NEW JERSEY DEPARTMENT OF ENVIRONMENTAL PROTECTION

SCIENCE ADVISORY BOARD

FINAL REPORT

Biofuels

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Executive Summary

This report was generated by an ad hoc committee based in the Climate and Atmospheric Sciences Standing Committee of the Science Advisory Board of the New Jersey Department of Environmental Protection. In mid-2021, the committee was charged with providing information on the bioenergy feedstocks and sources available to New Jersey, the emissions benefits of the associated biofuels, and recommendations for biofuels that would aid New Jersey in meeting its net neutral electric generation goals. This charge to the SAB was triggered as a response to the projection in New Jersey's 2019 Energy Master Plan that the State will need to produce 10.1 TWh of electricity from biogas or other biofuels to meet the goal of 80% reduction of 2006 greenhouse gas emissions by 2050.

The report summarizes an exploration of scientific literature along with consideration of existing and potential sources of biofuels in New Jersey. In particular, the following topics are discussed in detail: New Jersey's energy economy, biomass feedstocks available, biogas production methods, estimated quantity of biogas feasible with current technology, methods capable of increasing biogas production, actions needed to introduce biogas into the existing natural gas pipeline system, identification of methods of using biofuels with existing powerplants and pipeline infrastructure, alternate uses for biofuels such as building heating, alternate uses of available biomass that could take precedence over using it to produce biogas, and assessment of the viability of biofuels to meet New Jersey's net neutral electricity generation goal.

The authors conclude that with current technologies, up to approximately 150 million m^3 of biogas could be produced annually. If cleaned up to acceptable standards and fed into the existing natural gas pipeline system and combusted in natural gas-burning power plants, this would allow for the generation of 0.7 TWh of yearly electrical production. There are large uncertainties associated with this estimate, so a value of 1 TWh can be considered plausible. This estimation includes reported and projected production from Trenton Biogas and the proposed Linden Renewable Energy facility, and conversion to biogas from 50% collection of all food wastes generated in the state, including residences and facilities not covered by NJ's food waste law, and 50% of potential generation from NJ landfills and wastewater treatment plants.

Although this report focuses on the availability of biofuels primarily from waste products in New Jersey using current technologies, the potential range for electricity production could be expanded if other sources are considered. Specifically, the use of lignocellulosic waste or the development of new technologies could increase methane production. Imports of food waste or other wet organic waste could also add to feedstock availability.

Introduction and Overview

In its "Revised Memo: SAB Research Task; Biofuels," DEP asks the Science Advisory Board (SAB) to gather available information on non-fossil carbonaceous materials that could potentially be used to produce energy. The Department also seeks a summarization of the emissions benefits of using these feedstocks, and recommendations, including a cursory evaluation of the associated economics, on which biofuels would be most viable for New Jersey to achieve its net neutral generation goals.

As explained in the Revised Memo, DEP's request is triggered by the projection in New Jersey's 2019 Energy Master Plan (NJ Board of Public Utilities, 2019) that, to meet the State's goal of 80% reduction of 2006 greenhouse gas emissions by 2050, the State will need to produce approximately 10.1 TWh of electricity from biogas or other biofuels. Further, these biofuels will need to be fed into the existing natural gas pipeline infrastructure and thereby supplied to existing gas-burning power plants.

The sections that follow discuss

1. New Jersey's energy economy,
2. Biomass feedstocks available and potentially available,
3. Biogas production methods currently in use in New Jersey and elsewhere,
4. Estimated quantity of biogas feasible to produce with current technology,
5. Methods potentially capable of increasing biogas production,
6. Actions needed to introduce biogas into the existing natural gas pipeline system,
7. Identification of possible methods and feasibility of using biofuels other than biogas coupled with the existing powerplants and pipeline infrastructure to generate electricity in NJ,
8. Alternate uses for biofuels that could take precedence over electric generation, including building/space heating
9. Alternate uses of available biomass that could take precedence over its use to produce biogas,
10. Assessment of the viability of biofuels to meet New Jersey's net neutral electricity generation goal and implications of possible associated policy options, and
11. Implications and Recommendations.

The SAB has augmented its team working on this project with academic scholars and researchers with relevant expertise. The combined team has searched the literature and gathered information from other available sources and subjected its findings to multiple reviews. Nevertheless, because of the wide varieties of biomass types and their potential uses, and the uncertainties of the results of ongoing and yet-to-be contemplated research, this report should not be considered definitive, but rather a guideline for future work to clarify the role of biomass in New Jersey's energy future.

1. New Jersey's energy economy

i. How we use energy and where our energy comes from

New Jersey uses energy for agricultural and industrial processes, space heating and air conditioning of buildings, transportation, cooking, the operation of tools and appliances, and for other purposes. Much of the total energy used is derived from direct combustion of fossil fuels, primarily natural gas, gasoline, and diesel fuel. Besides obtaining energy from direct combustion, New Jersey consumes electricity from both in state and out of state generation. In 2021 the State consumed approximately 72.6 terawatt-hours (TWh) of electricity (US DOE/EIA, 2021), which was produced chiefly through natural gas combustion and nuclear power, although coal combustion and solar photovoltaic energy and other renewables also contributed to the total. In 2019, the combustion of fuels accounted for 85% of the State's total greenhouse gas emissions, with the transportation sector contributing 38.0 million metric tons of CO_2 equivalents (MMT CO_2e), the electricity generation sector contributing 19.4.1 MMT CO_2e, the combined commercial and industrial sectors contributing 18.2 MMT CO_2e, and the residential sector contributing 15.3 MMT CO_2e, for a total emission from fossil fuel combustion of 90.9 MMT CO_2e (NJDEP, 2022). [1] The remaining emissions

[1] All numbers represented utilize the 100-year global warming potential values.

(14%) were from non-energy sectors, most of which consisted of non-CO_2 greenhouse gases: methane, nitrous oxide and the highly warming halogenated/fluorinated gases.

ii. Why we're trying to decarbonize

New Jersey's Global Warming Response Act (GWRA) establishes a goal to reduce emissions by 20% below 2006 levels by 2020 and 80% by 2050—known as the 80x50 goal. Largely due to a shift from coal to natural gas as a major fuel for electricity generation, New Jersey has already successfully reduced emissions by 20% below 2006 levels. To meet the considerably more challenging 80x50 goal, New Jersey must implement an economy-wide transformation that steadily phases out the use of fossil fuels and expedites the deployment of renewable energy resources and other measures (NJDEP, 2020).

As stated in the GWRA, the New Jersey Legislature found that (1) global warming, driven by emissions of greenhouse gases, risks catastrophic changes to Earth's ecosystems and environment, (2) each country and region within a country must do its part to reduce these emissions, (3) there are specific actions that a state can take to attack the problem of global warming, and (4) that it is in the public interest to establish a greenhouse gas emissions reduction program for New Jersey.

The current vision of the road to 100% clean energy by 2050 includes the rapid adoption of three key strategies: (1) replacing internal combustion vehicles with electric vehicles, (2) converting space and water heating in the residential and commercial buildings to electric heat, and (3) replacing fossil fuels in the electric generation sector with renewable energy sources. Included in the latter goal is augmenting the State's wind and solar photovoltaic (PV) capacity with biomass-based energy generation.

There is a wide variety of materials that can be considered biomass, including wastes and dedicated vegetative crops. Managing these resources in an optimum manner will require consideration of many perspectives. An important guiding principle is embodied in the circular carbon economy concept, which seeks to promote an economic system based on reuse of products and raw materials and the restorative capacity of natural resources. The circularity approach redefines waste as a "resource" and feeds the resource back into the economy efficiently.

iii. Decarbonization options

Regardless of the degree to which the State succeeds in minimizing and reusing carbon-containing wastes, to meet the goal of the Global Warming Response Act, it will need to reduce its greenhouse gas emissions to 24.1 million metric tons CO_2e by 2050 (NJDEP, 2019). Implementation of the strategies noted above will require replacement of fossil fuel combustion energy sources with a greater than two-fold increase in electricity consumption by 2050 (NJDEP, 2020). This will require the following:

1) In-state solar capacity will have to grow at a rate approximately three times as fast as it has grown over the last decade, and it will have to maintain this faster rate of growth for the next 28 years. As referenced in the 80x50 report, the growth trajectory goal for in-state solar is for capacity to increase to 5.2 GW by 2025, increase to 12.2 GW by 2030, and continue to grow by 1 GW/year until 2050. During the period 2011 through 2021, total solar PV capacity in NJ grew from 0.7 GW to 3.8 GW, an average growth rate of approximately 0.3 GW per year (NJCleanenergy, 2022).

2) Growth of offshore wind capacity to 10.7 GW by 2050.[2] The largest wind turbines currently feasible are reported to be able to generate 13 MW of power each (Reed, 2021). To achieve 10.7 GW of capacity will require over 800 such units to be in place by 2050, meaning that approximately 25 to 30 of these units will need to be installed each year. If smaller capacity turbines are used, proportionately more will be needed.
3) The state's existing nuclear generation capacity will need to be maintained through 2050.
4) 34.9 TWh of electricity generated by wind and/or solar will need to be imported via the PJM Interconnection by 2050.
5) Fossil gas and fossil coal will need to be completely phased out for electricity generation by 2050, and enough generation capacity will be maintained, powered with biogas, biofuels, and/or hydrogen, to provide 10.1 TWh/year of electricity.

It's likely that achieving these goals will be challenging, perhaps extremely so. The section below discusses the feasibility of a key aspect of item #5, the replacement of fossil gas with biogas, which is essentially methane produced from recently produced carbonaceous material. Also discussed are ways that this feasibility could be enhanced.

2. Biomass feedstocks

Biomass is a broad definition for biologically derived renewable materials that can be used to produce heat, electric power, transportation fuels and bio-based intermediaries, as well as products and chemicals. Sustainable biomass, however, can be more narrowly defined and does not include biomass feedstocks that follow food-to-fuel pathways and/or that result in forest conversion to plantations or land clearing for biomass production. Biomass sustainability has been long discussed and is a well debated matter. For instance, the use of first-generation biofuels/bioenergy such as corn ethanol and soybean biodiesel, have raised numerous environmental concerns such as greenhouse gas (GHG) emissions, land use change, eutrophication, loss of carbon sinks and increased carbon release from soils (Guran et al., 2018., Fargione et al., 2008, Hertel et al., 2010, Searchinger et al., 2008). There is also the social concern over the food-to-fuel pathway and diverting food crops to energy generation. Considering the development of new types of sustainable energy crops and utilizing unrecycled fractions of waste coupled with efficient clean energy technologies can help alleviate many of these issues. Additionally, other land use problems associated with traditional energy crops, such as clearing additional land for agriculture, increasing the net carbon-footprint by releasing stored soil carbon and eliminating the carbon sink function of the once-intact ecosystem should be avoided.

i. Energy Crops

a. Short rotation woody crops - Switchgrass, miscanthus, hybrid poplar, willow, etc.

The dedicated energy crops of interest here are grown specifically for their utilization in energy conversion processes in ways that do not displace food production. They provide a source for the production of renewable energy, chemicals, and materials due to their composition of sugars, lipids, proteins, and fibers (Guran et al., 2018).

These crops are often referred to as cellulosic biomass and are further classified into herbaceous and short-rotation woody crops (fuel wood). Short-rotation woody crops are subdivided into softwood and hardwood, each of which has individual benefits, depending on the conversion

[2] Through executive order Governor Murphy has now committed New Jersey to 11 GW of OSW by 2040.

process, desired products, or applications. Softwoods produce less ash than hardwoods, but they also contain less carbon, have a lower energy density, and have less availability as residues. Herbaceous energy crops are divided into perennials (3–10 year growing cycles) and annuals, with perennials generally being the preferred resource.

In general, energy crops with a larger fraction of fibrous material (lignocellulose) contain the highest calorific value, making it advantageous to maximize the yield of this plant fraction for the production of energy and fuels. Fuel wood produces usable heat for the residential, commercial, and power in the electric utility sector (Gent et al., 2017).

Short rotation woody crops are primarily intended for the production of biomass for energy but could also contribute in the future to an integrated forestry wood industry chain. The fast- growing tree species of the genera *Populus* (poplars) and *Salix* (willows) are the most experimented with as bioenergy candidates. Elemental ash content in bark and wood can be problematic for thermal conversion and can decrease pretreatment efficiencies in liquid fuel conversion. It is assumed that a high bark-to-wood ratio in short-rotation crops like shrub willow (Salix spp.) will necessarily contribute to high elemental ash content, but little data exists on the genetic and environmental contributions to elemental composition in willow (Speight, J.G., 2020).

Switchgrass, *Panicum virgatum*, is a warm season perennial plant native to the tallgrass prairies in the United States. Switchgrass has been identified by the U.S. Department of Energy as a leading energy crop because it tolerates a wide range of environmental conditions and offers high biomass yield, compared to many other perennial grasses and conventional crop plants (USDA Technical Report No.3, 2009).

While the use of switchgrass as an energy crop has been the subject of scientific investigation for the past three decades, the large-scale commercial cultivation as a biomass crop is just emerging in the US. Switchgrass requires little maintenance, no annual planting, and only one harvest per year. Established from seed, it is less costly to plant than miscanthus or willow, but once established, it provides attractive rates of return if a market is available for the harvested crop. Switchgrass biomass can be condensed into fuel pellets for combustion, or it can be used as a feedstock for cellulosic biofuel production. Bioenergy markets for switchgrass are emerging (USDA, 2009).

Miscanthus is a perennial rhizomatous grass with the C4 photosynthetic pathway that is native to East Asia. Its average annual biomass yield reportedly can reach 30 tons per hectare (dry matter) with minimal agricultural inputs. It has remarkable environmental adaptability, able to grow under a wide range of climatic conditions. Giant Miscanthus (*Miscanthus giganteus*) is considered as an energy crop in the US while other Miscanthus types are considered invasive (USDA Fact Sheet, 2011).

In addition to short rotation woody crops, forest residues can serve as feedstock candidates for low carbon energy.

Currently, most suitable conversion technologies for dedicated energy crops and forestry waste are based on thermochemical conversion, in which biomass is degraded at high temperature. These technologies include gasification and pyrolysis. In gasification, biomass is reacted with a gasifying agent, (e.g., air, oxygen, water) at high temperature. Pyrolysis is a thermal process in which biomass is reacted with a limited amount of oxygen under high temperature.

Gasification can be used to provide gas called syngas, which is a mixture of carbon monoxide and hydrogen. Syngas can be directly combusted for power generation or can be treated further to produce liquid fuels such as jet fuel. Pyrolysis can be used to decompose biomass to generate oil and biochar. However, the oxygen content of biomass may require further refining of the bio-oil. Pyrolysis can also produce charcoal ("biochar") that is resistant to further degradation and thus represents carbon storage. Biochar is also reported to be beneficial as a soil treatment that enhances plant growth. (Aluiddin, 2010, Ruiz, 2013, Devi 2003, Lehmann, 2007).

ii. Waste Biomass as feedstocks for Bioenergy

a. Food

Food wastes appear to be low hanging fruit that emerging circular carbon systems can utilize as feedstocks to produce low-carbon energy in the form of biopower and biofuels, and end-products including chemical industry intermediates. These approaches can further displace fossil fuels and increase GHG mitigation efficiency overall.

Food waste is defined by NJ's food waste law (NJDEP, 2023). For this discussion, the generalized definitions proposed by the Food and Agriculture Organization of the United Nations (FAO, 2022) are used, and are summarized as follows:

- Food loss refers to a decrease in mass (dry matter) or nutritional value (quality) of food that was originally intended for human consumption. These losses are mainly caused by inefficiencies in the food supply chains, such as poor infrastructure and logistics, lack of technology, insufficient skills, knowledge and management capacity of supply chain actors, and lack of access to markets. In addition, natural disasters play a role, for example storms can knock out refrigeration systems, causing spoilage.

- Food waste refers to food appropriate for human consumption being discarded, whether or not it is kept beyond its expiration date. Often food is discarded because it has spoiled but it can be for other reasons such as oversupply or consumer shopping/eating habits.

- Food wastage refers to any food lost by deterioration or waste. Thus, the term "wastage" encompasses both food loss and food waste.

Food waste can be classified into four major groups by source: *residential*: kitchen waste; *institutional*: pre- and post-consumer cafeteria waste from schools, hospitals, and correctional facilities; *commercial*: supermarkets, restaurants, farms and other commercial establishments; and *industrial* waste: food processing industry. Commercial and industrial food waste can also be classified as pre- and post-consumption food waste. Residential and institutional 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, Hochman, Guran & Gottlieb et al., 2021).

Food wastes, based on their physical and chemical properties and end-product interests, can serve as feedstock for a variety of processes, including anaerobic digestion[3], transesterification[4], gasification[5], pyrolysis[6] and combustion. If food waste has a high sugar, moisture, or oil content, it can be a useful feedstock for anaerobic digestion or hydrothermal liquefaction. If food waste has a low moisture content, such animal bones or nut shells, thermochemical conversion technologies are suitable to convert it into low-carbon fuels and energy.

b. Agricultural Waste (crop waste and animal waste)

Crop Wastes: Agricultural waste generally refers to crop waste such as the straws of cereal, corn husks and ears. In addition to primary agricultural crop residues there are other types of residues including organic material from excess or unwanted production, animal manures and slurries. Crop wastes can also serve as feedstock for anaerobic digestion, transesterification, gasification, pyrolysis and combustion (Guran 2018, ch 8).

Crop residues can be sub-grouped as follows:

- Grains: Barley, Maize, millet, oats, rice, rye, sorghum, wheat
- Legumes: Beans, peas, nuts, lentils, soybeans
- Oil crops: Linseed, rapeseed, safflower, seed cotton, sesame, sunflower
- Sugar crops: Sugar beet, sugar cane
- Tubers: Potatoes, sweet potatoes
- Vegetable residue
- Orchard residues

Ideally, reutilization of crop residues will be performed sustainably without causing direct and indirect impacts. Research indicates that excessive straw reaping can deplete soil organic matter and thus have adverse impacts on soil, environment and crop yield. Thus, a reasonable removal ratio is needed.

Animal Manure: Animal manure's decomposition is one of the main sources of the greenhouse gases methane and nitrous oxide (Park et al. 2006). Confined animal-feeding operation (CAFO) wastes if not managed properly can create additional environmental pollution (Wang et al. 2014) including exposure to pathogens harmful to livestock, wildlife and humans. Animal manure from small farms is usually spread onto cropland. However, animal manure from large farms and industrial style confinement facilities is often present in such large quantities that it requires further management. New technologies that are technically and environmentally efficient are

[3] Anaerobic digestion (AD) is a series of entrained biological processes in which micro-organisms digest plant and/or animal-based material in sealed containers producing biogas.

[4] Transesterification is the chemical conversion of triglycerides with alcohol into alkyl esters. It is part of the reaction process used to produce biodiesel fuel.

[5] Gasification is a process that converts carbonaceous materials at high temperatures without combustion, with a controlled amount of oxygen and/or steam, into carbon monoxide, hydrogen, and carbon dioxide.

[6] Pyrolysis is conversion of carbonaceous materials at high temperatures in a limited oxygen environment. Products typically include charcoal and/or tars.

needed to utilize animal wastes for energy to displace reliance on fossil fuels while improving soil, water, and air quality (Wang et al. 2014).

Based on its physical and chemical properties, animal manure can be utilized via thermochemical and biochemical conversion technologies. If animal manure has a high moisture content the most suitable technology is anaerobic digestion. Generally, swine and dairy waste are suitable for this technology. For animal manure such as equine and poultry manure of low moisture content, thermochemical conversion technologies are more suitable.

c. Residential – yard and municipal waste

Residential biomass waste consists of food waste, cardboard and other cellulose-containing parts of packaging, yard waste (grass clippings, leaves, branches and other biomass debris) and non-recycled wood from construction and demolition activities. These kinds of wastes are generally used for mulch, landfilled or incinerated.

Similar to the above waste reutilization approaches, dry residential waste can be utilized through thermochemical conversion technologies.

3. Biogas production methods currently in use in NJ and elsewhere

Biogas from food waste anaerobic digestion, landfill gas (LFG), and anaerobic digester gas from wastewater treatment facilities (WWTF) is currently being considered as a viable part of the solution to the twin challenges of providing renewable energy and minimizing waste.

Although the terms biogas, LFG, and digester gas sometimes are used interchangeably since their main constituents are CH_4 and CO_2, they may have other impurities such as water vapor and traces of nitrogen, hydrogen sulfide and ammonia depending on decomposition type, location and feedstock. Problematic contaminants in some cases are volatile organic silicon compounds (VOSCs), primarily siloxanes. If food waste is not contaminated by other waste such as personal care products and cleaning products, VOSCs are not typically observed. All these gases are the result of anaerobic decomposition of complex organic materials either in the landfill cells or in digester vessels. However, in addition to where the digestion occurs, other important factors that contribute to gas composition are the type of feedstock and conditions of the decomposition. All these gases can be used as clean energy sources. If all the impurities and CO_2 content are successfully removed, the remaining methane can be used as Renewable Natural Gas (RNG). Eight of the twelve operating commercial landfills in the New Jersey have installed these energy producing systems to help meet their energy needs and supply electricity to the grid (NJDEP, 2020).

Biogas is also generated at the wastewater treatment facilities and this gas is typically called digester gas. Digester gas is also primarily CH_4 and CO_2. However, digester gas also contains relatively high amounts of VOSCs because of widespread use of silicon-containing compounds in personal care products and cleaning materials that make their way into wastewater upon their disposal.

i. Deposition of municipal solid waste (MSW) in landfills and collection of landfill gas

Landfill gas (LFG) is a natural byproduct of the decomposition of organic material in landfills. It is composed of approximately 50 percent CH_4, 50 percent CO_2 along with water vapor and traces of other compounds including siloxanes. Removal of siloxanes and related compounds from LFG and digester gas is needed before the gas is fed into power generation equipment (Wheless and Pierce, 2004).

Without such removal, when the landfill gas or digester gas is combusted in gas turbines, boilers, microturbines or internal combustion engines to generate power, siloxanes convert into silicon dioxide (SiO_2) and deposit in the various parts of the power generation equipment causing high maintenance costs, prolonged down time, and even serious equipment failure. Deposition on turbine blades, heat exchangers and emission control equipment can result in reduced or total loss of heat transfer efficiency, equipment failure and possible poisoning in catalytic converters requiring expensive repairs and causing service interruptions (Wheless and Gary, 2002; Pierce, 2005; Popat and Deshusses, 2008). The amount of siloxanes varies depending on the source, and concentrations in landfill gas are reported up to 140 mg/m^3 (Wheless and Gary, 2002) which is significantly above the 15 mg/m^3 limit recommended by most equipment manufacturers (Schweigkofler and Niessner, 2001). Older landfills are reported to have lower siloxane concentrations due to lower historic use of personal care products with polydimethylsiloxane (PDMS) which causes formation of siloxanes (Ajhar et al., 2010).

Evidence of siloxanes in LFG and digester gas at wastewater treatment facilities is observed in the form of white powder in gas turbines' moving parts, as a light coating on various types of heat exchangers, as deposits on combustion surfaces in reciprocating engines, and as a light coating on post-combustion catalysts. Literature suggests that microturbines and fuel cells may not be able tolerate siloxanes. Since these technologies offer performance advantages, economic returns may justify the cost of siloxane removal. Landfills are estimated to be the third largest source of anthropogenic methane emissions in the US and NJ. The environmental impacts of landfills with gas recovery facilities depend on proper management, but regardless of management efficiency (Barlaz et al., 2009), current landfill designs and operational practices are generally not capable of collecting LFG fully. 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.

Because of the problem of methane emissions from landfills there is a growing interest in diverting organics, particularly highly putrescible food wastes, out of landfills to utilize them more efficiently for clean energy production and for nutrient recovery. In landfills, organic material residuals/nutrients are not recovered for beneficial reuse primarily due to the cost and difficulty of separating impurities from mixed MSW prior to disposal.

ii. Anaerobic digestion

Anaerobic digestion can be used to produce biogas. The organic material left over, known as digestate, is rich in organic matter and nutrients such as nitrogen, phosphate and potash. Biogas and digestate are both important outputs of anaerobic digestion (AD). Anaerobic digestion of organic waste such as manure food waste, the organic fraction of MSW, and organics at wastewater treatment facilities is a well-established technology.

In New Jersey, at least 37 wastewater treatment facilities utilize anaerobic digesters to process sludge; 11 of these facilities have energy recovery systems generating electricity or heat from the produced digester gas that is fed back into the process helping to defray operational costs. (NJDEP 80x50 report p 96). At other facilities the biogas is flared. The digestate from wastewater treatment facilities is sometimes not suitable as fertilizer for edible crops because of the high metals and pharmaceuticals contents of residential sludge.

There is growing interest in AD. Some cities and states in the US have started to require the diversion of organics from landfills and their management with AD (EPA, 2021). The food and drink industry is an example of a well-established use of biogas to fuel boilers producing hot water and/or steam. Some examples include Toyama City Eco Town where food waste-based biogas boilers provide energy for Mitsubishi Rayon Toyama Production Centre; Bonduelle canning facility in Nagykoros, Hungary; Elgin Fruit Juices in South Africa and Diageo's Glendullan distillery in Scotland (Jain and Newman, 2018).

Biogas plants generating renewable electricity are present around the world at various scales, including: local food courts in Malaysia using food scraps to generate electricity; Harvest Energy Garden processing food waste from Walt Disney World Resort and other industrial, commercial and institutional sources to generate 3.2 MW of electricity (and 2.2 MW of recoverable heat); City of Chiba, Japan digesting food waste from food manufacturing industries, retailers and households; and Elgin Fruit Juices, South Africa running part of their juicing operations on electricity generated from fruit, vegetable and other food waste.

In Trenton, New Jersey, Trenton Renewables produces electricity and heat from food waste using AD (Trenton Biogas, 2022). Also in the State, the Landis Sewerage Authority in Vineland has a combined heat and power plant (CHP) that burns CH_4 from its treatment process to make electricity and hot water. The facility also operates a liquid food processor waste receiving station that accepts liquid waste from the food industry as well as food grade fats, oil, and grease that enhances the methane production process. The Rahway Valley Sewerage Authority, in Rahway NJ, operates anaerobic digestion units and in a public/private partnership with Waste Management, Inc., it blends and co-digests wastewater sludge with a food waste slurry. (This operation is also known as the Elizabeth WM CORe WM CoRe facility.) Overall, in the U.S. there are more than 150 facilities (standalone AD, wastewater treatment facilities and farm ADs) that utilize AD biogas for power, heat or power and heat generation (USEPA, 2021).

In addition, biogas is utilized by some cities for district heating. Long-term successfully operating projects include the municipality of Este, in the Veneto region of Italy, Hengelo in the Netherlands, and Dannenberg, Germany.

CITIES with Anaerobic Digestion (AD)

Residential Food Waste AD:

Munich (Germany), Milan (Italy), Forbach (France), Madrid (Spain), Vienna (Austria), Upsala (Sweden), Oslo (Norway), Zurich (Switzerland), Wijster (the Netherlands), Hinjewadi, Pune (India), Malur (India)

Commercial Food Waste AD:

Bernau (Germany), Hartberg (Austria), Skrzatusz (Poland), London (UK), Chennai (India), Chiba (Japan)

FOOD PROCESSING & BEVERAGE INDUSTRY

•BREWERIES – Heineken (Nigeria), SABMiller (Uganda) AB InBev (Russia), Diageo (Kenya, Ghana), Beer Thai (Thailand), Khon Kaen Brewery (Thailand), Brakina Brewery (Burkina Faso);

• ABATTOIRS – Jan Kempdorp Abattoir (South Africa), Grossfurtner St Martin (Austria);

• FRUIT AND VEGETABLE PROCESSING – Bonduelle (Hungary);

• DAIRY PROCESSING – Lactalis Retiers (France), Danone (Belgium), Amul Dairy (India); and

• CONFECTIONARY – Mars, Veghel (Poland).

Co-digestion (digesting food waste along with wastewater sludge:

In addition to the New Jersey facilities in Vineland and Rahway noted above, there are a number of examples of co-digestion of wastewater sludge and food waste in the U.S. These include the Central Marine Sanitation Agency, San Rafael, California; Sheboygan Regional Wastewater Treatment Facility, Wisconsin; West Lafayette Wastewater Treatment Facility, Indiana; and Janesville Wastewater Treatment facility, Wisconsin. It has also been implemented in South Korea in many plants, including Yongyeon, Ulsan, Hyuncheon Goyang-si, Anrak Busan, Seobyun Daegu and Dongchun Incheon, Riihimaki, and Oulu in Finland, Zirl in Austria and Radeberg in Germany (Jani and Newman, 2018).

Animal manure and some other agricultural wastes are amenable to anaerobic digestion. Over 263 animal manure anaerobic digestion units operate on livestock farms in U.S. (USEPA, 2021). To the SAB's knowledge, there are no such agricultural waste anaerobic digestion units operating in New Jersey. Should conveniently located centralized anaerobic digestion facilities become established in New Jersey, they may create opportunities for small farms.

Food waste is well suited to anaerobic digestion. New Jersey's Food Waste Recycling and Waste-to-Energy Production Act (P.L. 2020, c.24) was signed into law by Governor Murphy on April 14, 2020, and it went into effect on October 14, 2021. It requires facilities that generate a projected volume of 52 tons of food waste or more per year to source separate and recycle their food waste. Consequently commercial, institutional and industrial food waste will be more available as a feedstock to AD facilities in New Jersey for biogas generation. This approach will also create opportunities to create synergies between AD and composting industries since the digestate from food waste AD facilities can serve as a better feedstock for composting. With this approach, food waste can be fully utilized within a circular carbon economy framework. Currently in New Jersey the only standalone food waste anaerobic digester facility is Trenton Biogas, noted above. At least one additional facility, the Linden Renewable Energy Project (LRE, 2022) is under development.

A recent economic modeling study (Dill , 2021) found that the construction and operation of an anaerobic digestion facility to process food waste in Bergen County would be economically attractive. Although their literature review revealed that several other food waste AD facilities in the U.S. had proved to be unprofitable, they found that a facility in Bergen County by taking advantage of all possible revenue streams, NJ incentives for renewable energy, and by savings due to avoidance of relatively high tipping fees for waste in the County, could be profitable. These researchers had access to limited actual data, so they depended on some estimated values and assumptions for input parameters.

Input parameters include the estimates and assumptions that: 1) the facility would become operational in 2029, 2) the collection of food waste would not require a separate system or entail extra costs (the study assumed that weekly solid waste pickups would become biweekly, with food waste pickups in alternate weeks using the same equipment and personnel), 3) 60% of non-regulated and residential food waste generators would voluntarily separate food waste from other waste, 4) Bergen County commercial and industrial facilities and institutions producing >52 tons of food waste per year would generate between 53,168 and 124,572 tons per year of food waste (all of which exceedthe 40,400 tons per year calculated for Bergen County facilities using data developed by EPA (NJDEP/BCCCE, 2021), 5) the AD facility would be able to sell electricity it produced at the average NJ retail price instead of the wholesale price, and 6) the AD facility would be able to sell digestate at $10/ton. The estimated cost of permitting and constructing the facility was based on national data, and so may not reflect the likely high cost of land and its availability in Bergen County.

Possible differences between their model's input parameters and potential real-world data notwithstanding, Dill et al. (2021) make the case that an AD facility could be economically successful in NJ. The study points out that two New Jersey policies appear to work at cross-purposes in terms of the quantity of feedstock potentially available for anaerobic digestion. These policies are 1) the requirement for facilities that generate 52 tons/year or more of food waste to source separate this waste and transmit it to a recycling facility and 2) the statewide goal to reduce all food waste generation 50% by 2030.

Regarding the first of these policies, acceptable recycling facilities include those that directly compost food waste. The study did not consider the impact on food waste feedstock of a composting facility that might also be developed in the region. Dill, et al. noted that feedstock could fall short of the designed capacity of a reactor because it is not assured that there will be enforcement and compliance of the new food waste recycling law, and further that residential food waste collection might not prove to be significant. In the event of a feedstock shortfall, the authors stated that a facility might be forced to reach outside of Bergen County for organic matter to be able to run the digester. A point emphasized by the study is that diverting food waste from landfills and processing that waste via dedicated anaerobic digestion facilities is likely to yield greenhouse gas emission benefits because all the methane produced can be captured and used to provide energy rather than partially escaping into the atmosphere as happens with landfills.

Based on a run of EPA's waste reduction model, WARM, using its default input parameters (Aucott, 2022), composting and incineration of food waste, neither of which have significant emissions of methane, yield greenhouse gas emissions benefits similar to AD when compared to landfilling, on the order of 0.5 to 0.6 $MTCO_2e$ per ton of food waste. It should be emphasized that WARM also indicates that source reduction of food waste yields by far the biggest emissions benefit when compared to any waste management method; on the order of 4 $MTCO_2e$ per ton of food waste reduced. This is presumably because WARM incorporates impacts throughout the life cycle of the wastes.

Modeled outcomes are of course dependent on input parameters, which can be highly uncertain. This dependence emphasizes the importance, as discussed in the recommendations section below, of obtaining comprehensive data on AD facilities actually operating in New Jersey.

4. Estimated quantity of biogas feasible to produce and/or access in NJ using current production methods

As discussed above, biogas is currently produced by the anaerobic digestion of wet organic waste such as sewage sludge and food waste. The quantity of such waste available and the portion of the carbon content of such waste that is amenable to conversion to methane are the key predictors of the total amount of biogas feasible to produce with current production methods. Estimates of the quantities of biogas that could be produced upon full implementation of New Jersey's food waste law, with expanded collection from landfills and wastewater treatment plants, with expansion to include the residential wet organic portion of municipal solid waste, and upon further expansion to include out-of-state sources delivered by existing natural gas pipelines are provided below.

i. Upon full implementation of NJ's food waste law

As noted above, NJ's Food Waste Recycling and Waste-to-Energy Production Act went into effect in October 2021. Details of how the law will be implemented, and thus what will constitute "full implementation" remain to be determined. The law specifies that food waste generators must comply with the separation and recycling mandate only if they are located within 25 miles of a recycling facility with sufficient capacity to accept the waste, and only if the cost of transporting and processing the food waste at the recycling facility does not exceed 110 percent of the cost of transporting and disposing of the waste as solid waste. Food waste recycling facilities must be authorized by the NJDEP. They may recycle the food waste by subjecting it to anaerobic digestion, thus producing biogas as well as residual compost. On the other hand, they may process the waste in other ways, such as aerobic composting, which would not produce biogas. The law also allows a food waste generator to comply with the law via an alternative authorized food waste recycling method, which could include on-site composting or digestion and shipping food waste off-site for agricultural use or any other method authorized by NJDEP.

New Jersey has two other food waste laws that are relevant. In 2017 the Food Waste Reduction Act (P.L. 2017, c.136) and the School Food Waste Guidelines legislation (P.L. 2017, c.210) were signed into law. The Food Waste Reduction Act established a goal of reducing food waste by 50%, based on 2017 food waste estimates, by the year 2030 (NJDEP, 2019a). To the extent that this law is effective, it will reduce the amount of food waste generated in the State, and thus could reduce the overall amount of biogas that could be produced from this source.

Clearly, the overall quantity of food waste generated that is susceptible to the requirements of these laws, the number of authorized recycling facilities that exist (and that will come online in the future), and the type of processing done by either the generators themselves or the off-site facilities are all factors that will influence the total amount of biogas that can be produced upon full implementation of the food waste laws. There is uncertainty about the total amount of food waste that is subject to the food waste recycling law. However, a study by USEPA (NJDEP/BCCCE, 2021) produced data that identifies New Jersey facilities that are expected to produce more than 40 tons per year of food waste. These data were sorted to include only those facilities expected to produce 52 or more tons per year. The total generation from these facilities is estimated in the referenced study as 319,076 tons. Approximately 69% of this total is contributed by food products manufacturers and processors.

In the discussion below, it will be assumed that biogas produced from food waste will be cleaned of CO_2 and impurities and will thus be essentially equivalent to natural gas, which in turn is essentially equivalent to methane, CH_4. There is a wide range of estimates available on the amount of methane expected to be generated from a ton of food waste using existing anaerobic digestion technology. An operating New Jersey facility, Trenton Biogas, reports that it produces approximately 58 m^3 of methane per ton of received food waste (Trenton Biogas, 2022). A planned facility (LRE, 2022) expects to produce 67 m^3 methane per ton. References in the literature, reflecting in part different mixes of carbonaceous materials in differing food waste streams, range from 87.5 m^3 per ton to a theoretical upper limit of 376 m^3 per ton (EBMUD, 2008; Kuo & Dow, 2017; Guran, 2022). Another food waste recycling facility, the WM CORe facility in Elizabeth, also operates in the state, although its biogas is apparently not used to produce electricity (NJDEP, 2023a). Data from this facility were not used in this analysis but could prove useful to the DEP in the future.

Assuming an approximate mid-range of 100 m^3 methane produced per ton, 319,076 tons of food waste, in the unlikely scenario that all generators of 52 tons or more per year delivered all their food waste to anaerobic digestion facilities, could conceivably produce as much as 32 million m^3 of methane. If a lower generation potential, e.g. 62.5 m^3 methane per ton (the average of Trenton Biogas's reported production and the planned LRE facility's expected production) is assumed, the maximum methane production would be approximately 20 million m^3 methane. With this calculation, the total generation potential is thus in the range of 20 to 32 million m^3 methane per year. To this estimate can be added the current production of Trenton Biogas and the projected production of the proposed LRE facility, which together are reported to total approximately 40 million m^3 per year.

How much electricity could be produced from this biogas, if it were all collected, compressed, and injected into the pipeline system and delivered to New Jersey gas-burning power plants can be estimated with the assumption that it would have the same heating value as natural gas (i.e. essentially pure methane) and that it would be combusted and turned into electricity with the same efficiency as the current average of New Jersey's gas-burning power plants. In 2019, these plants consumed 3.03 trillion Btu (about 8.3 billion m^3) of natural gas and produced 40.5 TWh of electricity (USDOE/EIA, 2019; US DOE/EIA, 2021). On this basis, 20 to 32 million m^3 could be expected to produce between 0.09 and 0.15 TWh of electricity.

It should be noted that this is a gross quantity, not a net quantity. Upgrading biogas from the anaerobic digestion process requires the removal of CO_2 and trace gases, which takes energy. It is estimated (LRE, 2022; Sun et al., 2015) that upgrading one m^3 of biogas requires between 0.2 and 0.3 kWh of electricity. Biogas is approximately 50% carbon dioxide and 50% methane; so it can be assumed that approximately 38 to 64 million m^3 biogas would have to be upgraded to produce the 19 to 32 million m^3 methane referenced above, which, as also noted above, could be expected to produce between 0.09 and 0.15 TWh of electricity per year. Upgrading this 19 to 32 million m^3 would require enough electricity to reduce the net electricity production from this source to the range of 0.08 to 0.14 TWh/year.

To this amount of electricity production can be added the current production of Trenton Biogas and the projected production of the proposed LRE facility, which together are reported to total approximately 0.19 TWh/year,. Adding all these together brings the total electricity that could be produced in New Jersey if all food waste from generators of >52 tons/year were delivered to AD facilities and if Trenton Biogas continues its current reported production and if the proposed LRE facility is built and produces as projected to between 0.27 and 0.33 TWh per year.

ii. With expanded collection from landfills and wastewater treatment plants

It is technically possible that more gas could be collected from New Jersey's landfills, and that it could be upgraded sufficiently and introduced into the natural gas pipeline system. However, many landfills, especially those that were closed in the past, are small and have steadily declining emissions of gas. Collecting gas from these landfills and upgrading it to pipeline standards would present logistical and economic challenges.

A recent study (Dyer et al., 2021) investigated the feasibility of collecting landfill gas in New Jersey and upgrading it. They identified 7 landfills with a realistic potential of producing what they termed renewable natural gas; they estimated that these landfills could produce a total of 4.89 billion standard cubic feet of this gas per year. This is equivalent to 138 million m^3.

Dyer, et al. (2021) also identified wastewater treatment plants that appeared to be capable of producing renewable natural gas. They identified 22 such facilities, from which a total of 1.65 billion standard cubic feet (44.2 million m^3) could feasibly be produced.

The National Renewable Energy Laboratory also estimated the amount of methane that could be generated from New Jersey's landfills and wastewater treatment plants. A search of its Biopower Atlas (NREL, 2016) yielded an estimate for NJ landfills of 24 million m^3 and for wastewater treatment plants of 127 million m^3 methane. While these estimates differ from the estimates of Dyer, et al. (2021), Biopower Atlas's total is not inconsistent with Dyer, et al. (2021)'s estimated total.

The total high-end estimate of the amount of methane that could feasibly be produced by these two source categories is thus approximately 182 million m^3. In the unlikely scenario that all this methane was collected from these landfills and wastewater treatment plants, transmitted to the natural gas pipeline infrastructure, and burned by power plants to produce electricity, and using the same electricity production per m^3 factor as discussed above, this amount of methane could produce as much as 0.86 gross TWh of electricity, which, after accounting for the energy required to upgrade the biogas to essentially pure methane, might amount to a net of approximately 0.81 TWh per year.

iii. Upon further expansion to include the residential wet organic portion of municipal solid waste

The wet portion of residential solid waste is assumed herein to consist largely of food wastes. Estimates of the amount of such wastes generated in the State vary. Guran (2022) indicated that approximately 105 kg/year of food waste is generated per person. Using NJ's approximate population of 9 million leads to a total generation of 1,042,000 short tons of food waste per year. Another study (Kuo & Dow, 2017) reported that 15.5% of municipal solid waste is food waste. Using a figure of 6 million tons of solid waste generated in the State in a year leads to an estimate of 960,000 short tons of food waste per year. RTS (2022) reported that each person generates 219 pounds of food waste per year. Using a population estimate of 9 million leads to an estimated food waste generation of 985,500 short tons per year. Guran (2022), based on a survey of a sample of New Jersey municipal solid waste, found that 22% of solid waste is food waste. This leads to an estimated generation of 1,320,000 tons/year. Another source (NJDEP, 2019a) estimates a yearly generation of 1,460,000 tons/year.

Using the range of these estimates and an estimated methane generation factor of 100 m^3 per ton leads to an estimated methane production of between 9.60×10^7 and 1.46×10^8 m^3 of methane per year. Using a lower generation factor of 62.5 m^3 per ton (the average of the reported and projected methane generation of food waste recyclers using anaerobic digestion) leads to a range of 6.00×10^7 to 9.13×10^7 m^3 per year.

The NREL's Biopower Atlas also provides an estimated total methane production potential from New Jersey's food waste (NREL, 2016) of 46 million m^3. An overall estimated gross production range is thus between 46 and 146 million m^3 methane per year, which, using the same calculation basis as above, would translate to a net electricity production in the range of 0.21 to 0.65 TWh.

The expansion of biogas production to include all of the residential wet organic portion of municipal solid waste would require separation of this portion from the remainder of the waste and an altered collection system. This process could entail significant energy costs, which would reduce the net electricity production and greenhouse gas reduction benefits. A countering effect, however, as discussed in Section 4i, is that the natural degradation of wet organic waste in landfills eventually leads to methane generation, not all of which is successfully captured by landfill gas scavenging systems. Minimizing landfills' methane generation by separating the wet organic waste, converting it to methane under controlled conditions in dedicated anaerobic digestion facilities, and transmitting to the pipeline system for combustion to produce electricity would have positive greenhouse gas reduction benefits because of methane's high global warming potential relative to carbon dioxide.

iv. Upon further expansion to include out-of-state sources delivered by existing natural gas pipelines

NREL (2013) has also estimated the national potential to produce renewable natural gas, defined as high quality methane scrubbed of impurities to allow it to be transported using the existing natural gas pipeline network. They estimate the methane potential from U.S. landfill material, animal manure, wastewater, and industrial, institutional, and commercial organic waste to be approximately 7.9 million tons per year, which can be converted to 420 billion cubic feet of natural gas equivalent (11.9 billion m^3) or 431 trillion BTU.

As noted in Section 2, lignocellulosic biomass contains a relatively large fraction of fibrous material. Such materials are not amenable to the production of biogas via anaerobic digestion with current technology. However, if technological developments facilitate biogas production from such resources and these materials are also included, then NREL (2013) finds that the U.S. renewable natural gas supply could reach 4.2 trillion cubic feet (119 billion m^3) per year (4,318 trillion BTU).

New Jersey's total natural gas consumption in 2019 was 761 billion cubic feet (781 trillion BTU), of which approximately 294 billion cubic feet (8.3 billion m^3 or 303 trillion BTU) was consumed by the electricity sector (EIA, 2022). If New Jersey was the only U.S. state mandating 100% renewable natural gas, then it might be able to supply 55% of its needs by consuming all of the potential U.S. renewable natural gas production from non-lignocellulosic sources. Or, if applied only to New Jersey's natural gas consumption for generating electricity, New Jersey's electricity sector would need to consume 70% of total potential U.S. non-lignocellulosic production, or 7% of total potential

U.S. production including lignocellulosic sources. In short, unless lignocellulosic feedstocks and the capacity to convert a significant portion of these wastes to biogas become widely available, New Jersey's electricity sector is unlikely to be able to satisfy its current natural gas needs with out-of-state renewable natural gas.

It should be noted however, that the 80x50 Report and Energy Master Plan estimate that only enough renewable natural gas will be needed in 2050 to produce 10.1 TWh of electricity. With the current generation efficiency calculation, as discussed above, this would require about 2.15 billion m^3 of natural gas. Thus, if New Jersey could import 2% of the total production estimated to be possible from wastes including lignocellulose sources, the State might be able to meet the 10.1 TWh/year goal.

It should also be noted that converting lignocellulose wastes to biogas, while being explored extensively, has not been proved at large scale for biomass resources (NREL, 2013). Considering only the currently feasible anaerobic digestion process, and its potential to produce methane from U.S. landfill material, animal manure, wastewater, and industrial, institutional, and commercial organic waste, the State would have to import 20% of the renewable natural gas estimated to be possible to generate nationally these sources.

For New Jersey to import this high a percentage of nationally produced renewable natural gas that would be coming from what would likely be many thousands of small sources, some of which would have their own uses for the gas, would require changes to the current gas collection and distribution system for which there is no precedent and that may well be infeasible.

On the other hand, should the State find a way to fund or partially fund the development of biogas production technology at some of the larger sources of manure and other wastes (e.g. industrial-scale confined animal operations in relatively nearby states) it might be able to claim some greenhouse gas reduction benefits.

5. Methods of increasing biogas production

i. Increasing available feedstock suitable for production with current technology

The challenge of increasing available feedstock beyond food waste for biogas production in the state requires a look at different types of feedstocks. Common feedstocks that can be considered are manure, other wastes such as agricultural and forest residues, park and garden waste, sewage sludge, and aquatic plant-based feedstocks. With increased biogas production required to meet the State's decarbonization priorities, increased feedstock availability might best be acquired through a generic statewide perspective rather than a case-specific perspective (e.g., considering a specific biogas plant in New Jersey). The primary aim would be to target decision makers, biogas producers, and other biogas stakeholders.

a. Imports of wastes and manure

The State of New Jersey ranks 30th in the nation for methane production potential from biogas. There is potential for more than 120 new projects to be developed based on the estimated amount of available organic material sources (American Biogas Council, 2022). The current availability of feedstock for biogas production in the state limits the amount that can be produced to meet decarbonization goals (see Section 4 for detailed analyses). Efforts must be channeled to increase in-state collection of feedstocks as well as imports from viable neighboring states to facilitate increased biogas production pathways through biodigesters.

Rather than focusing on more theoretical potentials, with biogas yield being the primary criterion for importing a certain feedstock, one can look more thoroughly from a producer profitability perspective. This is important as biogas feedstocks have higher volume and lower energy content as compared to conventional fuels; thus, distance from conversion plants such as digesters can be a key factor determining economic viability of imports. For example, livestock manure tends to be a relatively low-energy feedstock, as this material has predigested in the gastrointestinal tracts of the animals. However, manure is easily used in anaerobic digestion and can be made available in large quantities. A 1,000-pound dairy cow provides an average of 80 pounds of manure daily, which is typically stored in holding tanks before being applied to fields. In 2015, livestock manure and associated management contributed about 10% of all methane emissions in the country, and only 3% of livestock waste was recycled by AD (USEPA, 2022a). Based on the 2012 Agriculture Census, more than three-fourths of the manure produced by confined livestock is recoverable and may be collected and utilized (Gollehon et al., 2016). This provides an opportunity for the State of New Jersey to utilize manure collected not just within the state, but from a more agrarian neighboring state like Pennsylvania for biogas production.

This is applicable for other wastes that can be used for biogas, whereby distance from the conversion facility and the extent of conversion efficiency is important for the techno-economic feasibility of biogas. However, the management and stabilization of the biodegradable fraction of those wastes must be viable. The technical conditions of the AD plant and the joint use of different types of feedstocks and manure influence the stability and performance of biogas production from an operational standpoint (Zheng et al., 2015; Tsapekos et al., 2017). Besides yields of biogas feedstocks, there is variation in effort and cost associated with different volumes of feedstock as well. Rather than increased cost associated with maximum in-state waste collection, feedstock imports offer the possibility of maintaining supply chain continuity, stabilizing loading rates of biogas digesters, and helping production facilities operate closer to permitted capacity.

b. Changes in amount of waste exported

New Jersey, the most densely populated state in the nation, generates considerable waste that could be used for biogas production. A 2015 study conducted by Rutgers New Jersey Agricultural Experiment Station assessed the biomass energy potential in New Jersey and found that biomass in the state is primarily concentrated in the counties of central and northeastern New Jersey (Guran and Specca, 2015). Bergen County had the highest total tons/year generation capacity in the state. Biomass availability is spread across the state in central and southern parts and transporting it to a bioenergy producing unit was found to be an important factor economically. However, a significant portion of the waste generated in the state is exported. For example, nearly 18.22% of the solid waste produced in the New Jersey from 1985-2018 was disposed outside the state. Reducing the waste export and utilizing it locally to replace conventional fuels is a pragmatic approach to help meet decarbonization goals.

Increased waste utilization would help expand the presence of in-state biodigesters and encourage the construction of new ones. The continuous flow of organic material in significant quantities requires a structured system to collect industrial quantities of waste (IEA, 2020). The biogas output could be linked to a captive power or cogeneration plant involving additional investments to meet state priorities. Biogas plants with assured feedstock supply can offer higher levels of efficiency and automation.

c. Increased source separation and collection of food waste in NJ

As noted above, New Jersey's food waste law went into effect in October 2021. This law requires large food waste generators in New Jersey located within 25 road miles of a NJDEP authorized food waste recycling facility to source- separate food waste from their general waste stream and ensure the food waste is recycled in one of three ways: (1) sending the food waste to NJDEP approved recycling centers, (2) managing the food waste on-site where it is generated, or (3) sending the food waste offsite for use in agriculture. However, source segregation and collection of food waste is still a challenge. A concerted effort geared towards small waste generators including households is required.

The process of separation of food waste at its generation source can be an efficient way to reduce unnecessary food purchase and ultimately lowering associated greenhouse gas emissions (Girotto et al., 2015). Source-segregated food waste can be used as feedstock for AD (Salemdeeb et al., 2018).

Food waste occurs both at the retail and final consumption stages, and its generation is related to both retailers' and consumers' behaviors (Jamal et al., 2019; Ando and Gosselin, 2005). Household food waste generation is influenced primarily by socio-demographic characteristics, consumption behavior, and food patterns of the household (Glanz and Schneider, 2009). Rousta et al. (2015) found that convenience in sorting habits, storage space at home, availability of sorting facilities, access to a curbside collection system, and distance to collection points are important influential factors that can increase the food waste collection and source separation. They also found that information stickers regarding food waste sorting along with nearby proximity of drop-off points reduced the miss-sorted fraction by more than 70%. Parizeau et al. (2015) concluded that convenience was a major issue when asking families to implement source segregation.

d. Increased use of anaerobic digestion at wastewater treatment plants

As also discussed above, AD is a well-established method of waste treatment that has been shown to effectively treat and reduce the volume of sewage sludge at wastewater treatment plants (WWTPs), particularly in plants with limited space and strict odor regulations. Implementing AD where it is not currently used has benefits. According to Ranieri et al. (2021), sewage facilities with AD systems save more than 50% of total energy consumption (1.0 kWh m-3) when compared to companies with only aerobic systems (0.4 kWh m-3). AD technology can reduce the amount of sewage sludge and the content of pathogenic microorganisms contained in it, hence decreasing the environmental hazards associated with this waste. At the same time, this process allows sludge to be bio-converted to methane, which can be collected and used as biogas to generate electricity and heat, or as a transportation fuel known as biomethane (Amin et al., 2021). AD also has the greatest practical potential for apprehending the embedded energy content of wastewater. AD digestate can be utilized with artificial wetlands when there are standards limiting waste from the plant (Borges et al., 2016; Butterworth et al., 2016). AD treats approximately 48% of total wastewater flow in the United States (Qi et al., 2013). The majority of the organic input from wastewater is anaerobically digested in WWTPs to generate biogas (Vutai et al., 2016).

The use of AD for WWTP has traditionally been driven by the plant treatment needs rather than the economics of gas production or energy generation (Hale, 2018). Furthermore, due to low degradability of dry solids, most of the WWTP digesters tend to operate at low loading rates, leading to poor biogas yields (Maragkaki et al., 2017). With a potential for widespread implementation of WWTP facilities using AD in the State, favorable support programs can help motivate facilities that are not using AD to change their sludge digestion practices.

e. Aquatic plants

Algae: Algae encompass a broad spectrum of organisms classified into two main categories: microalgae (microscopic photosynthetic eukaryotic organisms and cyanobacteria) and macroalgae (seaweed). While microalgae are phytoplankton found in both freshwater and marine systems, seaweeds are marine organisms.

Different strains of algae vary for combinations of chlorophyll molecules. Algae comprise proteins, carbohydrates, fats, and nucleic acids, yet the proportions vary across the various types of algae. There are numerous macro and microalgae (Jong et al., 2012; Golden et al., 2015), each differing in their chemical composition and, therefore, the biobased chemicals that they can produce. Accordingly, the literature reports a wide range of growth rates for macroalgae (Palatnik & Zilberman, 2017). For example, Cai et al.'s (2013) review showed that the growth rate of algae varies between 0.2 to 10.86% per day for red seaweed while reaching 15% of average daily growth for green seaweed. This uncertainty in feedstock yield has a significant impact on the cost-effectiveness of the technology. In addition, algae has much higher solar energy conversion efficiency than most terrestrial crop species: 3% vs. 1% respectively (Packer, 2009).

Microalgae can fix CO_2 from three different sources: atmosphere, discharge gases, and soluble carbonates (Wang et al., 2008). Under natural growth conditions, microalgae assimilate CO_2 from the air and can tolerate and utilize substantially higher levels of CO_2--up to 150,000 parts per million by volume (ppmv), see Brown (1996). As a result, microalgae could sequester CO_2 emitted from power stations or other industrial sources, significantly reducing overall greenhouse gases emissions (Nigam & Singh, 2011). Similarly, the use of seaweed aquaculture beds in potential CO_2 mitigation efforts has been already proposed with commercial seaweed production in China, India, Indonesia, Japan, Malaysia, Philippines, Republic of Korea (Chung et al., 2013), Thailand, and Vietnam, and more recently in Australia and New Zealand (Golberg et al., 2020a; Kelly et al., 2020). Algae can act as a novel form of carbon capture and storage (Economist, 2021). The market for carbon offsets led other start-up companies to implement their technologies in pilot and commercial settings, with some targeting the transition of the stored carbon from the ocean's surface to the deep seas (e.g., Running Tide: https://www.shopify.com/climate/sustainability-fund/partners#ocean). However, the supply chains of these industries are yet to mature, and many hurdles exist for the industry to become a mature industry that helps reduce carbon footprints (albeit a different challenge, recall the hurdles faced by the efforts and needs of using algae to replace a barrel of oil (https://www.greentechmedia.com/articles/read/lessons-from-the-great-algae-biofuel-bubble)).

A large body of literature shows the high potential of microalgal biorefinery to extract biogas, liquid and gaseous transportation fuel, kerosene, ethanol, aviation fuel, biohydrogen, biodiesel, bioethanol, and bio-oil (Sharma et al., 2011; Gallagher, 2011; Levitan et al., 2014). Others investigated various microalgae-produced gases such as biogas, biohydrogen, and syngas (Demirbas, 2010; Nigam & Singh, 2011). USDOE identified microalgae to have the potential to synthesize 100 times more oil per acre of land than any other plant, and they are even better than soybeans (US DOE, 2016). Several firms have been working to establish the economic feasibility of microalgae-based biofuels.

Even though agricultural production uncertainties are inherent, aquafarmers growing macroalgae face significant production uncertainty. Feedstock growth depends on saturation kinetics by light intensity, ambient dissolved inorganic nutrient concentration, and temperature (Buschmann et al., 2004). Cultivation uncertainty is exacerbated by stochastic weather seasonal variability between regions, within years and between years. Studies point at biomass productivity as the primary constraint against being competitive with other energy and protein-producing technologies (Seghetta et al., 2016). Environmental factors negatively affecting the performance of seaweed farming include grazing by fish or other organisms and rising sea temperatures, which could slow seaweed growth (Hurtado 2013). In addition, the type of cultivation system (Golberg et al., 2020b) and wild harvesting technologies (Mac Monagail et al., 2017) also significantly impact the yield.

Duckweed: Aquatic monocots in the *Lemnaceae* family, commonly called duckweeds, are plants endemic to most parts of the world that could fit all these criteria (Landolt, 1986). Duckweed, like algae, is a highly productive and nutritious aquatic plant, requiring low water input and does not compete for arable land. The duckweed abbreviated structure and tendency to float allows for rapid, low energy input collection with minimal carryover water. The low lignin levels (< 5%; [Blazey & McClure, 1968]), together with a high protein content (up to 40% dry weight) in some strains and a large surface area to body mass ratio, makes duckweed easy to collect and use.

The industry uses duckweed for what it contains, including starch, protein, fat, mineral, vitamin, and phytosterol content, as well as amino acid and fatty acid spectrum (Hillman, 1976; Appenroth et al., 2017 & 2018). Currently, end-users consume duckweed because of its nutritional value (Bhanthumnavin & McGarry, 1971), for use in spices, food additives, feed, or bioplastics (Zeller et al., 2013).

In addition, studies showed duckweed can be used in fuel production (Sun et al., 2007). The renewed interest in bioenergy during the 21st century did not skip duckweed. Duckweeds, like algae, are viewed as a potential feedstock for bioenergy production (Cheng & Stomp, 2009). Although the plant is not rich in starch, it is possible to enhance the duckweed starch accumulation (Cui & Cheng, 2015; Liu et al., 2018; Guo et al., 2020; Shao et al., 2020; Xu et al., 2018). Duckweed biomass can also produce biogas via anaerobic digestion (Ren et al., 2018), significantly enhancing duckweed's total energy output (Calicioglu & Brennan, 2018; Kaur et al., 2019).

Processing technologies:

Algal biomass intended for beneficial or commercial purposes is grown in open raceway ponds, closed systems like photobioreactors and fermenters, harvested from seaweed farms, or obtained from natural standing stocks and potentially, with careful controls, from harmful algal blooms.

Anaerobic digestion, fermentation, transesterification, liquefaction, and pyrolysis can convert algal biomass into proteins and sugars, resulting in food, chemicals, and biofuels (Torres et al., 2019). An example is Zamalloa et al. (2011), who propose the preconcentration of algae to decrease the cost and energy required for harvesting and using it in a high-rate anaerobic digester to produce biogas. Zamalloa et al. (2011) offered a comprehensive technological and economic assessment that is then applied to estimate the cost of energy production using microalgae as feedstock. An alternative is hydrogen production which can efficiently use photolysis of water by algae. 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 challenging to commercialize hydrogen production this way.

Numerous studies focus on evaluating algal production process's future costs that are currently primarily available on a small (lab) scale (Korzen et al., 2015; Seghetta et al., 2016). Developing a new biorefinery, its design, and its construction require significant investments (Stichnothe et al., 2016). Moreover, introducing and perfecting innovations is a process whose trajectory is difficult to assess, and the economic conditions that face a technology vary over time. Learning takes time, and the dynamics of knowledge accumulation affect the introduction of innovations, their refinement, and commercialization. Timing also affects the decision regarding the capacity of creation and the extent of reliance on external sources.

Price variations yield uncertainties to the aquafarmer, to the feedstock produced, and to potential alternative outputs (backstop technologies). To this end, a seaweed industry that contains many small-scale entrepreneurs is prone to boom-bust cycles. An example is the range of prices and annual growth rates for one macroalgae species – *Kappaphycus*. During 1991-2016, when strong demand for dry seaweeds drove up the price, seaweed farmers increased their planting efforts and harvested immature crops. However, seaweed farmers reduced production when the price was low, which created sourcing difficulties for the biorefineries. On the other hand, biorefineries declined the supply when algae prices rose and substituted with cheaper alternatives. As a result, the feedstock supply often exceeded demand and led to the collapse of price (McHugh, 2006). The industry is in its infancy, the paths to maturity are challenging, and expectations should be tuned to reality (https://www.greentechmedia.com/articles/read/lessons-from-the-great-algae-biofuel-bubble).

ii. Technical developments making biogas production feasible from additional biomass

Green technologies for biofuel production are developing, but the productivity and yield of these technologies is minimal. In recent years, a variety of pretreatment techniques have been cultivated and successfully used to enhance the techniques to improve the digestibility, biogas yield, and volume productivity of various microalgae biomass. Mechanical (e.g., shaking, ultrasound, microwave, and sonication), thermal (e.g., hydrothermal and steam explosion), chemical (e.g., acid and alkali), biological (e.g., bacterial and enzymatic), and combined pretreatment (e.g., thermo-chemical) methods are the most commonly classified as pretreatment methods. Mechanical pretreatment modifies the structure of microalgal biomass by destroying the cell wall through mechanical force. Mechanical pretreatments have less species-dependent actions on biomass than other pretreatment methods, but they require more energy (Lee et al., 2012). Thermal pretreatment of microalgae biomass is usually performed by exposure to heat of 50-270°C. This causes structural changes and solubilization of biomass (Carrère et al., 2010). Acids or alkali have been used in the chemical pretreatment of microalgae biomass and have proven to be particularly effective in combination with thermal pretreatment (Mendez et al., 2013). Biological pretreatment is also simple to use and has low capital investment requirements (Mshandete et al., 2008)

Stokes et al. (2015) investigated the ability of ruminal microbial communities to hydrolyze residual microalgae biomass as ruminant feedstuffs. The study found that ruminal microorganisms digested the extracted lipid microalgae very well. This demonstrates their ability to break down the cell walls of microalgae and their potential as pretreatment methods for biofuel generation. Electro-fermentation (EF) is a novel technology that boosts biogas generation by incorporating electrodes into the microbial fermentation process (Liu et al., 2019). EF improves the stability of AD as well as the production of methane. Electrode placement and voltage application enhance the metabolic rate and electronic kinetics of bioproducts in increasing biogas production (Sravan et al., 2018). Sravan et al. (2018) found that EF succeeded in increasing the stability of the system, demonstrating the potential for producing methane from food waste. According to the findings, electrical stimulation of biocatalysts advanced the transformation of food waste to a variety of high-value end products, including biogas.

Joshi et al. (2019) presented a new approach using ultrasound-induced cavitation for feedstock material pretreatment with the aim of enhancing the AD process for biogas production. Their findings illustrated the effective use of ultrasounds in the pretreatment of feedstock and subsequent AD process, resulting in a much higher yield of biogas in a shorter period of time.

Extrusion pretreatment exposes feedstock to heat, compression, and shear force, resulting in physical destruction and chemical modification of the feedstock as it passes through the extruder. Novarino and Zanetti (2012) determined that when the organic fraction of municipal solid waste was pretreated using an extrusion method, an enhanced biogas yield of 800 L/kg with a methane content of approximately 60% was obtained.

Anaerobic co-digestion (AcoD) can be an alternative option for addressing the shortcomings of single substrate digestion systems in terms of substrate characteristics and system optimization. Food and animal waste are both appealing substrates for co-digestion. Aside from increasing methane and biogas production, AcoD balances the biodegradation process and nutrients, while also increasing the synergetic effect of microorganisms (Siddique and Wahid, 2018, Zamanzadeh et al., 2017). Food waste from various sources, namely the kitchen (Ma et al., 2011) and leachate from fertilizer-producing centers (Lee et al., 2009), can also be utilized in this process to generate productive yield of biogas. High-solid anaerobic digestion (HSAD) of sewage sludge can additionally be explored as an alternative to AD as it can reduce treatment volumes, transportation costs, and energy consumption for heating and can increase the fertilizing potential of sewage sludge (Di Capua et al., 2020). By centralizing sludge treatment, HSAD represents an opportunity to improve the energy balance of sewage sludge valorization compared to conventional AD.

Technical developments can be directed towards ameliorating inconsistencies in the quality or quantity of biogas systems or in the safety and quality of solid and liquid end products from digesters. The state currently lacks adequate environmental, technical, and economic performance data related to biogas-system production of energy, co-products, GHG and other emissions, grid connection and cost of upgrading to methane, water quality and other societal benefits. Consolidation of this data could help market analysis and associated investments.

iii. Enhancing anaerobic digester efficiency and function

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 how we accomplish treatment of the organic matter. The higher the methane production, the more we generate usable energy. Food wastes with high moisture content, 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) decreases), 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 process control. Stand-alone food waste AD is more susceptible to instability than, for example, manure-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, that is 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 CO_2 and H_2S. 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.

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° C, 10% v/v of whey, and 5 $NaHCO_3$. 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 assessed 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 (with an IRR of 9% and 27%, respectively). 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 reduces the plant dependence on external energy sources. Therefore, the optimal level of the bio-methane output minimizes carbon dioxide emissions with higher biomethane subsidies amplifying this effect.

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 (i.e., the heating value (known as calorific value) of gases used as fuels) within the range of 46-51; thus, it is possible to apply it in the natural gas gird. Purification for high quality 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.

6. Actions needed for biogas technically feasible to produce in NJ with current technology to be introduced to the existing natural gas pipeline system, cost estimates and related aspects of such introduction

NJ has three options to utilize biogas (Hochman et al., 2022):

A. Combusting the biogas:
- In boilers to generate heat.
- In internal or external combustion engines to produce electricity.
- In combined heat and power (CHP) plants to produce both heat and electricity; and
- Using tri-generation systems that provide cooling via absorption chillers in addition to heat and electricity

B. Upgrading the biogas to methane (RNG):

- Injecting the RNG into the pipeline system and using in place of natural gas in industrial, commercial, and domestic applications; and
- Once biogas is upgraded and its methane is separated from carbon dioxide, using the carbon dioxide for commercial use, for example as a plant growth enhancer in greenhouses.
- Using compressed RNG in place of compressed natural gas (CNG) to power vehicles.

C. Processing upgraded biogas into higher-value products such as bioplastics or bio-chemicals.

The generated biogas can either be used directly for power generation after removing the impurities (i.e., moisture, H_2S, ammonia) or upgraded to pipeline quality gas (RNG). NJ can achieve biogas upgrading through available state-of-the-art technologies to methane-rich, pipeline-quality RNG.

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 H_2S. 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.

Upgrading biogas to pipeline quality incurs costs. Sun, et al. (2015) state that the energy required to upgrade one normal m^3 biogas is 0.2 to 0.3 kWh. The description of the proposed Linden Renewable Energy (LRE) project (RNG Energy, 2023), which anticipates receiving food waste from NYC as well as NJ, states that their anaerobic digestion process would require 3.2 MW of energy, which will be provided by solid oxide fuel cells. This electricity use presumably includes the electricity used for the upgrading process. Data provided in the description of this project appears approximately consistent with the Bauer et al. energy use estimate. Assuming that the LRE facility would use 3.2 MW on a continuous basis it would consume 28 GWh/year (0.028 TWh) of electricity while producing 3300 dekatherms/day of RNG (about 34 million m^3/year). This amount of RNG, assuming it is essentially pure methane, using the calculation approach discussed in section 4, would be sufficient to produce about 0.16 TWh of electricity, so the net production would be in the range of 0.13 TWh/year. (This figure does not include estimation of the energy cost in electricity or GHG emissions from the collection and transportation of the processed waste.)

The need to upgrade biogas and otherwise use energy in its production process is one reason for the estimated high cost of renewable natural gas compared to fossil natural gas. A summary of a recent report (NYSERDA, 2022) states that the estimated average costs for RNG from various feedstocks are $11.29 per million Btu (MMBtu) for RNG from landfills, $23.86/MMBtu from food waste, $27.68/MMBtu from wastewater treatment plants, $34.56/MMBtu from animal manure, and $25.67/MMBtu for RNG produced via thermal gasification from MSW, forestry residues, energy crops, and agricultural residues. These figures can be compared to the approximate wholesale cost of fossil gas (City gate price of about $5/MMBtu in January, 2022) (US DOE/EIA, 2022).

The overall costs of producing electricity via biogas have been estimated as well. The IEA (IEA, 2022) states that the levelized cost of generating electricity from biogas varies depending on the feedstocks used and the capacity of the conversion plant, and can range from $50 per megawatt-hour (MWh) to $190/MWh. This makes biogas costlier than some of the variable renewable energy sources such as solar, which (excluding the cost of electricity storage) can be as low as $28/MWh under some conditions, or wind, which (excluding storage) can be as low as $26/MWh (Lazard, 2021). However, as discussed above, biogas has significant potential in terms of meeting clean energy goals set by policymakers, as it can use the existing natural gas infrastructure and provide the system the same benefits of natural gas such as storage, flexibility, and high-temperature heat without the associated net carbon emissions.

Blanton et al. (2021) assessed the role that natural gas infrastructure could play in reaching net-zero targets and bridging emerging energy technologies such as biogas and biofuels in the country. They suggest adjusting existing infrastructure to minimize the costs and accelerate the speed of the clean energy transition. They also emphasize that retrofitting and improving the existing pipeline system can facilitate storage and delivery of cleaner fuels and gases while lowering the overall cost of the transition and ensuring reliability across the energy system. Phadke et al. (2020a) found that 90% of the existing clean grid in the country can be dependable without new coal or natural gas fuel plants. In another report, the authors explored a number of options for eliminating the remaining 10% of emissions from the power sector, including retrofitting existing natural gas plants and hydrogen technologies (Phadke et al., 2020b).

McKinsey & Company (2022) suggests that a decarbonization pathway based only on electrification, renewables, and storage, without clean fuels or carbon sequestration, results in a net higher societal cost. They also highlight that gas infrastructure can be partially repurposed to deliver clean fuels, while gas utilities could utilize decarbonization opportunities to repurpose some assets, invest in new ones, and work with electric utilities, policy makers, commercial and industrial customers, investors, and other stakeholders towards a cleaner future. However, they caution that investments in a clean fuel infrastructure require a long time-horizon (potentially several decades) and should be made early enough to accelerate the market transition. The aforementioned works highlight the need for the State of New Jersey to move towards a clean fuel future and work with the utilities and other stakeholders towards a pathway where clean fuel infrastructure should enable increasingly low-carbon molecules to be transported across the grid.

Detailed and current data about the amount of available organic waste is critical with given its varied composition and seasonal variability. In addition, the properties of the organic feedstock directly influence the performance and outputs of the system. Therefore, feedstock assessment and feedstock preparation are essential for achieving steady-state operating conditions. To this end, there are significant economies of scale in feedstock preparation. For example, the capital costs for preparation fall from around $29,100/tons/day with AD systems using 90 tons a day to $8,700/tons/day with a plant that employs 800 tons a day (Ghose & Franchetti, 2018).

The efficiency of the waste treatment and the energy output determines the performance of an AD system. For example, food wastes with high moisture content (i.e., low VS, TS), such as salads or whey, have a much lower yield than high-solid content food wastes, such as grains or cereals. Besides, in the United States, most AD systems treat food waste in conjunction with other substrates, mainly in farm-based operations, where food wastes are co-digested with animal manures (Labatut & Pronto, 2018). Co-digesting enhances process stability and performance of the organic matter biodegradation. In addition, co-digesting recalcitrant manure with easily degradable food wastes improves the economic viability of the farm operation.

The supply chain and technology choice also impact its effect on emissions (Hermanowicz et al., 2011; Evangelisti et al., 2014). To this end, Vandermeersch et al. (2014) analyze the environmental performance of two food waste valorization[7] scenarios from a retail sector company in Belgium. Vandermeersch et al. (2014) introduced two scenarios:

(1) food waste is valorized in AD, producing electricity, heat, digestate, and food residue biomass material that can be used as fuel for the cement industry; and

(2) Some 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 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. Shirzad et al. (2019) studied electricity generation and GHG emission reduction potentials through AD in Iran in 2016 while focusing on agriculture and livestock wastes. 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. When considering a short-term horizon for generating electricity from different agriculture and livestock wastes, the reduction rate could achieve 24,153 thousand tons of CO_2eq/yr.

7. Identification of possible methods and estimation of likely feasibility of using biofuels other than biogas introduced to existing combustion turbines and pipeline infrastructure to generate electricity in NJ

i. Co-firing electricity generating facilities with dry biomass and liquid

Biomass co-firing is accomplished by combining biomass in a boiler with combustibles such as natural gas or coal to create electricity. This is one of the methods that can also be used in coal-fired plants to reduce non-renewable resources usage (Verma et al., 2017).

Direct co-firing, indirect co-firing, and parallel co-firing are the three co-firing technologies that are employed in power plants. In direct co-firing, biomass is the primary fuel that is supplied directly to the furnace. In this process, the biomass can be ground directly or separately with the primary fuel before being supplied to the furnace. Even though this is the simplest and least expensive technique (Agbor et al., 2014), it can lead to challenges including production of ash deposits (e.g., slagging and fouling), limited co-firing range, and inhibited use of various kinds of biomasses (Roni et al., 2017).

Indirect co-firing technology facilitates biomass to be co-fired in an oil or gas-fired system (Agbor et al., 2014). Indirect co-firing involves the installation of a separate gasifier to transform solid biomass into fuel gas, commonly referred to as syngas. The other type of indirect co-firing is related to pyrolysis, in which biomass fuel is subjected to a destructive distillation process to produce a liquid (bio-oil) and solid char. The bio-oil is then co-fired with natural gas in a station (Nieminen and Karki, 2007). The advantages of this technique outweigh direct co-firing, as (i) the ability to slag a boiler can be minimized, (ii) gasification shortens the time a gas spends in the atmosphere, and (iii) other base fuels like coal, oil, and natural gas can be utilized flexibly (Badour et al., 2012; Jiang et al., 2009).

[7] Valorization is defined as the act or process of giving, assigning, or enhancing value.

Parallel co-firing entails installing external biomass-fired boilers to make steam that generates electricity in the power plant. Parallel co-firing enhances the biomass percentage while avoiding biomass-related contamination issues. However, this technique has been proven to be more costly than the direct co-firing method since extra infrastructure is needed to support the system (Tillman and Harding, 2004). Electric efficiency in co-firing plants is, on average, higher than that of a dedicated biomass combustion system (IRENA, 2012).

Co-firing level refers to the amount of biomass fuel co-fired. According to the IRENA report (2012), the actual co-firing level used in most commercial facilities accounted for 5-10%, while biomass is believed to replace about 50% of the primary fuel utilized in a co-firing configuration. This shortfall came from the poor biomass quality, boiler type in plant installation, sulfur and nitrogen oxide emissions, and quality of by-product deposits.

ii. Generating electricity using biogas at biogas production sites and feeding this electricity into the grid

As discussed above, biogas is a mixture of methane, CO_2, and small quantities of other gases. Biogas for electricity generation offers an option that is flexible, demand-oriented, and assists in residual load balancing (Brosowski et al., 2016; Lauer et al., 2017; Purkus et al., 2018). Moreover, feeding biogas from production sites into the grid can help stabilize electricity grids, which can be overloaded by the fluctuation of electricity generation caused by use of variable renewable sources such as solar and wind power (Lemmer & Krümpel, 2017). Hybrid systems are also being currently developed where biogas plants are combined with other renewable sources such as solar or wind to produce electricity. Such hybrid systems can be explored in New Jersey particularly where biogas plants are combined with solar.

The advancement in biogas upgrading technology has also resulted in biogas production being upgraded to biomethane. Biomethane has similar qualities to natural gas with respect to methane, trace gases content, etc., and can be used in the grid as a substitute for natural gas to meet traditional end-user demand such as for power plants, industries, and households (Scarlat et al., 2018). To reach full grid injection potential, the biomethane and biogas facilities should be proximally situated to the natural gas grid. New Jersey can benefit from progress being made worldwide on biogas production ranging from commercial scale electricity biogas plants to small scale household digestors.

One can also learn from European experience in biogas production. European nations have emerged as global leaders in biogas production, with installed biofuel systems contributing to a total electricity capacity of over 10 GW, compared to a global electricity capacity of 16 GW (Scarlat et al.,2018). The contribution of biogas can meet a significant share of natural gas consumption; Germany, for example, obtains 12% of their natural gas consumption from biogas produced from manure generated by large livestock operations (Scarlat et al., 2018). The German biogas market is highly influenced by the supporting regulatory framework (Jin and Xu, 2021). The German Renewable Energy Sources Act (EEG) passed in 2000 is credited for promoting bioenergy development in the country (Yang et al., 2021). Under this act, the biogas sector became far more lucrative and biogas plant operators could receive almost twice as much returns as before. Between 2000 and 2017, the number of biogas plants in the country increased from 850 to 9,331, and cumulative installed capacity rose from 50 to 4800 MW/h (Daniel-Gromke et al., 2017; FNR, 2019; Thrän et al., 2020). With the 2009 EEG Amendment, the subsidy for small-scale plants increased, as the large-scale biogas plants led to problems such as a threat to food production and soil health (Gomeiro, 2018; Delzeit et al., 2012; Balussou, 2018).

The availability of biogas or bio-methane in the proximity of natural gas grids with their flexibility in supporting fluctuating, renewable power makes biogas a viable option for cleaner gas grids (Hahn et al., 2014; Vögelin, 2017). For New Jersey to increase biogas production and decarbonize the gas grids, supportive regulatory framework and policy incentives will be instrumental. The biogas sector needs to be made far more lucrative for both small operators and larger scale plants. For smaller operations, biogas can be used for running a micro-turbine for heating purposes and converting a portion of the energy to electricity. This electricity so generated can be used at the household or community levels, with excess energy produced fed to the electricity grid.

iii. Expanded generation of electricity by combined heat and power facilities and other small electricity generating facilities fueled by biofuels other than biogas

Combined heat and power (CHP), an efficient and clean technology, generates electric power and useful thermal energy from a single fuel source (USEPA, 2022b). By capturing the heat that would be wasted otherwise, and by avoiding distribution losses by being located at or near the site of energy use, CHP can achieve efficiencies higher than 80% compared to 50% for technologies such as conventional electricity generation and an on-site boiler (EPA, 2022c).

The enhanced energy efficiency through CHP for productive use of waste heat and reducing demands to the electric power grid has been incentivized by NJ Board of Public Utilities along with Fuel Cell installations. Approximately 87% of existing U.S. CHP capacity is located at industrial facilities such as chemical, refining, ethanol, pulp and paper, food processing, glass manufacturing, etc. (USDOE and USEPA, 2012). However, CHP installations can be expanded for commercial or institutional facilities such as schools, colleges and universities, hospitals, hotels, office buildings, nursing homes, prisons, and municipal facilities such as district energy systems and wastewater treatment facilities, and in military installations, prisons, etc. The CHP can also be promoted through utility partnerships with the CHP industry, innovative CHP policies and financing, as well as encouraging CHP in areas where new generation capacity is needed.

The increase in fuel use efficiency of CHP and other small electricity generating facilities with the use of biofuels can lead to reductions in GHG emissions and other criteria pollutants. Chiong et al. (2018) reviewed production and properties of biofuels and evaluated their combustion performances in gas turbines. The alternative fuels comprised of: i) straight vegetable oil (SVO) produced directly from mechanical, chemical and enzymatic extraction methods, ii) biodiesel produced via the process of transesterification of vegetable oil, iii) bioethanol produced from biomass via hydrolysis and fermentation processes, iv) bio-oil produced from pyrolyzing biomass along with synthesis gas, v) hydrogenated vegetable oil (HVO) produced from SVO and animal fats that undergo hydrogenation and isomerization processes, and vi) Fischer-Tropsch (FT) fuel produced from synthesis gas that contains H_2 and CO derived from pyrolysis and gasification processes. They found that for stationary power generation gas turbines, biodiesel, bioethanol, bio-oil and straight vegetable oil (SVO) can be used despite the variations in physical-chemical properties when compared to fossil fuels. Biodiesel has lower energy content and slightly higher viscosity and density than conventional fossil fuel, however, biodiesel can be a good replacement fuel for gas turbines. The similarity in physical properties between biodiesel and traditional fossil fuel allows its use in the gas turbine with minimal modification to the existing system. The SVO and bio-oil on the other hand have high viscosity and density which may result in reduced efficiency of fuel flow delivery, clogging of the atomizer orifice and would call for parallel development of fuel supply systems and atomization technologies to improve the fuel combustion (Chiong et al., 2018).

Bioethanol has a low flash point, low viscosity, and high vapor pressure, so use of bioethanol in gas turbines would require modification of fuel storage and delivery systems. The use of bioethanol in gas turbines would also increase operating costs as its calorific value is lower than natural gas or diesel. If needed, bioethanol may be blended with conventional or more viscous fuels rather than using neat bioethanol in gas turbines. Dual-fuel operation, bi-fuel operation or blending biofuels with conventional fuel can be used if biofuel availability or quality do not meet requirements. Bi-fuel feeds two different fuels during the combustion process together, while in the dual-fuel scenario two of three different fuels can be chosen (liquid-gas, gas-gas or liquid-liquid) during operation (Gralike et al., 2017).

Salman et al. (2020) retrofitted existing CHP facilities with pyrolysis and gasification thermochemical processes,and upgraded the intermediate bio-oil with hydrogen generated by onsite waste gasification. They investigated the technological and financial viability of such integrated plants and found that these plants were able to operate on approximately 180 days of the year by utilizing only excess heat from the CHP plant. Variations in power prices and CHP plant working hours, on the other hand, could reduce the system's economic benefits. Another study looked at how biorefineries upgrade pyrolysis products and the benefits of using bio-oil to supply vital transportation fuels and chemicals (Daraei et al., 2021). The study also emphasized the increased efficiency and cost savings of combining the pyrolysis process with other energy technologies in a single biorefinery.

Integration of pyrolysis oil production has the potential to be economically beneficial. Various technologies can be used to enrich the products acquired by pyrolysis. However, the conversion of bio-oil to a usable form has been a challenge despite the accessibility of certain techniques for bio-oil upgradation, such as hydrotreating, hydrocracking, esterification, and steam reforming. Improving the conversion of bio-oil to be more useable is important as these products have the potential to be used in place of fossil fuels (Gupta and Mondal, 2022).

A recent study suggests that a small-scale CHP system leads to lower emission and energy use through an integrated energy system (Falbo et al., 2022). The system is made up of a topping biodiesel-fired internal combustion engine (ICE) and a bottoming waste-heat recovery transcritical organic Rankine cycle (TORC). The TORC sub-system receives energy from the engine exhaust gas, while the ICE cooling circuit contributes energy to ensure low-temperature heat generation. There is also a thermal energy storage (TES) unit for utilizing the thermal surplus, as well as an auxiliary boiler. To determine the correct organic working fluid for the TORC sub-system, a preliminary analysis is performed. After, a biodiesel ICE-TORC combination system is used to meet a commercial center's thermal and electric needs. Hourly energy balances are examined for this purpose, and then supplemented with an annual techno-economic study. The researched system promises a primary energy savings of 16.7% and a payback time of 8.4 years.

Facilities that use biofuels—especially those with a lower heating value—in gas turbines can experience the added benefit of increased gas turbine performance due to the added mass flow in the cycle (Mikielewicz et al. 2019; Sallevelt et al., 2013: Seljak et al., 2020). The research on biofuel use in gas turbines have focused predominantly on fuel properties and its combustion characteristics, emissions and the effect of fuel, and combustion products on the turbine (IEnagi et al., 2018), however, the techno-economic aspects and site-specific factors can considerably influence biofuel utilization in turbines, and must be explored further in context for the State of New Jersey.

7. Alternative uses for biogas that could take precedence over electric generation: building/space heating

Instead of being used in the effort to reach the goal of the production of 10.1 TWh/year of electricity, biogas, once introduced to the gas pipeline infrastructure, could be combusted directly to provide space heating, industrial process heat, hot water, etc. While this use would not contribute to the 10.1 TWh/year goal and thus would not contribute to the needed firm capacity to help accommodate the intermittency of solar and wind power, it would nevertheless provide GHG reduction benefits.

An upside of solar and wind's intermittency, i.e., potential excessive electricity generation at certain times of the day or season, could represent another way in which a different type of renewable natural gas could play a role in GHG emissions reduction. This is the so-called "power to gas" concept (AGF, 2019) in which hydrogen produced by electrolysis of water with the use of surplus electricity could be combined with carbon dioxide that had been captured from fossil fuel combustion sources to produce methane that could then be introduced to the pipeline system. This would enable use of existing natural gas infrastructure and combustion technology without the issues such as metal embrittlement and need for retrofits that could accompany an attempted transition to hydrogen as a way of accommodating surplus electricity production from intermittent sources.

8. Alternate uses of available biomass that could take precedence over its use to produce biogas

i. Aviation biofuels:

The aviation sector holds much promise for the use of advanced biofuels. The European Union proposes an EU-wide minimum tax rate for polluting aviation fuels to reduce CO_2 emissions by 55% by 2030. In addition, several U.S. aviation companies show strong interest in renewable fuels, including United Airlines, whose hub is in Newark, NJ. U.S. civilian aviation consumes over 600 million gallons of jet fuel per year (US DOE/EIA, 2019a), a sizeable market by any standards. Besides, it is one of the areas emphasized by federal agencies: "The U.S. Department of Energy Bioenergy Technologies Office (BETO) empowers energy companies and aviation stakeholders by supporting advances in research, development, and demonstration to overcome barriers for widespread deployment of low-carbon sustainable aviation fuel (SAF). SAF made from renewable biomass and waste resources can deliver the performance of petroleum-based jet fuel but with a fraction of its carbon footprint, giving airlines solid footing for decoupling greenhouse gas (GHG) emissions from the flight. The U.S. Department of Energy is working with the U.S. Department of Transportation, the U.S. Department of Agriculture, and other federal government agencies to develop a comprehensive strategy for scaling up new technologies to produce SAF on a commercial scale." [https://www.energy.gov/eere/bioenergy/sustainable-aviation-fuels] Skaggs, et al. (2018) found that with conversion by hydrothermal liquefaction, biomass wastes have the potential to produce up to 22.3 GL/y (5.9 Bgal/y) of a biocrude oil intermediate that could be upgraded and refined into a variety of liquid fuels, in particular renewable diesel and jet fuel, and could potentially meet nearly a quarter of current U.S. demand for these fuels. Production of jet fuel and other liquid fuels from biomass can have negative impacts, however. A literature review (Jeswani, et al., 2020) noted that some studies have found that reductions in GHG emissions from biofuels are achieved at the expense of other impacts, such acidification, eutrophication, water footprint and biodiversity loss.

ii. Carbon sequestration:

Carbon sequestration can significantly reduce CO_2 emissions to the atmosphere and is essential to any climate mitigation scheme. Possibilities for carbon sequestration (i.e., its removal from the air) include a range of measures that can be broadly categorized as engineered and biological approaches.

One form of an engineered approach is geologic carbon sequestration which typically involves capturing CO_2 from fossil fuel combusting facilities' exhaust gas, pressurizing CO_2 until it becomes a liquid and then injecting it into porous rock formations in geologic basins. Variations of this approach involve direct air capture of CO_2 and subsequent deposition in geological formations. Other forms of carbon sequestration include biological carbon sequestration, which refers to the storage of atmospheric carbon in vegetation, soils, woody products, and aquatic environments. Biological sequestration methods that involve little engineering include improved ecosystem stewardship such as reforestation and afforestation (i.e., planting new forests), conservation agriculture (e.g., no-till systems), and coastal restoration. Biologically based methods that also require some engineering include biochar (which can be produced via pyrolysis of biomass) addition to soils, increased use of wood in buildings, and bioenergy with carbon capture and storage (Field & Mach, 2017).

Examples of large-scale bioenergy with carbon capture and storage projects (BECCS) include the ZEROS and DRAX projects. The ZEROS project introduced two oxyfuel combustion waste-to-energy (WtE) power plants to Texas. The project's capture target is 1.5 Mt of CO_2 per year. Another example is Bechtel and Drax, who work together to develop large-scale BECCS. The formerly coal-fired Drax power station in the U.K. now uses processed biomass fuel. With a capacity of 4.3 Mt per year, it is the world's single largest bioenergy capture plant. This project is part of a more extensive program to eventually deploy CCS on all four DRAX bioenergy power units by the mid-2030s. Biomass power generation is an opportunity for BECCS. Many, but not all projects, intend to store the captured carbon in deep saline formations and dedicated geological storage (Global CCS Institute, 2021).

Nevertheless, carbon sequestration strategies raise concerns. These include the potential for engineered carbon sequestration to be costly and risky and for biological carbon sequestration to be temporary and difficult to quantify.

iii. Soil amendments:

One of the attractions to soil carbon sequestration is that carbon stocks are most depleted in lands currently under agricultural management. Human activity over the past 12,000 years has reduced terrestrial carbon stocks on the order of 145 Gt from woody biomass and soils, 133 Gt from soil carbon stocks, and 379 Gt from other biomass. These estimates of historical losses indicate a hypothetical though highly impractical upper bound for restoring terrestrial carbon stocks through adjustments to land management (NAP, 2019).

However, even if this upper bound limit is out of reach, there is reason for optimism that, if phasedown of fossil fuel emissions begins soon, improved agricultural and forestry practices, including reforestation and steps to improve soil fertility and increase its carbon content may provide much of the CO_2 extraction that will be necessary (Hansen, et al., 2017). Land under cultivation or in rangeland or forestry management does not require conversions and does not compete for land resources. Besides, soil organic matter/soil carbon content increases are beneficial to soil health and fertility.

10. Assessment of viability of biofuels options to meet NJ's net neutral electricity generation goals

The options that could enable expanded production of electricity from biomass fuels in New Jersey span a continuum ranging from 1) currently feasible, 2) reasonably possible with current technologies, 3) technically feasible with current technologies but requiring major new efforts, to 4) hypothetical; requiring major new efforts and new technology.

The total amount of biomass generated in New Jersey that could be available each year for conversion to energy in some form has been estimated to be from 1.9 million tons (NREL, 2016) to 4.1 million tons (NJAES, 2015). Much of this material is waste wood or woody material, also termed cellulosic wastes. Harvesting all the energy potential of all of this biomass and converting it to electricity is not feasible with current technology. This is because the carbon in this woody material is present in refractory substances such as cellulose and lignin. These substances resist degradation and conversion to methane without high inputs of energy such as heat. On the other hand, using the wet organic portion of biomass waste to produce biogas through anaerobic digestion, and combusting this biogas to generate electricity is feasible and is already being done to a small extent. Unless new methods are developed, the feedstocks of choice for biogas production are thus food waste and other wet organic wastes such as wastewater treatment plant sludge.

The SAB has searched scientific literature and other sources of information in an effort to gain a better picture of the degree to which existing biogas production could be expanded and to clarify the issues, challenges, and complexities associated with such an expansion. Significant uncertainties remain, making quantitative predictions speculative. However, the SAB has gathered an approximate categorization of the range of electricity production that could result from biogas production that could be accessible to New Jersey by 2050. Uncertainties of these numbers are not well defined but should be assumed to be at least plus or minus 50%.

The availability of biogas as CH_4 for combustion at New Jersey natural gas facilities by 2050 was estimated under multiple scenarios. At this time, the availability of approximately 60 million m^3 of biogas annually appears feasible, if 50% of food wastes covered by NJ's food waste law are collected and used to produce biogas through anaerobic digestion, if the estimated production from Trenton Biogas continues, and if the projected production from the proposed Linden Renewable Energy facility materializes. This amount of biogas, if injected into the existing natural gas pipeline system, could produce 0.3 TWh of yearly electrical production, assuming the current average efficiency for NJ natural gas combustion facilities is unchanged.

With current technologies, it is reasonably possible for 150 million m^3 of biogas to be available annually. This amount of biogas could lead to 0.7 TWh of yearly electrical production. This estimation includes reported and projected production from Trenton Biogas and the proposed Linden Renewable Energy facility, and conversion to biogas from 50% collection of all food wastes generated in the state, including residences and facilities not covered by NJ's food waste law, and 50% of potential generation from NJ landfills and wastewater treatment plants.

This report focuses on the availability of biofuels primarily from waste products in New Jersey using current technologies. The potential range for electricity production could be expanded if other sources are considered. Lignocellulosic wastes could contribute to the quantity of available biogas if thermal conversion is perfected, or another new technology is developed. Importing biogas from other states could also support additional electricity generation. However, the SAB could find no valid way of estimating the volume of biogas available annually and the associated yearly electricity production possible for these hypothetical situations.

It should be noted that collection of food waste that is currently disposed of as municipal solid waste, regardless of whether this waste is generated by facilities subject to New Jersey's food waste law or the waste collection is expanded to include residential and other small generators' food waste, and its processing by dedicated anerobic digestion facilities implies a separate waste stream, which would eventually lower the amount of methane produced by landfills. It would take many years for landfill gas production to decline however, because much of the gas generated is from waste already in place.

Separate collection of food waste, unless it could displace regular waste collection by, for example, shifting weekly collections to biweekly collections alternating between food waste and other waste, will also require some energy expenditure, which, whether it is derived from direct combustion of fuels (e.g., diesel-powered collection vehicles) or use of electricity, will detract from the overall greenhouse gas benefit. It should also be noted that, for food-waste generated methane to reach its maximum production potential, competing uses of food waste and other wet organic waste such as direct composting to yield soil amendments will have to divert only a relatively small portion of the wastes, and reductions in the amount of food waste generated will have to be minimal.

Overall, unless massive quantities of food waste and other wet organic waste are imported to the State, or dramatic new technology is developed to transform biomass into gaseous fuels it is hard to see how even a greatly expanded system to process food waste and to extensively capture biogas produced by wastewater treatment plants and landfills could produce enough biogas to be capable of adding much more than 1 TWh per year of electricity to NJ's production.

11. Implications and Recommendations

i. Implications

The SAB concludes that, unless technology yet to be developed changes the picture, achieving 10.1 TWh per year from biogas produced in the State from biomass wastes is unrealistic, and basing the plan to achieve the 80x50 goal in part on this production calls into question the validity of that part of the plan in its current form.

The SAB must stress, however, that A significant production of biomass from food and other wet organic waste is possible, and its introduction to the existing natural gas distribution system should not be excessively problematic. Even considering that this production will incur some energetic and economic costs, offsetting the emissions of methane that would otherwise occur with current management of wastes is likely to have a net greenhouse gas emission benefit because of methane's high global warming potential relative to the CO_2 released upon its combustion.

Emissions benefits of using biogas derived through anaerobic digestion of wet organic wastes versus landfilling these wastes can be modeled using EPA's Waste Reduction Model (WARM). A recent study (Dill, 2021) also estimated these benefits for Bergen County, NJ using various assumptions and calculations (see Section 4, above). A simplified run of the WARM model using its default parameters indicates that managing these wastes with AD will reduce greenhouse gas emissions in the range of 0.5 to 0.6 $MTCO_2e$ per ton of food waste (Aucott, 2022). WARM also indicates that a similar degree of GHG reduction results from composting or incineration vs. landfilling (unlike landfilling, these management methods also do not release methane). WARM further indicates that source reduction of food waste yields by far the biggest emissions benefit when compared to any waste management method; on the order of 4 $MTCO_2e$ per ton of food waste reduced.

If an approximate WARM-derived estimate of 0.55 $MTCO_2e$ reduced per ton of food waste managed via AD instead of landfilling is projected to the entire state, and with the assumptions (as discussed in Section 4, above) that approximately 1,000,000 tons of food waste are generated annually in New Jersey, and that all of this food waste is source separated and managed with AD, the total GHG emissions benefit would be in the range of 1,000,000 x 0.55 metric tons of carbon dioxide equivalent, or approximately 550,000 $MTCO_2e$ per year. Since the state's current GHG emissions are approximately 97,000,000 $MTCO_2e$ per year, statewide emissions would be reduced by approximately 0.57%.

Achieving practical and equitable organic materials management in the State will require a balancing of various interests that may not be consistent with maximizing the production of biogas. There are several reasons why biogas production from wastes could be lower than even the relatively conservative general estimates presented in section 10, above. One of these is that there are important, environmentally friendly, and economically attractive competing uses for some wastes. Many carbon containing wastes such as agricultural wastes and woody plant matter are currently returned to the soil directly or composted and applied to soils with beneficial impacts, and their exclusion from their current role in favor of biogas production could exacerbate the loss of soil organic matter with deleterious results.

Biomass wastes also may be a prime feedstock for the production of liquid fuels, especially jet fuel and diesel fuel. Aircraft and heavy-duty construction and freight hauling equipment will be harder to electrify than light duty vehicles. Available biomass may find a more attractive market for liquid products than for biogas, and in this manner play a key role in decarbonizing the economy.

Another reason for lower biogas production expectations is that there are efforts in play to lower the generation of food waste, and these efforts could conflict to some degree with efforts to glean more food waste for biogas production. New Jersey's Food Waste Reduction Law, P.L. 2017, c. 136 (S3027), established a goal of reducing food waste by 50%, based on 2017 food waste estimates, by the year 2030. It should be noted that reducing food waste, if done in a way that makes quality food available that would otherwise be wasted, could play an important role in reducing the persistent problem of food insecurity and food inequity in the State.

ii. Recommendations

The SAB analysis finds that by 2050, up to 1 TWh of electricity could conceivably be produced from currently available biogas and biofuel feedstocks available in NJ. This number (i.e., 1 TWh of electricity) was based on the 0.7 TWh of electricity that was stated to be available with current technology in Section 10 but was rounded up to 1 TWh of electricity to account for the uncertainty associated with the value. This could contribute towards meeting the state's goal of 17 GW of firm capacity based on biogas, biofuels and hydrogen that would be capable of generating 10.1 TWh of electricity by 2050. The SAB has not researched the possibilities of hydrogen, which could be a potentially significant source of electricity for the state as well. The SAB recommends further research and analyses in this area to meet the state's GHG reduction goal by 2050.

When assessing the feasibility of using biomethane as the means of delivering primary energy to power plants, it should be considered in the competitive economic context of related energy carriers such as hydrogen and ammonia, where much innovation is underway (Clark et al., 2022; Bhandari & Shah, 2021; Hochman et al., 2020; Andrews, 2006). Such innovation could lead to a restructuring of the electricity grid if, for example, hydrogen becomes an important energy carrier (Shih & Haile, 2022; Andrews, 2006).

Although emissions benefits can be estimated with models, modeled outcomes are dependent on input parameters, which can be highly uncertain. This dependence emphasizes the importance of obtaining comprehensive data on AD facilities operating in New Jersey. The current biogas systems in the state are installed primarily to manage wastes but could improve profitability for operations through energy and co-product sales, nutrient recovery, and avoided energy costs. In addition to data on AD facilities, more data on waste, food waste, agricultural waste, and composting would also be valuable.

New Jersey has an excellent opportunity in the years ahead to gain a much clearer picture of the costs and benefits of the production of biofuels from biomass via large-scale biogas facilities currently or planned to be operating in New Jersey. Practical foci for data acquisition are the functioning Trenton Biogas facility and the proposed Linden Renewable Energy facility. The SAB recommends that NJDEP adapt existing data gathering capacity, and put in place additional data gathering procedures as necessary. If done in association with existing applicable permitting programs, it would allow for the assessment of all aspects of the energy use and methane production from these facilities as well as the energy use of the associated waste-gathering and processing systems. These data should enable the NJDEP to gain a much clearer picture of the greenhouse gas emissions benefits of biofuels produced from wet organic wastes. The SAB further recommends that the NJDEP expand access to these data to researchers and other interested parties by making such data publicly available.

Also, existing biogas producing plants in other states and nations, especially in the European Union, should be researched. Section 3 of this report includes a list of known facilities in different regions. The SAB encourages the DEP to seek data that sheds light on overall lifetime net carbon emissions from these facilities and their associated systems.

The introduction of algae and its use in biogas production shows much potential, albeit still at the research and development stage. Further investigation into the potential for farming macroalgae is recommended. The numerous benefits from algae include carbon sequestration, reduction of ocean acidification, and habitat generation for many marine creatures, including fish. Some examples of such systems include bicarbonate-based integrated carbon capture and macro-algae production, systems integrated algae bioenergy carbon capture and storage, and macroalgal ocean afforestation (Leong et al., 2021). Kelp farms co-located with shellfish aquaculture in Maine have been found to raise pH and oxygen concentration while absorbing excess nutrients, thereby preventing eutrophication and improving growing conditions for shellfish (Price and Arnold, 2019). Seaweed farming is also a geoengineering remedy for climate mitigation, whereby dumping the algae grown on the ocean floor is used to stop the carbon from returning to the atmosphere (Hochman and Palatnik, 2022).

The State will need to carefully track and evaluate technological developments of other power sources such as wind, solar, biogas, and next-generation nuclear and geothermal. Energy generated from the anaerobic digestion of wastewater sludge and CHP should be expanded. Further research, including a better understanding of barriers to digesters that prevent full utilization of anaerobic digester capacity and digestion of feedstocks is recommended. High initial project costs pose challenges for the widespread investment and scaling up of biogas systems. The state should consider designing a comprehensive program geared towards WWTPs focused on promoting current incentives, reviewing the efficacy of available incentives, and implementing support programs. This program should be prepared to make long-term modifications, enact supporting regulatory updates, and increase education and outreach. Actions to increase the degree to which biogas receives awareness related to renewable electricity, fuel, carbon reductions, and water quality improvements beyond NJ BPU energy efficiency programs (e.g., renewable energy credits, carbon offsets, nutrient trading credits) can further the commercial viability of different biogas and biomethane production pathways in the State.

As electrification of buildings and transportation proceeds in the coming years and beyond, New Jersey will need considerably more electricity. However, the expansion of renewables will not occur without difficulties, from dealing with intermittency and storage to scaling up and mitigating the transition costs to a sustainable and resilient electricity grid. Energy issues will increasingly be of high priority in the State. Therefore, the DEP should consider augmenting the SAB's Standing Committee on Climate and Atmospheric Sciences with a sub-committee focusing primarily on energy issues or establish a separate standing committee on energy.

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