipment (circulation pumps, blade mixers), and
  - power and fuel-refining equipment (electricity generators, gas scrubbers) are also factors.

A list of potential incentive programs from state, federal, and local governments which these food waste to energy systems may qualify under. The paper recommends using the Database of State Incentives for Renewable Energy. Some of the programs mentioned are the USDA Rural Energy for America Program Renewable Energy Systems & Energy Efficiency Improvement Loans & Grants, USDA Biorefinery, Renewable Chemical, and Biobased Product Manufacturing Assistance Program, Federal Business Energy Investment Tax Credit, Federal Renewable Electricity Production Tax Credit, US Department of Energy- Loan Guarantee Program, and USDA Rural Energy for America Program Energy Audit & Renewable Energy Development Assistance Grants.

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