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Biogas and Biomethane Production from Anaerobic Digesters and the Influences of Policies and Carbon Credit Systems on the Biogas Markets in the United States and the European Union

TESI DI LAUREA MAGISTRALE IN
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Abstract

Global warming from greenhouse gases (GHGs) has become a major concern within the world and many policies and procedures have been adopted to avoid additional emissions and even decrease emissions below pre-industrial levels. One of the most emitted GHGs is that of methane, one of the main gases found in biogas, which naturally occurs in landfills, wastewater treatment plants, and livestock farms. Dairy farms are particularly pollutant due to the methane expelled by cows during their digestive process as well as their manure when left to ferment in uncovered lagoons. Anaerobic digestors offer a solution to capturing the highly pollutant methane and through various upgrading methods can be purified to natural gas grid quality containing >99% methane, known as biomethane or renewable natural gas (RNG). Today, biomethane offers project owners various revenue streams, including the gas itself in addition to environmental attributes thanks to incentive programs tied to carbon credit systems.

The biogas markets in Europe and the United States have developed at different rates, with the European market being much more mature yet plateauing in recent years due to policy shifts such as the latest Renewable Energy Directive (RED III). There is a call upon the European biogas industry to provide 35bcm of biogas by 2030, roughly 10% of Europe's natural gas consumption, which will likely come to fruition given current geopolitical events between Europe and Russia as the continent looks to wean itself off Russian imports. On the contrary, RED III specifically calls for the phase out of biogas by 2045; however, this may be revised given current circumstances and depending on the installation rate of other renewable technologies such as solar and wind. Initially the biogas markets in Europe were driven by incentive programs with a heavy focus on energy crops, especially in Germany. The market is still seeing growth in other countries while growth in Germany is stagnating. Meanwhile, in the US the biogas market is relatively young and is growing rapidly. There have been 8,574 livestock related biogas projects identified by the American Biogas Council, a majority of the nearly 15,000 potential projects identified. Programs such as the Low Carbon Fuel Standard (LCFS) in California and the Renewable Identification Number (RIN) offer RNG projects additional incentives for offsetting emissions and decreasing the carbon intensity of the transportation sector, respectively.

Key-words: Anaerobic Digesters, Biogas, Biomethane, Carbon Credit Systems, Emissions, Greenhouse Gases

Abstract in italiano

Il riscaldamento globale causato dai gas serra (GHG) è diventato una delle principali preoccupazioni nel mondo e sono state adottate molte politiche e procedure per evitare emissioni aggiuntive e persino ridurre le emissioni al di sotto dei livelli preindustriali. Uno dei gas serra più emessi è quello del metano, uno dei principali gas presenti nel biogas, che si trova naturalmente nelle discariche, negli impianti di trattamento delle acque reflue e negli allevamenti. I caseifici sono particolarmente inquinanti a causa del metano espulso dalle mucche durante il loro processo digestivo e del loro letame quando lasciato fermentare in lagune scoperte. I digestori anaerobici offrono una soluzione per catturare il metano altamente inquinante e, attraverso vari metodi di potenziamento, possono essere purificati alla qualità della rete del gas naturale contenente >99% di metano, noto come biometano o gas naturale rinnovabile (RNG). Oggi, il biometano offre ai proprietari dei progetti vari flussi di entrate, incluso il gas stesso oltre alle caratteristiche ambientali grazie a programmi di incentivi legati ai sistemi di crediti di carbonio.

I mercati del biogas in Europa e negli Stati Uniti si sono sviluppati a ritmi diversi, con il mercato europeo molto più maturo e stabilizzato negli ultimi anni a causa di cambiamenti politici come l'ultima Direttiva sulle Energie Rinnovabili (RED III). C'è un appello all'industria europea del biogas a fornire 35 miliardi di metri cubi di biogas entro il 2030, circa il 10% del consumo di gas naturale in Europa, che probabilmente si realizzerà visti gli attuali eventi geopolitici tra Europa e Russia mentre il continente cerca di svezzarsi dalle importazioni russe. Al contrario, RED III richiede specificamente l'eliminazione graduale del biogas entro il 2045, tuttavia, questo potrebbe essere rivisto date le circostanze attuali e in base alla velocità di installazione di altre tecnologie rinnovabili come il solare e l'eolico. Inizialmente i mercati del biogas in Europa erano guidati da programmi di incentivi con una forte attenzione alle colture energetiche, soprattutto in Germania. Il mercato è ancora in crescita in altri paesi mentre la crescita in Germania è stagnante. Nel frattempo, negli Stati Uniti il mercato del biogas è relativamente giovane e sta crescendo rapidamente. Ci sono stati 8.574 progetti di biogas relativi al bestiame identificati dall'American Biogas Council, la maggior parte dei quasi 15.000 potenziali progetti identificati. Programmi come il Low Carbon Fuel Standard (LCFS) in California e il Renewable Identification Number (RIN) offrono ai progetti RNG incentivi aggiuntivi rispettivamente per compensare le emissioni e ridurre l'intensità di carbonio nel settore dei trasporti.

Parole chiave: Digestori anaerobici, Biogas, Biometano, Sistemi di credito di carbonio, Emissioni, Gas serra

Contents

Introduction

In a time where information is the tips of nearly everyone's fingertips people are becoming more informed about global issues. One of the biggest issues faced in today's world is that of global warming and climate change. There are many policies and agreements in place such as the Paris Agreement which seek to limit the global warming to just 2°C by 2050, however, their success depends greatly on the adoption of renewable technologies and other GHG reducing, capturing, or sequestering technologies. One of these technologies, not so often in the spotlight, is that of anaerobic digesters, which take feedstocks such as food waste, animal manure, energy crops, crop residues, and others and produce biogas from them. The feedstock undergoes anaerobic digestion while in the digester (AD) for approximately 2-60 days depending on the technology, after which, the produced biogas can be used to generate electricity or upgraded to natural gas quality and injected into the grid for consumption by households and industries. The upgraded biogas, known as biomethane, is regarded as a renewable energy source because the CO_2 which is later emitted from its combustion was recently sequestered by the plants (through photosynthesis), which ultimately make up the feedstock, whether used directly as food/crop waste and residues, or after digestion by humans and livestock in wastewater treatment plants or manure feedstock-based ADs, respectively.

The renewable aspect of biogas offers particularly interesting opportunities for the anerobic digester technology since it may then profit not only from selling the gas itself (or electricity and heat in the case of CHP plants) as well as carbon credits for qualifying as emission offset projects. In some instances, renewable natural gas projects involving anaerobic digesters and dairy cattle can be highly profitable and even have a negative carbon intensity. In Europe and the US however, the industries are at different stages of maturity and show different potentials for growth in the upcoming decades which will be highly influenced by policies aimed at climate change prevention and decarbonization of various industries and sectors.

1 Anaerobic Digesters

1.1 How Anaerobic Digesters Work

An Anaerobic Digesters (AD) are a specific type of biodigester. They produce biogas through the decomposition process of organic material in an environment absent of oxygen. The biodegradable source, also referred to as the feedstock, plays a great role in the chemical composition of the biogas produced. Common feedstocks include animal manures, wastewater/biosolids, food wastes, and other organics. Different feedstocks are also more suited for distinct types of digesters which will be discussed further in section 1.2. (3)

1.1.1 Advantages and Disadvantages of AD

In a world of increasing energy demands and sustainability goals, ADs offer many benefits to the global energy sector. The main advantages and disadvantages of ADs are shown below in Table 1.1.1. (1)

Table 1.1.1 Advantages and Disadvantages of AD's

Advantages	Disadvantages
Form of Renewables Energy	Sensitive to temperature
Reduction in greenhouse gas emissions (GHG)	Sensitive to feedstock composition
Recovery of value from previously considered waste	Complexity
Scalability for larger applications	Uneconomical for small farms
Multiple products	Biogas is corrosive

With policy makers across the globe aiming to decrease emissions of GHGs and improve sustainability in the energy sector, ADs are a potential solution to do so in the right environment. ADs earn the classification as a renewable energy source because they have a net carbon dioxide emission equal to zero. This is possible thanks to the fact that the carbon dioxide emitted by the combustion of the methane in the biogas collected by the AD is equal to the carbon dioxide absorbed from the atmosphere by the original plant or crop. For example, the crops that undergo photosynthesis to grow collect carbon from the atmosphere, in the case of a manure fed AD, these crops are digested by livestock and supplied to the system in the form of manure to undergo digestion. When manure is left in settlement ponds/lagoons for extended periods of time in between irrigation, as is the case in many farming operations, the manure will undergo natural anaerobic digestion leading to the release of methane and nitrous oxide directly into the atmosphere. Note, methane and nitrous oxide have 25 and 300 times more global warming potential than carbon dioxide, respectively. (2) Thanks to these benefits, biogas is regarded as a renewable source of energy.

In addition to the environmental benefits of AD's, there is also an opportunity for profit making. Through an upgrading process the biogas can be purified to natural gas quality, at which point it takes on the name renewable natural gas (RNG) can be injected into the natural gas pipeline grid and used by homes and industries for various applications. RNG can also be used immediately in an internal combustion engine (ICE) or a combined heat and power plant (CHP) to generate electricity and heat. Some farms implement this technique to generate their own electricity, giving them grid independency. The profitability of biogas is discussed further in Chapters 3 and 4. (3)

In the case of farms found in the United States of America, ADs are scalable for the larger farms which range from 4,000-20,000 head of cattle. However, the minimum quantity of 4,000 head of cattle leaves many smaller farms left untouched and thus GHG's escape from the lagoons. In some instances, the manure feedstocks from multiple farms can be combined by pipeline or virtual pipeline to reach the minimum requirement. However, in many cases this is uneconomical. Until an arrangement for small scale farms becomes more economical, they will remain as spectators in the RNG industry. (3)

Additionally, ADs allow for the collection of multiple products. Previously, farmers were left with only one useful byproduct from their animals: manure, which they would spread on crop fields as fertilizer. Now with ADs they can profit from 3 byproducts. (4)

- RNG collected from their manure while utilizing the AD
- The liquid and solid byproducts of the AD act as a fertilizer
- Recycled bedding from the solid byproducts of AD

Recycled bedding, also known as Recycled Manure Solids (RMS), or Dried Manure Solids (DMS) have their own advantages. With the increase in costs of traditional bedding options such as saw dust, straw, wood shavings, etc. farmers can decrease costs while using a more sustainable product. (5)

Some disadvantages to ADs include their sensitivity to the temperature and feedstock composition. The digestion of the feedstock in the anaerobic environment is thanks to the bacteria residing there. Shifts in temperature outside of the optimal range for the type of bacteria present of the optimal design of the digester cause severe changes in the RNG production. Similarly, the feedstock plays an important role in the RNG production and therefore the pH and chemical composition are important to ensure a healthy, productive digester.

Biogas collected from digestion has an approximate chemical make-up of 60% methane (CH4) and 39.9% carbon dioxide (CO2) and trace amounts of hydrogen sulfide (H2S) making it corrosive by nature. This adds complexity to the design of anaerobic digester plants. In some cases of direct power generation, the biogas can be combusted in an ICE with minimum upgrading. However, in the case of injection into the natural gas pipeline grid the biogas must undergo a rigorous upgrading process to achieve natural gas quality, hence the term renewable natural gas. Without the upgrading process the biogas would corrode and metal pipes, tanks, or fittings it encountered in the grid. (6)

1.1.2 Feedstock

The feedstock greatly effects the design on the AD system. There are four main categories from which feedstock can be obtained from. (7)

- Agriculture: Manure from various animals, swine, cattle, sheep, etc.
- Municipal: Human excreta and biowaste from water treatment plants
- Food waste: Food from households, restaurants, resorts, buffets, etc.
- Industrial waste: Byproducts of premade foods and products

A key indicator for biogas production is the biological methane potential (BMP) of the feedstock. BMP is by definition the maximum possible biogas produced per mass of solid or volatile solid matter. Feedstocks may be described by their composition of total solids, which is comprised of volatile solids and inorganic materials. The volatile solids are made up of the three macronutrients, protein, carbohydrates, and lipids, which dictate their BMP. Figure 1.1.1 shows the breakdown of a generic feedstock. (1)

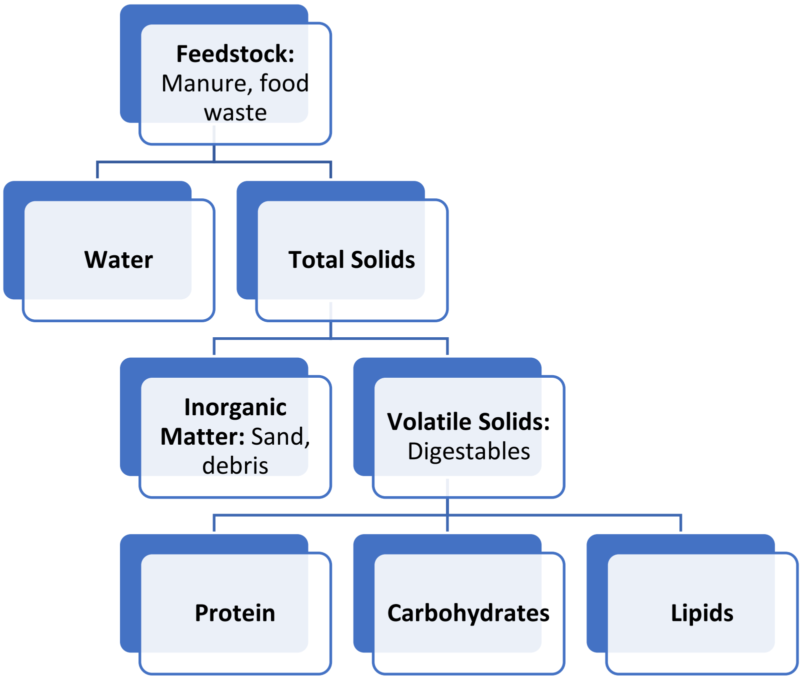

Figure 1.1.1 Outline of the make-up of a generic feedstock. Adapted from Vögeli (1)

Total solids (TS) are a percentage of the raw feedstock, while volatile solids (VS) are a percent of the total solids (TS). The VS can further be divided into the three principal macronutrients of proteins, carbohydrates, and lipids. The percent makeup of feedstocks varies greatly and are highlighted below in Table 1.1.2.

Table 1.1.2 TS and VS of various feedstocks. (1)

Substrate	TS (% of raw waste)	VS (% of TS)	Literature Source
Spent fruits	25 – 45	90 – 95	Deublein and Steinhauser (2011)
Vegetable wastes	5 – 20	76 – 90	Deublein and Steinhauser (2011)
Market wastes	8 – 20	75 – 90	Deublein and Steinhauser (2011)
Leftovers (canteen)	9 – 37	75 – 98	Deublein and Steinhauser (2011)
Overstored food	14 -18	81 -97	Deublein and Steinhauser (2011)
Fruit wastes	15- 20	75 – 85	Gunaseelan (2004)
Biowaste	25- 40	50 – 70	Eder and Schulz (2007)
Kitchen waste	9 – 37	50 – 70	Eder and Schulz (2007)
Market waste	28 – 45	50 – 80	Eder and Schulz (2007)

The methane quality (concentration of methane in biogas) of a feedstock is proportional to the quantity of proteins and lipids present in the feedstock, feedstocks rich in soluble carbohydrates do not enhance biogas quality. (8) However, manure feedstocks rich in carbohydrates do have a higher BMP than feedstocks with more lipids. In the case of manure feedstocks, the ratio of proteins, carbohydrates, and lipids present in the VS is directly related to the diet of the livestock from which it came and the livestock itself. In a study published by Waste Management & Research concerning dairy cows, it was concluded that BMP was proportional to carbohydrate content, inversely proportional to lipid content, and indifferent with the fluctuations found in the protein levels of the feedstock. The study compared the BMPs of mono-digestion of manures from lactating cows, dry cows, and young cows, with enhanced co-digestion of these manures with waste milk and waste grains. Again, because the AD is a living environment filled with anaerobic micro-organisms there is a sensitivity to feedstock changes and therefore caution should be taken when drastically altering feedstock characteristics in the field. Experimentally, the study proved that BMP can be enhanced with proper ratios of manure and milk waste from various types of cows. The study also showed that the addition of grain waste to the manure feedstock negatively impacted the BMP of the feedstock, in terms of L of CH_4 per kg^{-1}VS. Of course, in an industrial setting more feedstock will yield more total methane production hence the use of most waste available from the farm in the AD. However, the input of the feedstock will greatly affect the organic loading rate (OLR) and the hydraulic resistance time (HRT) of an AD. (9)

1.1.3 Organic Loading Rate

As shown below in Equation 1.1 the organic loading rate (OLR) is simply the mass of volatile solids entering the digester per the volume of the reactor multiplied by time.

$$OLR = \frac{m_{VS}}{v_{reactor} * t} \qquad \left[\frac{kg}{mm^3 day}\right] \tag{1.1}$$

Techniques such as stirring, optimal temperature, and an overall healthy AD environment can lead to higher OLRs. 3

Table 1.1.3 Typical OLRs for unstirred and stirred ADs.

Unstirred AD	Stirred AD
< 2 $kg_{VS}/(m^3*day)$	4-8 $kg_{VS}/(m^3*day)$

1.1.4 Hydraulic Retention Time

The hydraulic retention time (HRT) is simply the amount of time the feedstock spends in the AD. Ideally the feedstock is present in the AD long enough so that all the potential methane may be produced from the volatile solids while not exceeding this minimum amount of time and slowing down the process. HRT is defined as reactor volume dived by daily volumetric input of feedstock. (3)

$$HRT = \frac{V_{reactor}}{\dot{V}_{daily\ input}} \quad [days] \tag{1.2}$$

HRT is greatly affected by temperature and typically ranges between 10-40 days. Shorter HRTs are associated with higher AD temperature which are known as thermophilic conditions and have a temperature range between 45-60°C. Longer HRTs are associated with mesophilic conditions which have a temperature range of 30-40°C. Thermophilic reactors are faster yet more unstable than mesophilic reactors. Therefore, a mesophilic reactor is more appropriate in instances where feedstock characteristics are difficult to predict or transient, such as food wastes. Dairy farms tend to keep nutrition constant and thus very rarely experience great changes in feedstock quality making them candidates for short to medium length HRTs. (3)

1.1.5 Other Factors

rarely Attention should be brought to additional factors including C:N ratio, particle size, pH. The C:N ratio is defined as the ratio of carbon to nitrogen in organic materials. Ideally C:N will range between 16-25 in an AD. In the case of too low C:N ratios there will be ammonia accumulation which equates to high pH levels that may exceed 8.5. A high C:N ratio can yield less gas production due to methanogens consuming the nitrogen present too rapidly. Typical pH range for an AD is between 6.5-7.5 pH. If the pH is too acidic it will cause acidification wreak havoc on the microorganisms. A very high pH can be caused by a high OLR. There are in fact different stages during anaerobic digestion in which pH levels vary. There is a husbandry between pH, C:N ratio, and OLR which cannot be ignored. Lastly, particle size can affect the consumption rate of the nutrients by the bacteria. In the case of animal manure this is not of concern; however, grinding processes may need to be added to achieve particle sizes less than 5cm with food waste in order to maximize surface area. (3)

1.1.6 Stages of Anaerobic Digestion

There are four main stages to anaerobic digestion:

1. Hydrolysis
2. Acidogenesis
3. Acetogenesis
4. Methanogenesis

Figure 1.1.2 below shows the inputs and products of each stage.

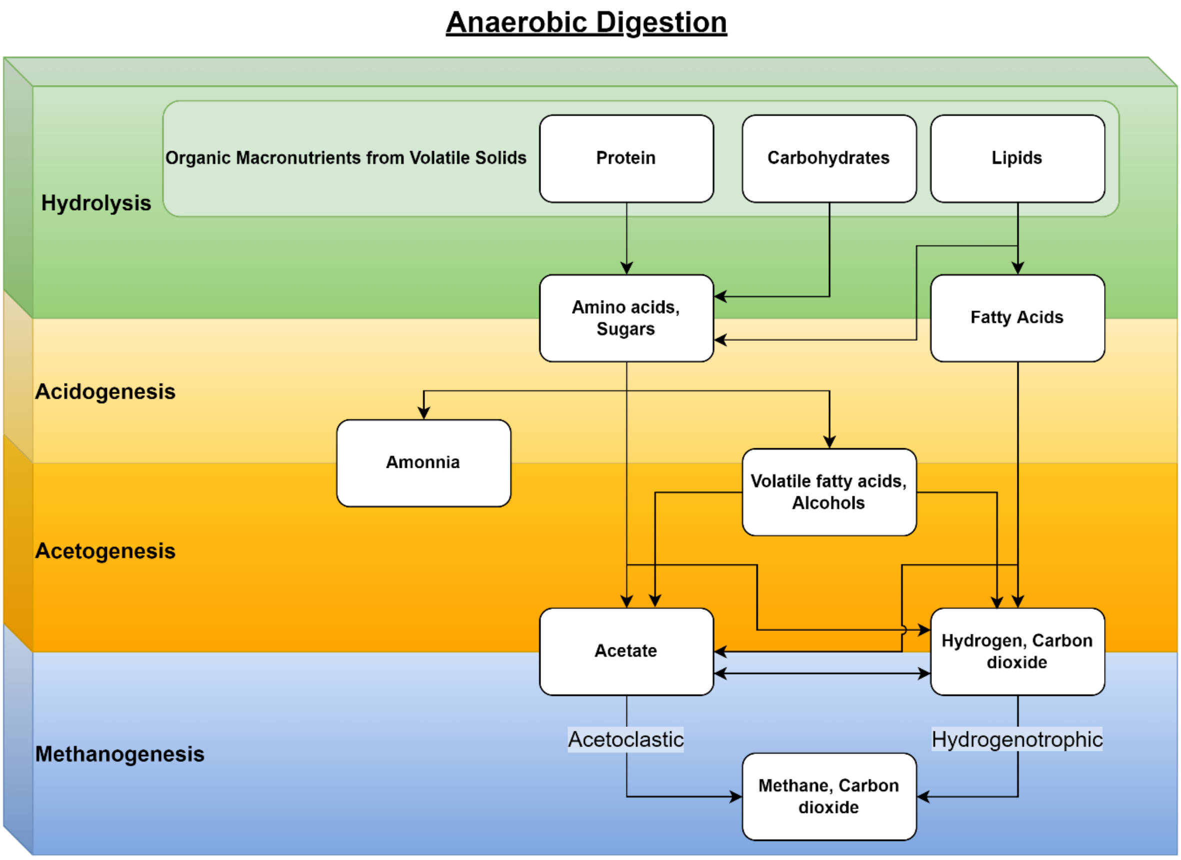

Figure 1.1.2 Stages of anaerobic digestion Adapted from Vögeli (1)

1.1.7 Hydrolysis

In the first step of anaerobic digestion hydrolysis occurs. During the hydrolysis process polymeric organic matter (proteins, polysaccharides, and lipids) are broken down into monomers (sugars, fatty acids, and amino acids) by hydrolases released by the microorganisms present in the AD. Estrases, glycosidases, and peptides are the three main hydrolases involved with the hydrolosis process and they catalyze the cleavage of ester bonds, glycoside bonds, and peptide bonds, respectively. *Firmicutes* (*Clostridia*, *Bacilli*), *Bacteroidetes* and *Gammaproteobacteria* are the bacteria which carry out the hydrolysis process and provide the needed hydrolases. These same bacteria can carry out the acidogenesis process as well. (10)

1.1.8 Acidogenesis

The monomers are further converted and yield both gaseous and non-gaseous products. The non-gaseous products include short-chain fatty acids, alcohols, aldehydes, while the gaseous products are only carbon dioxide and as shown previously in Figure 1.1.2. Monosaccharides transform into pyruvate through either glycosis or the 2-keto-3-deoxy-6-phosphogluconate pathway. From the pyruvate state various types of fermentation may occur to yield the products of ammonia, volatile fatty acids, alcohol, acetate, hydrogen, and carbon dioxide. Fatty acids may also undergo the same transformation as monosaccharides through fermentation or they may experience beta-oxidation where they become acetate and hydrogen. Amino acids experience deamination before undergoing oxidation and transforming into non-gaseous acetate, propionate, butyrate, valerate, and glutamate and gaseous carbon dioxide and hydrogen. (10)

1.1.9 Acetogenesis

Similarto the acidogenesis stage, CO_2, H_2, and acetate are formed during the acetogenesis stage by acetogenic bacteria. However, rather than forming from amino acids, sugars, and fatty acids, they are formed from volatile fatty acids and alcohols. CO_2 and H_2 may become methane through a hydrogenotrophic process. Likewise, acetate transforms into methane through an acetoclastic process. Interestingly, during acetogenesis it is also possible for CO_2 and H_2 to convert to acetate, or for acetate to oxidize back into CO_2 and H_2. Acetate is the majority intermediate product during anaerobic digestion, ahead of CO_2 and H_2, but different bacteria use different processes to create methane, hence the possibility for multiple pathways. (10)

1.1.10 Methanogenesis

During the methanogenesis stage of anaerobic digestion the products of the previous three stages are converted to methane (CH_4), CO_2, and acetic acid (CH3COOH) by methanogens, which are methane producing bacteria. The reduction of CO_2 by H_2 is one possible pathway of methane creation. Methane may also be created through the cleavage of acetic acid molecules in which ethanol and CO_2 form methane and acetic acid. The reduction of CO_2 by H_2 into methane; however, is restricted by the theoretical limit of H_2 produced within the anaerobic digester. Estimations reveal that approximately 30% of the methane produced comes from CO_2 reduction by H_2 while the remaining 70% is produced from acetate. (10)After the methanogenesis stage, the gases produced are extracted from the AD and the liquid and solid byproducts are removed for fertilization in agriculture practices or recycled bedding. (10)

1.2 Types of Anaerobic Digesters

Anaerobic digestors are designed and constructed to best convert the feedstock to methane, therefore, ADs can take on numerous designs, shapes, and sizes and many crossovers are possible. The contents of the feedstock, temperature, volume, and location all dictate in some way the AD design. The primary ways to describe an AD from a mechanical perspective are mixed vs. unmixed and batch loaded vs. continuous fed. Co-digestion is another characteristic of some ADs and refers to the ability of a digester to accept multiple feedstocks such as food waste and manure, combining difficult to digest materials with a more rich, easily digestible feedstock. (11)

1.2.1 Plug Flow

Plug flow digesters are one on the most common types of digesters thanks to their simplicity, adaptability to the different environments, and ability to handle common livestock manures from dairy cattle and swine. They operate on the simple principle that the feedstock mass flow entering the system pushes out the effluent, or older sludge, which retains a "plug" shape and moves throughout the corridors of the AD in unison. (11) Plug flow digesters are also suitable for any climate because they can be equipped with a heating system. (12)Plug flow digesters are able to accommodate feedstocks with a total solids makeup by percent (TS) between 11-13%. They are also operated under thermophilic conditions allowing for an HRT as short as 15 days. Although co-digestion is not optimal in plug flow ADs, they are still very common because of the many large scale livestock farms found in the US. Plug flow digesters can be both unmixed or mixed. Plug flow digesters are typically five times longer than they are wide. (11)

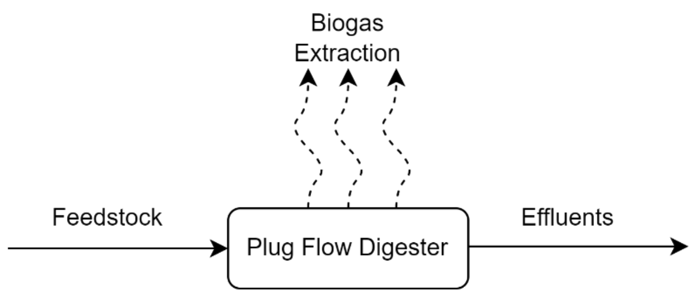

Figure 1.2.1 Plug flow digester schematic

1.2.2 Complete Mix

Complete mix digesters are also very commonly constructed for livestock manure and thanks to their mixing components they are also suitable for co-generation, making them excellent candidates for locations where more than one feedstock may be present. Complete mix ADs prefer feedstocks with a slightly lower TS ranging from 3-10% and often have a HRT of 20-30 days. Complete mix digesters are simply large tanks which may face sizing challenges as TS approaches the lower limit and tank volume is maximized to accommodate more feedstock. Increasing tank temperature to the thermophilic range of 45-60°C can aid in decreasing the HRT to as low as 15 days. The mixing process and warmer thermophilic temperatures allow for a shorter HRT. (11) Figure 1.2.2 below shows a complete mix digester schematic.

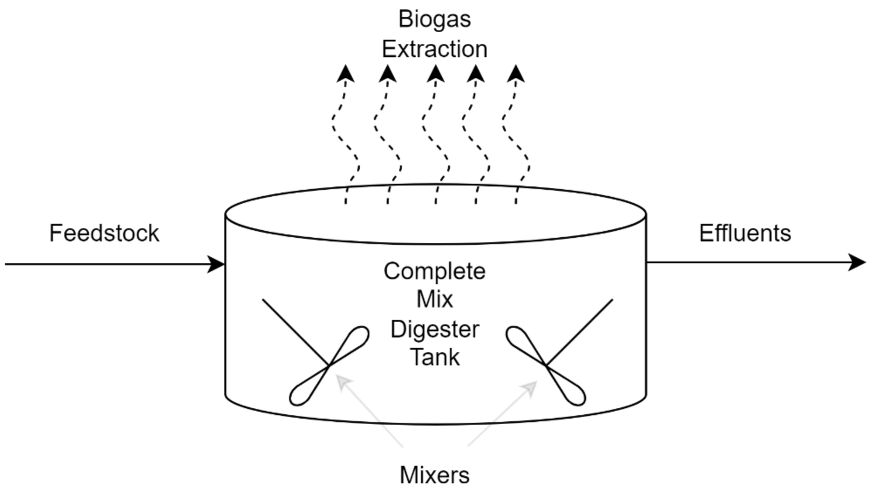

Figure 1.2.2 Complete mix digester schematic

1.2.3 Lagoon

Lagoon style digesters can hold large volumes of feedstock due to their simple construction being built into the ground and a non-permeable gas tight cover. In some instances the bottoms of lagoons are also lined to prevent leakage from polluting the environment. Due to the lack of cover insulation lagoons are not heated and operate in the mesophilic temperature range of 30-40°C. Lagoons also experience seasonal temperature changes but are not susceptible to drastic daily temperature swings thanks to their own thermal inertia. Due to their susceptibility to environmental temperatures, lagoon ADs are best suited for warmer climates. In some instances, mixing devices may be added to lagoons to promote better circulation of the feedstock in the lagoon and increase methane production. Due to the high HRT of lagoons ranging from 40-60 days and their lower operating temperature, cogeneration in lagoons are not optimal. One other caveat to lagoon ADs is the use of a second lagoon to control the discharge rate of the primary lagoon with digestion occurs. (11) The effluent from the digester lagoon are expelled into an effluent storage lagoon as shown in Figure 1.2.3.

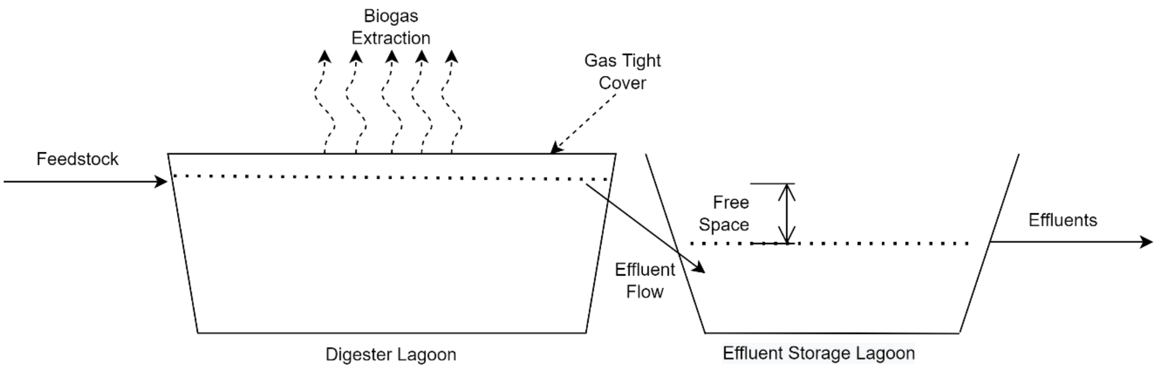

Figure 1.2.3 Lagoon digester schematic

1.2.4 Suspended Media

Up-flow Anaerobic Sludge Blanket (UASB) and Induced Blanket Reactor (IBR), as shown in Figure 1.2.4 and Figure 1.2.5, are both suspended media digesters and are a much less common type of AD but boast faster HRTs and are suitable for co-generation. UASBs operate best with more diluted feedstocks containing less than 3% total solids while IBR is better suited for 6-12%. Within suspended media digesters there is a constant upward flow of the feedstock such that smaller particles are removed from the mix while larger particles remain inside the tank. The larger particles are coated in a film of microorganisms which perform the digestion of the biomass. Effluent can even be recycled back into the digester tank to keep a constant upward flow if there is a lack of new feedstock. An artificial media such as sand may even be added to the AD to provide microorganisms to form a biofilm on, these are known as fluidized bed digesters. An individual suspended media digester is limited in size by the tank but as a whole the system is scalable with the opportunity to add more tanks. (11)

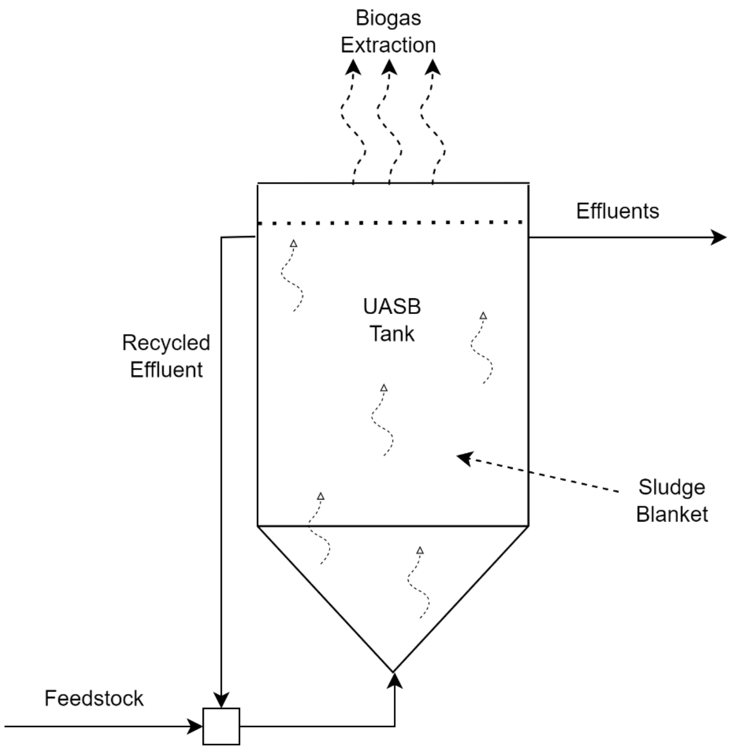

Figure 1.2.4 Up-flow Anaerobic Sludge Blanket schematic

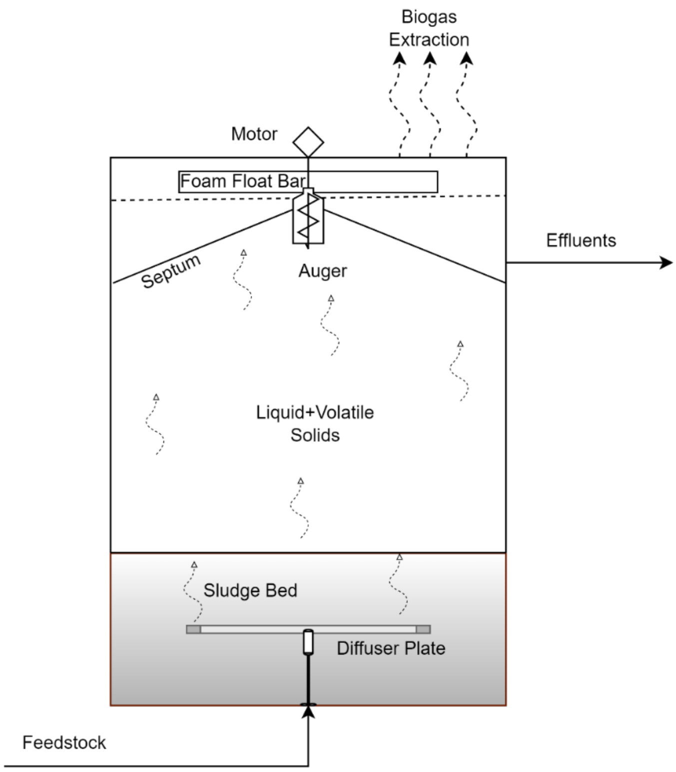

Figure 1.2.5 Induced Blanket Reactor schematic

1.2.5 Fixed Film

Fixed Film also commonly referred to as Attached Media Digester or Anaerobic Filters are fast rate, small digesters. They typically have an HRT less than 5 days and are suitable for cogeneration. Due to the fixed, filter/media inside the column they require a feedstock with a low total solids content between 1-5%. A solids separation process is commonly performed on the feedstock prior to entering the digester to avoid clogging the fixed media. The media itself acts a growing environment for the microorganism on which they establish a biofilm to digest the manure/feedstock. Fixed film digesters also use an effluent recycling technique like UASBs and IBRs to promote a constant, steady upward flow of the biomass through the filters. (11) Figure below shows the Fixed Film Digester.

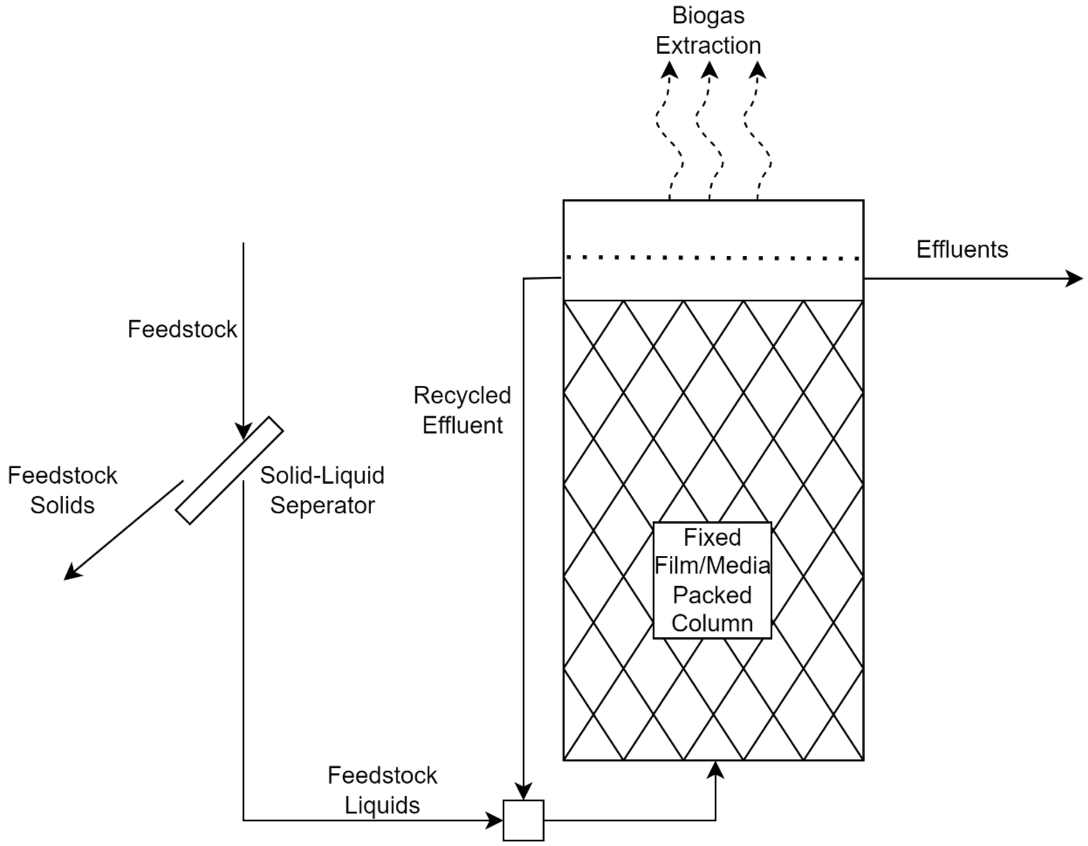

Figure 1.2.6 Fixed Film Digester schematic

1.2.6 Batch Reactors

Anaerobic Sequencing Batch Reactors (ASBR) operate in 4 stages:

1. Filling
2. Reacting
3. Settling
4. Decanting

Batch digesters can handle a low total solids feedstock ranging from 2.5% to 8% and work well for cogeneration while boasting a low HRT of approximately 5 days. According to Douglas W. Hamilton from Oklahoma State University, ASBRs are great for feedstock like wastewater from sugar plants or even swine manure due to their low solids content. (13) The ASBR tank is filled and then the feedstock reacts to produce biogas. After which the solids settle from the solution and can be recycled as fertilizer. Lastly, the tank is drained before restarting the process. Some drawbacks to ASBRs that have limited their popularity include construction challenges and managing the settled solids content. The cyclic draining and filling of the tank behaves like a piston and stresses the membrane lid on top of the tank, regardless of material type (rigid or a flexible membrane). Above 1% total solids the ASBR faces challenges with solids settling to the bottom of the tank and avoiding digestion. Jet mixing has been attempted to prevent premature solids settling. (11) Figure 1.2.7below depicts the changes in feedstock levels in the tank during each stage and the solids distribution within the feedstock during each stage.

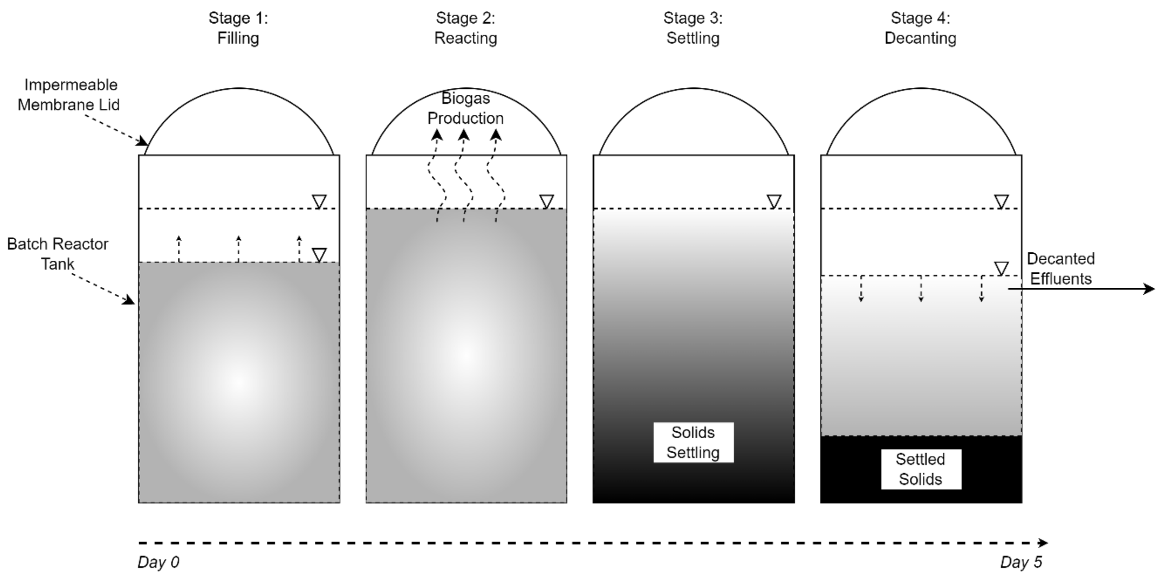

Figure 1.2.7 Batch Reactor stages

1.2.7 High Solids Fermentation

High Solids Fermentation (HSF) digesters are the fastest of digesters with just a 3-day HRT. They are also capable of cogeneration while accepting feedstocks with upwards of 18% TS. Common feedstocks include high TS manures mixed with waste grains, silage, corn, food waste, and even byproducts from ethanol and biodiesel production. (14)

Shown below is a Table 1.2.1 summarizing the characteristics of the discussed ADs.

Table 1.2.1 AD types and their characteristics. (14) (for number of systems: 15)

AD Type	Feedstock Total Solids (%)	HRT (days)	Suitable for Co-digestion	Approximate Number Operational in US
Plug Flow	11-13	15+	Not optimal	99
Complete Mix	3-10	15+	Yes	91
Lagoon	0.5-3	40-60	Not Optimal	112
Up-flow Anaerobic Sludge Blanket (UASB)/ Induced Blanket Reactor (IBR)	<3% for UASB 6-12% for IBR	<15	Yes	8
Fixed Film/Attached Media Digester/ Anaerobic Filters	1-5%	<5	Yes	2
Anaerobic Sequencing Batch Reactors (ASBR)	2.5-8	<5	Yes	3
High-Solids Fermentation	18+	2-3	Yes	5

Additionally, in Figure below there is the total number of each digester type displayed. Covered lagoon digesters are the most common in the US with 117 plants, followed by complete mix digesters and mixed plug flow digesters with 102 and 94 plants, respectively. In total there are 355 ADs in the US, 38 of which are under construction and the remaining of which are fully operational.

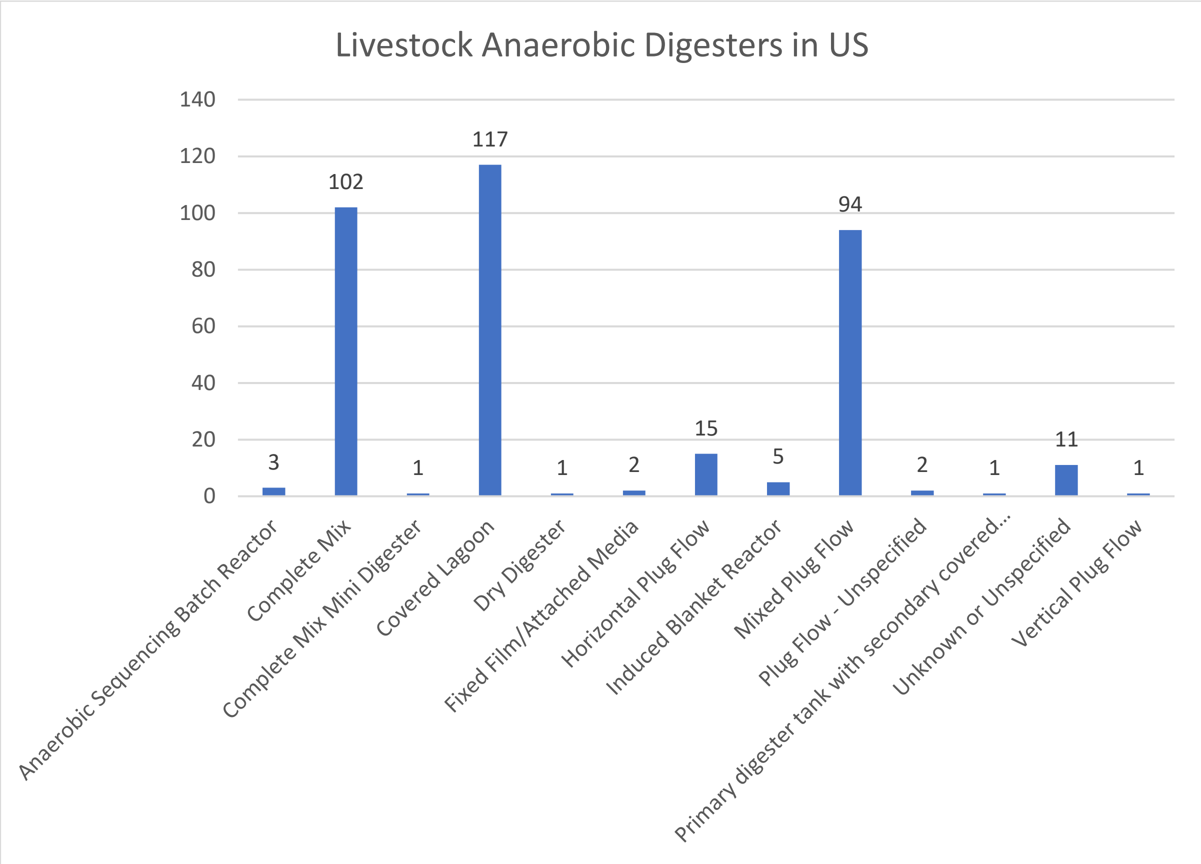

Figure 1.5. Count of anaerobic digesters under construction or in operation in US

Dairy manure is the most common feedstock for ADs in the US with 83% (294 AD's) of all digesters using solely dairy manure. An additional five ADs use cogeneration of dairy manure with poultry and swine manures.

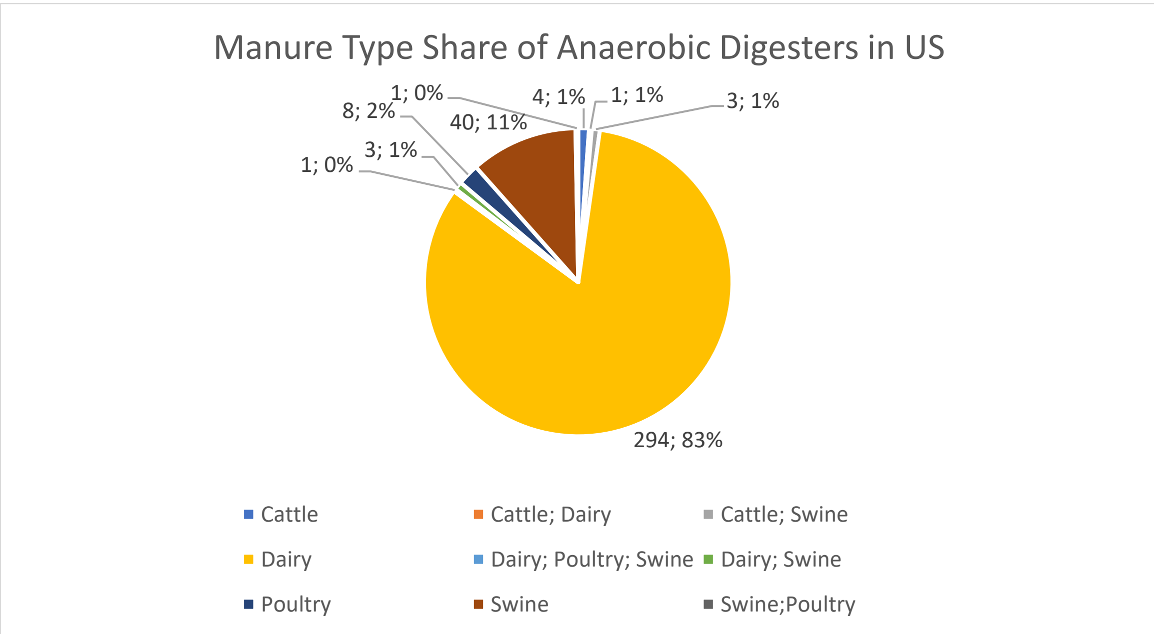

Figure 1.2.7 Manure share of ADs in US dominated by dairy cattle manure followed by swine manure.

1.3 Biogas Circular Economy

As mentioned, some of the main advantages of anaerobic digesters are their useful byproducts. The possibility of recycling biogas digestate byproducts makes it an active player in a circular economy since it can be used to fertilize soils. (16) An example of a biogas circular economy is shown below in Figure 1.3.1.

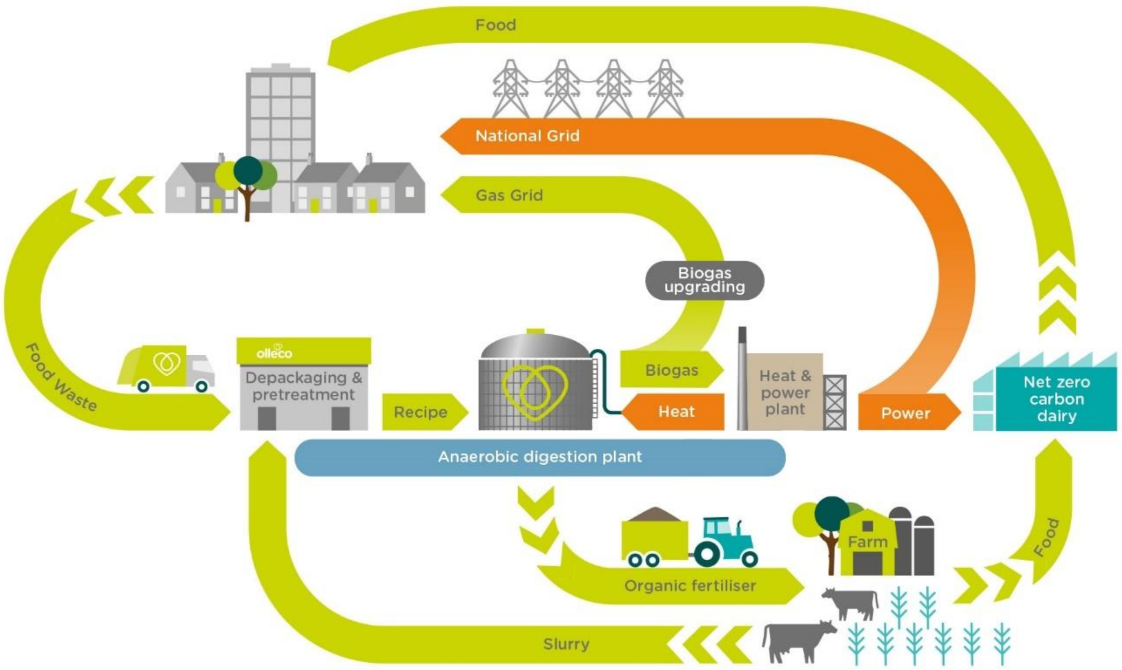

Figure 1.3.1 Biogas Circular Economy (17)

The anaerobic digester is the heart of the circular economy shown above in Figure 1.3.1. In this example food waste is used in conjunction with dairy cow manure slurry as the feedstock for cogeneration anaerobic digester to produce biogas which is upgraded to RNG quality to meet grid standards. The digestate is then recycled back to the farm as organic fertilizer, which in turn will be used to grow crops to feed the dairy cows and/or humans. The biogas is also used in a CHP plant which produces power for the national grid and recycles its waste heat back to the AD to maintain optimal temperatures for the biogas producing bacteria. The circular economy is completed, and net zero fuel source has been used and harmful GHGs have been avoided. *(17)*

Upon extraction of the biogas from an AD it can be used directly to generate heat and electricity in a cogeneration power plant or upgraded to natural gas quality and injected directly into the natural gas pipeline grid. Factors such as location, costs, and demand play a role in determining how the biogas will be used and is unique to each farm. As shown in Figure 1.3.1, the majority of ADs in the US use their biogas for cogeneration followed by electricity, compressed natural gas (CNG), and pipeline gas. Cogeneration of electricity and heat is the most common end use for biogas from currently operating or under construction ADs in the US. However, due to the market value of RNG, new ADs are designed to upgrade the biogas to RNG quality and inject it into the natural gas pipeline network. Figure 1.3.2 shows the share of each end use of the already operational and under construction ADs in the US and confirms an overall trend towards pipeline injection as the end use. (18)

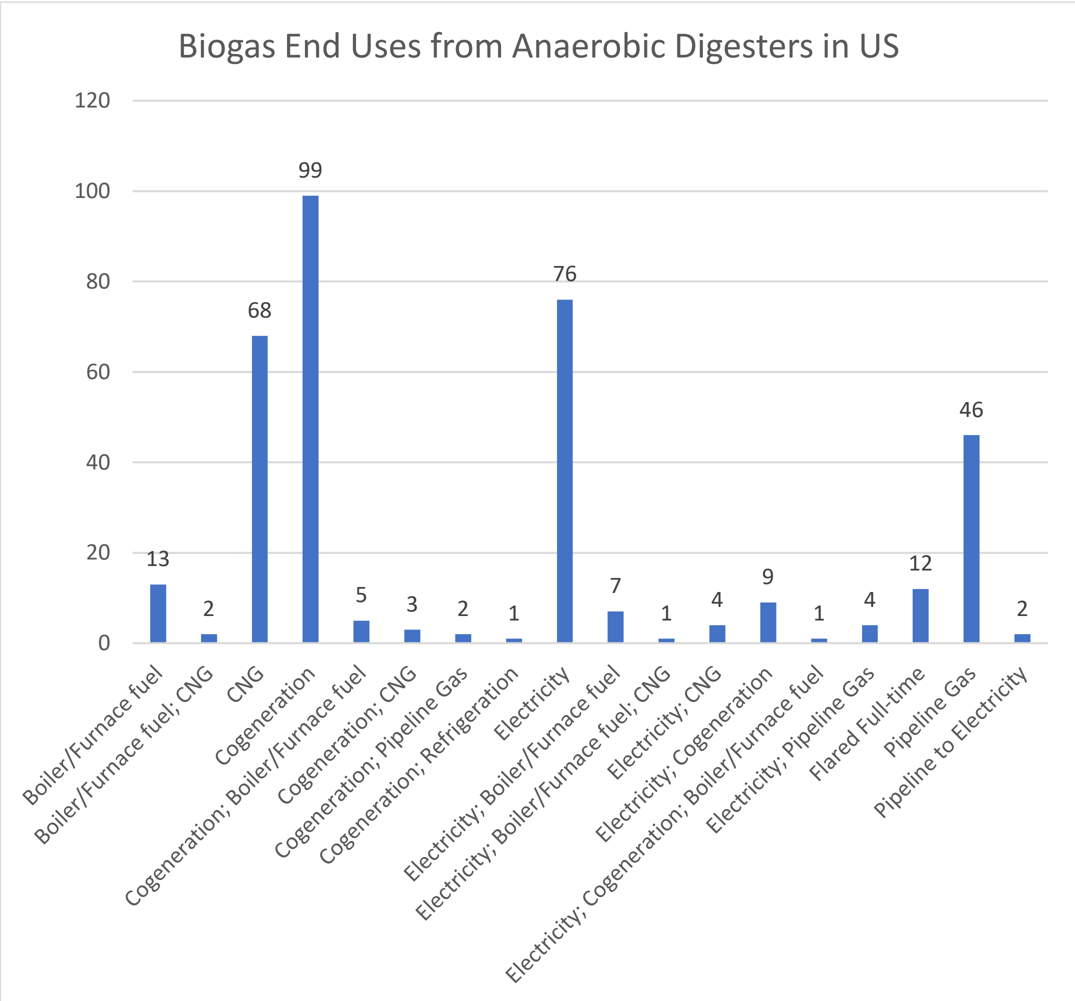

Figure 1.3.1 Number of anaerobic digesters for end uses

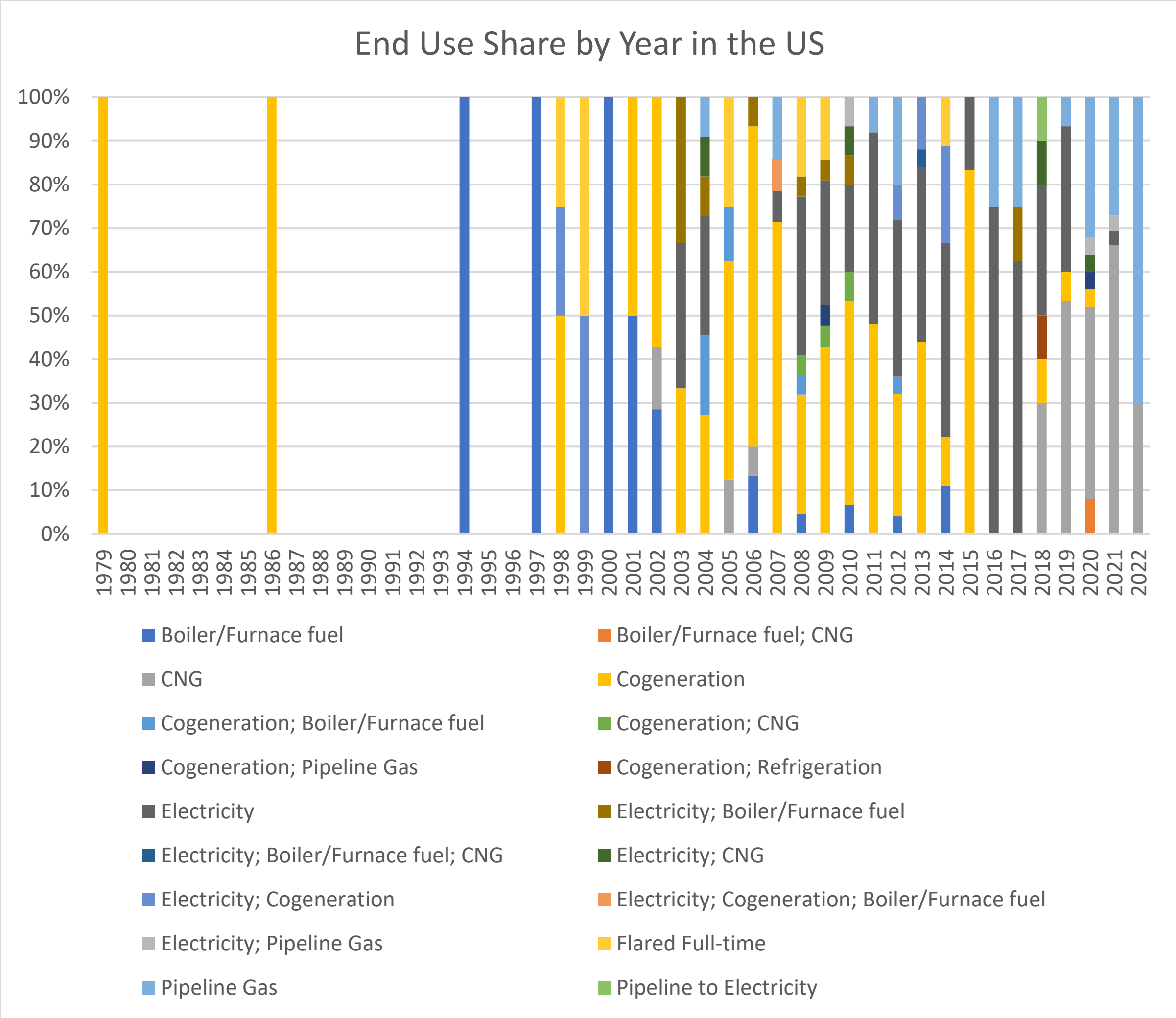

Figure 1.3.2 End use of biogas from AD's share by year in US

From Table 1.3.2 since 2020 pipeline gas has been a major end use for biogas in the US market. As of 2022 it is the top end use with seven projects under construction with an end use as pipeline gas and the remaining three projects destined for compressed natural gas (CNG).

2 EU vs. US Biogas Production

2.1 Biogas Production in Europe

In terms of biogas production, the latest report from EurObserv'ER published in 2020 shows that across the EU28 countries a total of 16.6Mtoe of biogas primary energy was produced in 2019. From that biogas, 62.5Twh of electricity were generated. (16)

There are three common types of biogas production methods used in Europe and are defined by the International Energy Agency (IEA) as the following (16):

- methanation of wastewater treatment plant sludge ("sewage sludge gas")
- non-hazardous waste storage facility biogas ("landfill gas")
- methanation of non-hazardous waste or raw plant matter ("other biogas")

A fourth category also exists which the IEA refers to as "biogases from thermal processes" and in this case biogas is generated from the pyrolysis or gasification of solid biomasses such as wood. This is a very uncommon methodology however and only makes up for approximately 1% of the biogas collected in Europe. (16)

The term "other biogas" refers to anaerobic digester plants and is the leader in production share of biogas in EU28. With that being said, anaerobic digesters accounted for 75.8% of the total biogas produced in EU28 for 2019, a 0.5% increase from 2018. Landfill gas is the second largest producer making up 13.6% of the market share, a 0.9% decrease from the previous year's 14.5%. Lastly, sewage sludge gas increased from 9.3% in 2018 to 9.6% in 2019. (16) The production by method is depicted below in Figure 2.1.1.

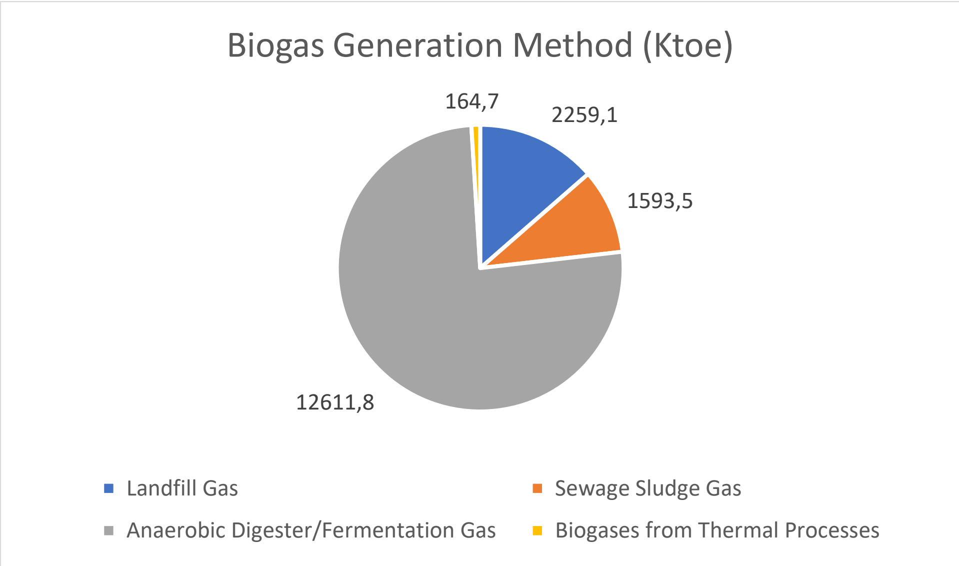

Figure 2.1.1 Biogas generation methodology share in EU28 for 2019. (16)

Unfortunately, while writing this report the data from EurObserv'Er's Biogas Barometer latest report does not highlight the distribution of primary energy production of various biogas stocks but solely their overall growth and trends. (16)

Figure 2.1.2 shows the annual biogas production throughout Europe and highlights additionally the share of each production method.

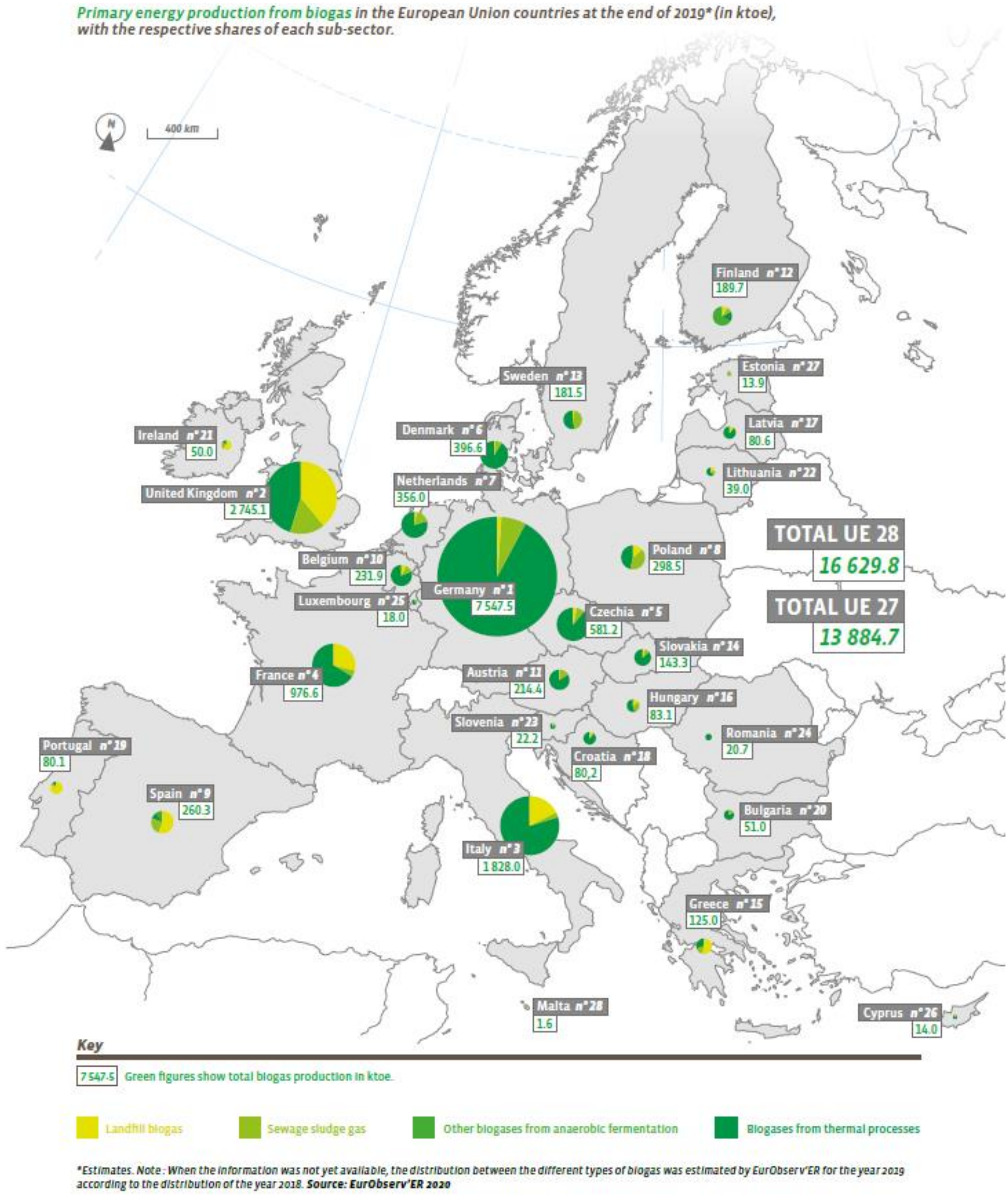

Figure 2.1.2 Biogas production method by country

As seen in Figure 2.1.2 leads Europe in biogas production with 7547.5Ktoe followed by the UK and Italy with 2745.1Ktoe and 1828Ktoe, respectively. Table 2.1.1 shows the production levels for all EU28 countries for each method.

Table 2.1.1 Primary production from biogas in EU28 for 2018 and 2019.

Country	Landfill Gas	Sewage Sludge Gas	Anaerobic Digester Gas	Biogases from Thermal Processes	2018 Total (Ktoe)	Landfill Gas	Sewage Sludge Gas	Anaerobic Digester Gas	Biogases from Thermal Processes	2019 Total (Ktoe)
Germany	115.8	492	6950.4	0	7558.2	102.7	487.2	6957.6	0	7547.5
United Kingdom	1168.1	387.1	1171.9	0	2727.1	1082	426.1	1237	0	2745.1
Italy	333.5	51.7	1500	6.8	1892	322.2	50	1449.1	6.6	1827.9
France	298.9	36.7	543.9	0	879.5	284.2	44.6	647.8	0	976.6
Czechia	21.3	44	538.5	0	603.8	20.4	43.6	517.1	0	581.1
Denmark	4	23.9	291	0	318.9	5	29.8	361.8	0	396.6
Netherlands	12.7	58.2	255.3	0	326.2	10.4	62.7	282.8	0	355.9
Poland	38.9	116.1	133.4	0	288.4	40.2	120.2	138.1	0	298.5
Spain**	149.3	66.3	24.2	25.2	265	145	64.4	23.5	27.4	260.3
Belgium	18.9	25.5	176.4	7.4	228.2	17.5	26.4	183.3	4.7	231.9
Austria	1.9	25	200.1	0	227	1.2	33.7	179.4	0	214.3
Finland	17.9	17.5	32.6	118.4	186.4	15.5	17.8	30.4	126	189.7
Sweden	4	78	93.8	0	175.8	5.9	77.8	97.8	0	181.5
Slovakia	6.8	13.3	128.7	0	148.8	6.5	12.8	124	0	143.3
Greece	64.8	17	31.1	0	112.9	67	20	38	0	125
Hungary	12.7	28.5	50.8	0	92	11.4	25.8	45.9	0	83.1
Latvia	7.6	2	77.4	0	87	7.5	2.1	70.9	0	80.5
Croatia	5	3.2	65.4	0	73.6	5.5	3.5	71.2	0	80.2
Portugal	67.8	5.9	8.8	0	82.5	65.1	6.4	8.6	0	80.1
Bulgaria	0	8.8	44.9	0	53.7	0	8.3	42.7	0	51
Ireland	33.5	9	7.8	0	50.3	31.1	11.2	7.6	0	49.9
Lithuania	10	6.9	20.2	0	37.1	8.7	6.8	23.4	0	38.9
Slovenia	2	2	20.4	0	24.4	1.5	1.2	19.5	0	22.2
Romania	0	0	20.7	0	20.7	0	0	20.7	0	20.7
Luxembourg	0	1.6	20.2	0	21.8	0	1.8	16.2	0	18
Cyprus	1.1	0.7	11.4	0	13.2	1.2	0.7	12	0	13.9
Estonia	1.4	7.5	4.8	0	13.7	1.4	7.6	4.8	0	13.8
Malta	0	0.9	0.8	0	1.7	0	1	0.6	0	1.6
Totals	2397.9	1529.3	12424.9	157.8	16509.9	2259.1	1593.5	12611.8	164.7	16629.1

The countries with the greatest growth in biogas production from 2018 to 2019 were France, Denmark, and The Netherlands which added 97.1Ktoe, 77.7Ktoe, and 29.7Ktoe of biogas, respectively. In terms of sector growth, Denmark, France, and Greece lead the pack with 24.36%, 11.04%, and 10.71% in added biogas production from 2018 to 2019. Germany, the leader in biogas production saw a decrease of 10.7Ktoe or -0.14% from 2018 to 2019.

Looking more specifically at biogas produced from each methodology, AD's saw the greatest increase in production with an added 186.9Ktoe of biogas from 2018 to 2019 followed by sewage sludge gas, and biogas from thermal process with 64.2Ktoe and

6.9Ktoe, respectively. Landfill gas production in EU28 decreased by -138.8Ktoe from 2018 to 2019, a decrease of -5.78%. However, this is not alarming due to the nature of landfill biogas production curves. (16) In terms of percent growth, thermal processes and sewage sludge saw the greatest increases with 4.37% and 4.19%, respectively, followed by ADs at 1.50%. Table 2.1.2 below highlights these developments.

Table 2.1.2 Developments in the biogas production methods from 2018 to 2019

Totals (Ktoe)	**Landfill Gas**	**Sewage Sludge Gas**	**Anaerobic Digester/Fermentation Gas**	**Biogases from Thermal Processes**	**Total**
2018	2397.9	1529.3	12424.9	157.8	16509.9
2019	2259.1	1593.5	12611.8	164.7	16629.1
Total Change (Ktoe)	-138.8	64.2	186.9	6.9	119.2
Percent Change	-5.78%	4.19%	1.50%	4.37%	0.721%

2.1.1 Gross Electricity Production

A majority of the biogas produced in Europe is used for electricity production. In 2019, 62465.1GWh of electricity were produced from Europe's biogas, which is equivalent to 5.37 Mtoe. However, this is a decrease of -0.40% from 2018. This decrease in electricity production is due to the decrease in electricity generated by electricity only plants where -3.81% less electricity was generated in 2019 than 2018. The electricity generated from CHP plants increased by 1.01% from 44422.4GWh to 44870GWh. The gross electricity of each country is shown below in Table 2.1.3 along with developments in the gross electricity production from biogas in Table 2.1.3. (16)

Table 2.1.3 Gross Electricity production from Biogas in EU28 (GWh)

Country	Electricity Only Plant	CHP Plant	Total 2018 (GWh)	Electricity Only Plant	CHP Plant	Total (2019) (GWh)
Germany	7100	26000	33100	6900	26000	32900
Italy	2895.7	5403.9	8299.6	2862.9	5433.9	8296.8
United Kingdom	5458.5	2234.9	7693.4	5169.6	2399.6	7569.2
France	370.1	1999.7	2369.8	338.8	2248.6	2587.4
Czechia	41.8	2565.4	2607.2	37.8	2468.5	2506.3
Poland	0	1127.6	1127.6	0	1123	1123
Belgium	70.5	874.2	944.7	77.3	869.5	946.8
Spain	740	183	923	699	205	904
Netherlands	23.3	863.6	886.9	21.3	873.6	894.9
Denmark	0.8	612.1	612.9	0.9	635.3	636.2
Austria	562.1	66.2	628.3	569.8	42.1	611.9
Slovakia	81	458	539	80	460	540
Croatia	27.8	327.1	354.9	30.6	359.7	390.3
Greece	55.8	260.5	316.3	46.8	330.7	377.5
Finland	234.9	184.7	419.6	161.7	201.5	363.2
Latvia	0	374.1	374.1	0	353	353
Hungary	111	220	331	102.3	202.7	305
Portugal	253.3	18.1	271.4	246.1	18.3	264.4
Bulgaria	85	127.2	212.2	78.9	118	196.9
Ireland	139.2	44.9	184.1	130.1	55.2	185.3
Lithuania	0	139.9	139.9	0	155	155
Slovenia	1.2	117.7	118.9	1.2	93.1	94.3
Luxembourg	0	75.5	75.5	0	70.9	70.9
Romania	40	30.2	70.2	40	30.2	70.2
Cyprus	0	56.9	56.9	0	60.2	60.2
Estonia	0	38	38	0	39	39
Sweden	0	10	10	0	17	17
Malta	0	9	9	0	6.4	6.4
Total	**18292**	**44422.4**	**62714.4**	**17595.1**	**44870**	**62465.1**

Table 2.1.4 Gross Electricity from biogas summary from 2018 to 2019 (GWh)

Year	Electricity Only Plant	CHP Plant	Total
2018	18292	44422.4	62714.4
2019	17595.1	44870	62465.1
Total Change (GWh)	-696.9	447.6	-249.3
Percent Change	-3.81%	1.01%	-0.40%

2.1.2 Gross Heat Production

Heat production is the second most common use of raw biogas with a total of 893.5Ktoe being produced in 2019, a 3.98% increase from 2018. Heat only plants are the minority compared with CHP plants and only generated 35.8Ktoe of heat while CHP plants produced 857.8Ktoe of heat in 2019. However, both technologies showed growth from 2018 to 2019 and the data is depicted for each country below in Table 2.1.5 and summarized in Table 2.1.6. (16)

Table 2.1.5 Gross Heat production from Biogas in EU28 (Ktoe)

Country	Heat Only Plant	CHP Plant	Total 2018 (toe)	Heat Only Plant	CHP Plant	Total 2019 (Ktoe)
Germany	8.6	358.3	366.9	10.5	382.2	392.7
Italy	0.1	213.7	213.8	0.2	211.1	211.3
France	9.4	60.2	69.6	8.3	68.8	77.1
Denmark	1.9	45.2	47.1	1.9	46.8	48.7
Poland	0.4	21.7	22	0.5	22	22.5
Finland	4.9	13.8	18.7	5.4	15.5	20.9
Latvia	0.1	21.2	21.4	0	19.3	19.3
Czechia	0	17.5	17.5	0	17	17
Slovakia	0.1	14.1	14.2	0.1	14.1	14.2
Croatia	0	11.5	11.5	0	11.9	11.9
Sweden	4.5	3.1	7.6	6	5.2	11.2
Belgium	0	9.1	9.1	0	10.7	10.7
Netherlands	0	8.5	8.5	0	8.9	8.9
Austria	1.1	6	7.1	0.7	3.8	4.5
Slovenia	0	5.3	5.3	0	4.4	4.4
Bulgaria	0	4.1	4.1	0	4.1	4.1
Romania	2.2	1.9	4	2.2	1.9	4
Luxembourg	0	2.4	2.4	0	2.5	2.5
Lithuania	0	2.8	2.8	0	2.5	2.5
Hungary	0	2.6	2.6	0	2.4	2.4
Estonia	0	1.8	1.8	0	1.4	1.4
Cyprus	0	1.3	1.3	0	1.3	1.3
United Kingdom	0	0	0	0	0	0
Total	**33.3**	**826.1**	**859.3**	**35.8**	**857.8**	**893.5**

Table 2.1.6 Gross Heat from biogas summary from 2018 to 2019 (GWh)

Year	Heat Only Plant	CHP Plant	Total
2018	33.3	826.1	859.4
2019	35.8	857.8	893.6
Total Change (Ktoe)	2.5	31.7	34.2
Percent Change	7.51%	3.84%	3.98%

2.1.3 Biogas Leaders in the EU

Biogas production is heading in different directions for different countries across the continent. Some countries are promoting the projects while others are shifting their efforts in new directions.

Germany is the leading nation for biogas production within EU28 and accounts for over half of the biogas produced within EU27 at 54.4% in 2019. However, Germany's status as the leaders of the biogas industry in Europe may be on the decline. Germany established itself as the head biogas producer because of high investment in the sector throughout the 2000s. This was primarily due to the renewable energy law (EEG) that was rolled out in Germany and promoted the production of electricity with energy crops. Due to the EEG, on farm biogas projects were the most commonly developed projects in Germany and for this reason on farm projects are responsible for 92.2% of the biogas produced from AD's and fermentation. On-farm methanation plants also account for 95% of all methanation plants present in Germany. The construction of new plants in Germany has been declining since 2011 when 1526 additional plants were added followed by just 456 in 2012. This was the result of new legislation that no longer promoted biogas as strongly. Additional plant construction has dropped off even further in more recent years with only 83 plants in 2019 preceded by 113 plants and 122 plants in 2018 and 2017, respectively. Sia Partners estimates that as of 2019 there were approximately 10000 plants in service across Germany, 10971 to be exact. (19) This greater slowdown was accelerated by the EEG 2014 law which initiated direct electricity sales on the market for electricity generated from plants with a capacity over 500kW and then the same legislation took effect on January 1, 2016 for plants over 100kw. This legislation change shocked the biogas market and severely slashed the feed-in tariff which previously made these projects so favorable and profitable. (16)

Interestingly, Germany has an electrical capacity from its biogas plants estimated at 5000MW in 2019 yet only exploited 3810MW of their capacity. This is due to a flexibility premium which passed in 2012 as part of the renewable energy law by EEG (EEG 2012). The flexibility premium aims to provide stability to the electrical grid and obliges plant operators to produce electricity during peak consumption periods and then dial back production to a minimum during off-peak hours. In doing so they are eligible for the flexibility premium which pays €130 per KW for the first 10 years and €40 per KW during the following 20 years (EEG 2014). (16)

Grid injected biomethane has also been on the rise in Germany with the addition of three new plants in 2019 taking the total number of plants online to 219, resulting in approximately 10TWh of grid injected biomethane in 2019. The 219 plants had a combined capacity of 133734Nm^3/h which accounts for only 1% of the natural gas consumed in Germany. (16)

On the contrary, France and Italy are shifting their biogas production efforts and funding to biomethane production. On March 2, 2018, Italy published a biomethane decree to increase biomethane's share in the transport sector. The decree allocated €4.7billion towards the construction of new biomethane plants or the renovation of preexisting biogas plants for biomethane upgrading of projects to go online by 2022. These funds were designed to cover a maximum of 1.1 billion Nm^3 of biomethane annually. (16)

Biomethane use in Europe as a biofuel grew tremendously in 2019. In EU28 a growth of 44.3% was witnessed as 2019 usage levels reached 269.9Ktoe compared to the 186.8Ktoe in 2018. This growth was a product of policies that included the French plans to ban natural gas for heating in new buildings by 2024, Guarantees of Origin (GO) for biomethane tracing, and the importing of biomethane by Switzerland from fellow EU28 countries like UK, Germany, and Denmark. GO's offer a traceability mechanism to ensure that users are purchasing renewable gas rather than well produced natural gas. Other countries like Switzerland have established certification mechanisms and the Association of Issuing Bodies (AIB) is seeking to unify the biomethane certifications across Europe. (16)

France saw immense growth in the biogas sector and particularly the use of biogas for electricity and biomethane injection into the natural gas grid. The French biogas electricity production increased by 9% in 2019 with a total production of 2587GWh, including 2249GWh from CHP plants. Biomethane injected into the natural gas grid was attributed with producing an additional 99.8GWh of electricity through its use in gas turbine combined-cycle power plants. This makes the total electricity produced from biogas 2687.3GWh for the year 2019 in France. In addition to electricity production from biogas France is very active in biomethane injection into the natural gas grid. This is thanks to a feed-in tariff that has been in place since 2011. The feed-in tariff takes into a account how the biomethane was produced based on it's feedstock and the project size. This program rewards two tariffs to its producers, the baseline tariff, and the feedstock premium. The baseline tariff depends on the project type and size and ranges from €64-€95 per MWh while the feedstock premium ranges from €5-$39. Institutional waste and household projects are rewarded a €5 premium while farm and food processing waste projects are rewarded €20-€30 . The premium may be even greater for some sewage plant residue treatment plants where the premium ranges from €10-€39 per MWh. In 2019 France reached 139 biomethane injected sites thanks to the addition of 49 new sites, a 62% rise over 2018. This jump makes Frances biomethane sector the fastest growing in all of Europe. Currently these 139 sites have 2.5TWh of capacity and the sector looks promising with a combined capacity of 25TWh from 1134 plants. This growth may encounter some roadblocks however due to France's multi-annual energy plan (PPE) which as of April 23, 2020 limited the Biomethane's ambitions to just 14-22TWh by 2028. Even at these levels the injected biomethane will account for 6-8% of France's estimated gas consumption needs in 2028. (16)

Due to recent geopolitical issues involving Russia and Ukraine these development ambitions might change as many EU countries look to wean themselves off Russian natural gas. Biomethane currently only makes up 1% of the gas used by France but some are optimistic about the potential growth of the sector, particularly Evergaz founder and CEO, Frédéric Flipo, who stated "We represent an alternative to Russian gas. By 2030 we will be able to replace 17 percent of French gas supplies imported from Russia." Flipo also recognized that although this will take time and is not scalable to the entire nation immediately that it will help in some areas; "It's not a short-term solution on a national scale. But on a local level, near our production sites, it's an immediate solution." (20) Additionally, biomethane prices have been an obstacle for entering the market against natural gas but with the PPE's plans the price is scheduled to be at €75 per MWh in 2023 and €60 in 2028. (16) In the EU natural gas is currently traded at approximately €85 per MWh according to the Dutch TTF Gas benchmark price. (21)

Recall that biomethane is upgraded biogas, a purer form of gas equivalent in quality to natural gas and can be injected into the grid.

Over the past decade the European biomethane market has increased by over 700%. In 2011 the market consisted of 4.9TWh of biomethane and as of a October 2021 reached 32TWh, or approximately 2.75Mtoe. From 2020 to 2021 the largest growth in the biomethane market was seen at 6.4TWh of new installed capacity, double the added 3.2TWh installed between 2019-2020. The growth of installed capacity is thanks to the 1023 biomethane producing facilities across the 20 participating member states. *(22)*

Although the EurObserv'ER report did not outline the primary consumption of biogas the EBA did highlight the primary consumption of biomethane. The majority of the biomethane produced is sent to the distribution grid at 47%, or 15.04TWh. Another 20% or 6.4TWh are sent to the transportation grid. Lastly, 10% or 3.2TWh are not connected to any grid and final use of the remaining 23% or 7.36TWh is unknown. Figure 2.1.3 below highlights the usage by sector. *(22)*

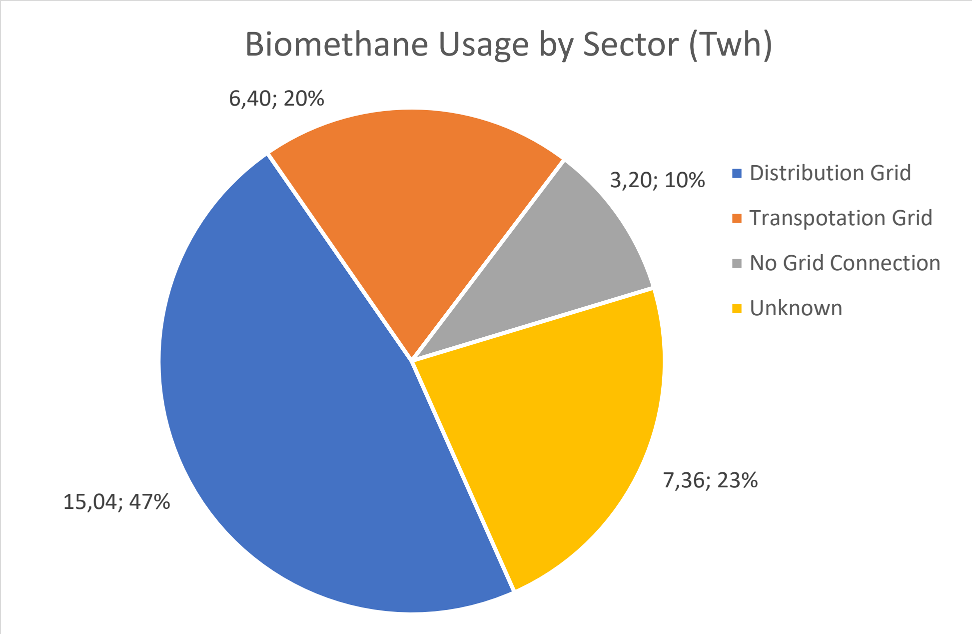

Figure 2.1.3 Biomethane Usage by Sector

Leading the EU in biomethane production is Germany with a biomethane production of 138698 m^3/h followed by the United Kingdom and France at 78450 m^3/h and 66455 m^3/h, respectively. In total Europe produces 424466 m^3/h of biomethane which corresponds to 32TWh annually. Figure 2.1.4 below shows a map of biomethane production intensity throughout Europe and is complimented by Table 2.1.7 with all numerical values shown. (22)

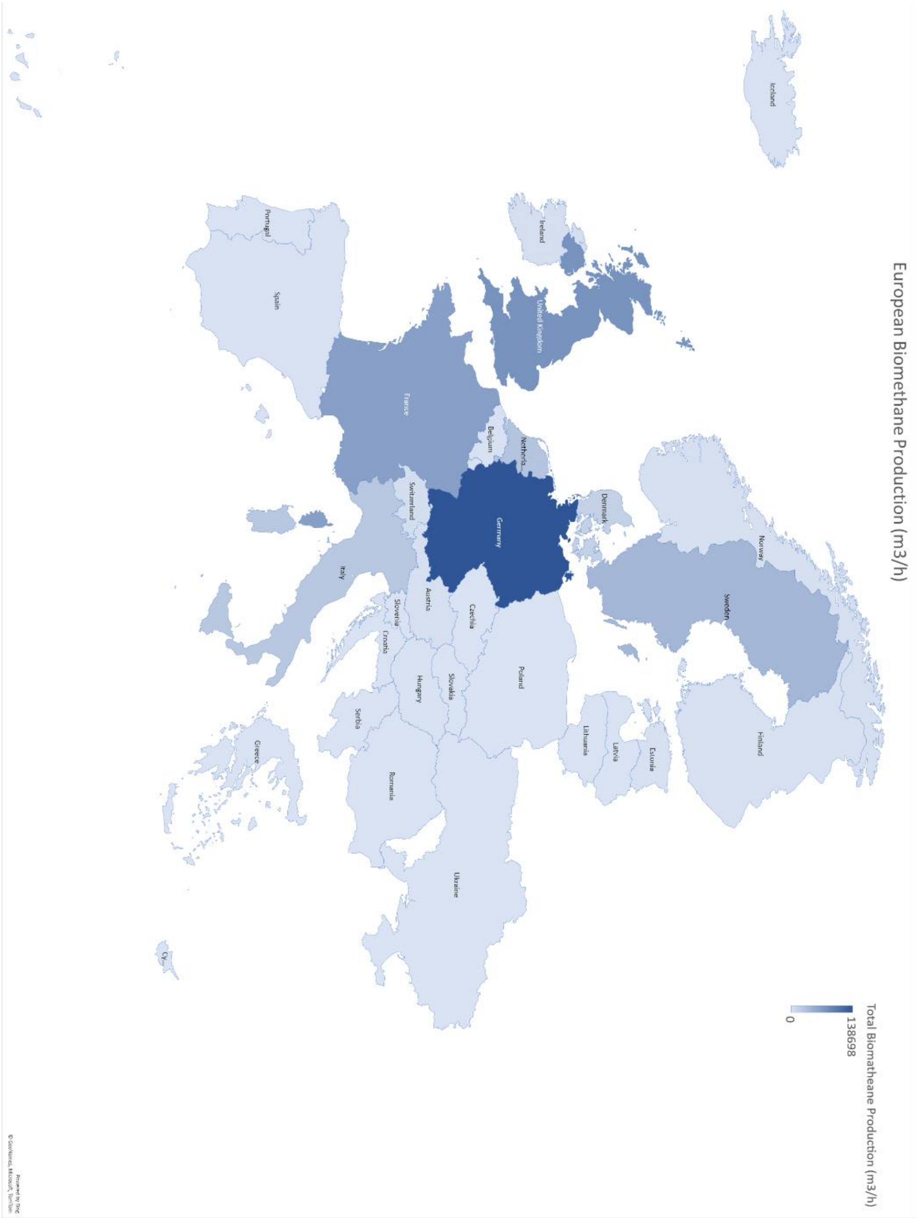

Figure 2.1.4 European biomethane production intensity map. Data courtesy of (22)

Table 2.1.7 Total Biomethane Production in each country. (22)

Country	Biomethane
Austria	3108
Belgium	1180
Croatia	0
Cyprus	0
Czech Republic	350
Denmark	17594
Estonia	2250
Finland	1837
France	66455
Germany	138698
Greece	0
Hungary	800
Iceland	550
Ireland	3900
Italy	26455
Latvia	100
Lithuania	0
Luxemburg	680
Netherlands	30011
Norway	2495
Poland	0
Portugal	0
Romania	0
Serbia	0
Slovakia	0
Slovenia	0
Spain	1450
Sweden	42790
Switzerland	5313
Ukraine	0
United Kingdom	78450

Note that the countries listed are either national members or have companies, research Institutes, universities, public authorities, or individuals active in the field of biogas of the European Biogas Association. For this reason, not all listed countries are biogas producers; however, they are involved with the biogas production in Europe through research or consumption. (23)

The greatest increase in biomethane production in Europe occurred in 2014 when 45,945 m^3/h were added. The addition of biomethane in Europe saw and upward trend until 2014 followed by a downward trend through 2018 when only 20,304 m^3/h of biomethane were added. An upward trend was witnessed again through 2020 when added biomethane production reached 40,631 m^3/h followed by a fall-off in added capacity of just 27,869 m^3/h in the year 2021. Figure 2.1.5below shows the annual added capacity and is followed by Figure 2.1.6 which shows the total capacity of biomethane production in Europe.

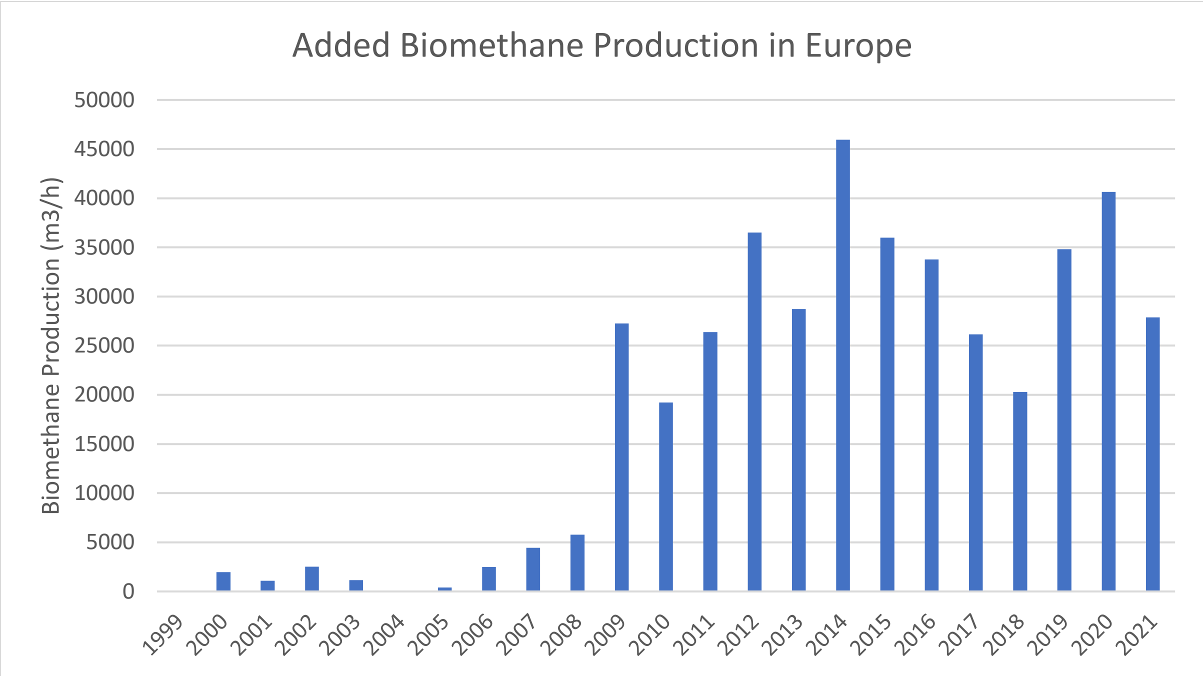

Figure 2.1.5 Annually added biomethane production in Europe. (22)

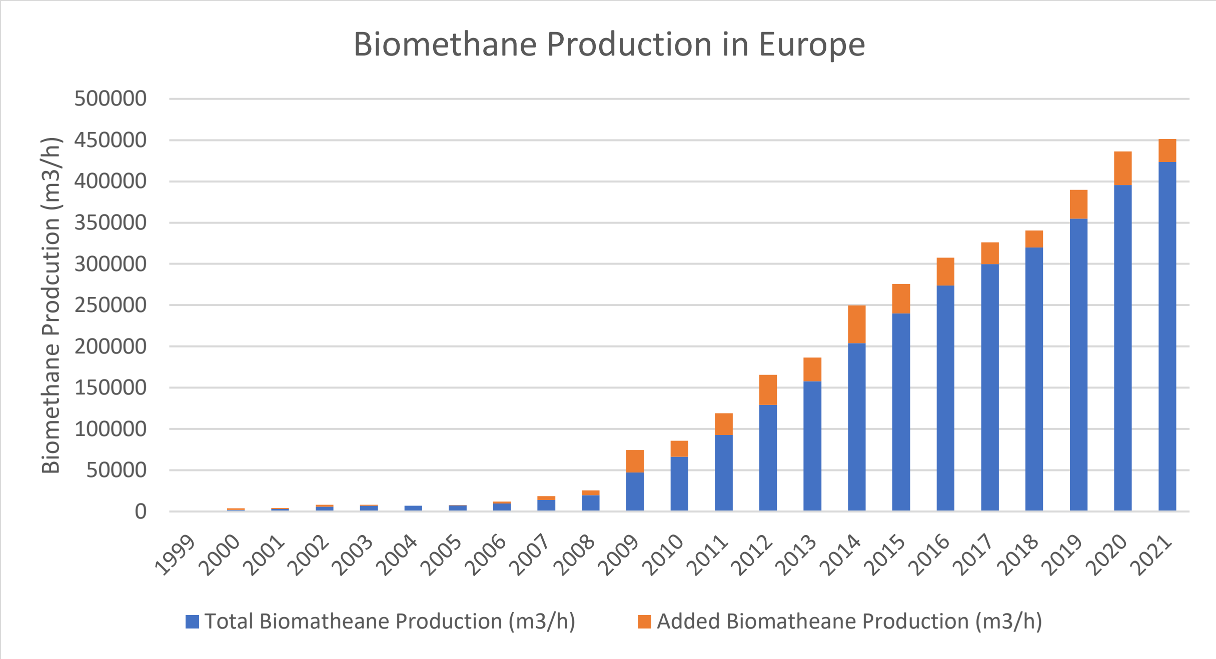

Figure 2.1.6 Total biomethane production in Europe with newly installed production. (22)

2.2 Biogas Production in the US

The number of biogas producing plants in the US is far smaller than that of Europe with just 2,300, according to the American Biogas Council (ABC), compared to Europe's approximate 18,000. The US biogas market produces approximately 2bcm of biogas annually while Europe's production is at approximately18bcm. A rule of thumb can be taken from this data to say the 1000 biogas plants equate to 1bcm of biogas production annually. The American Biogas Council estimates that the US biogas production output could be as high as 1,860 billion CUFT, or 52bcm (1bcm per 35.3147 Billion CUFT). (24) The number of biogas producing plants in the US, is more comparable to that of Italy which has 2041 plants. (25) Figure 2.2.1 shows the location of biogas producing plants within the US.

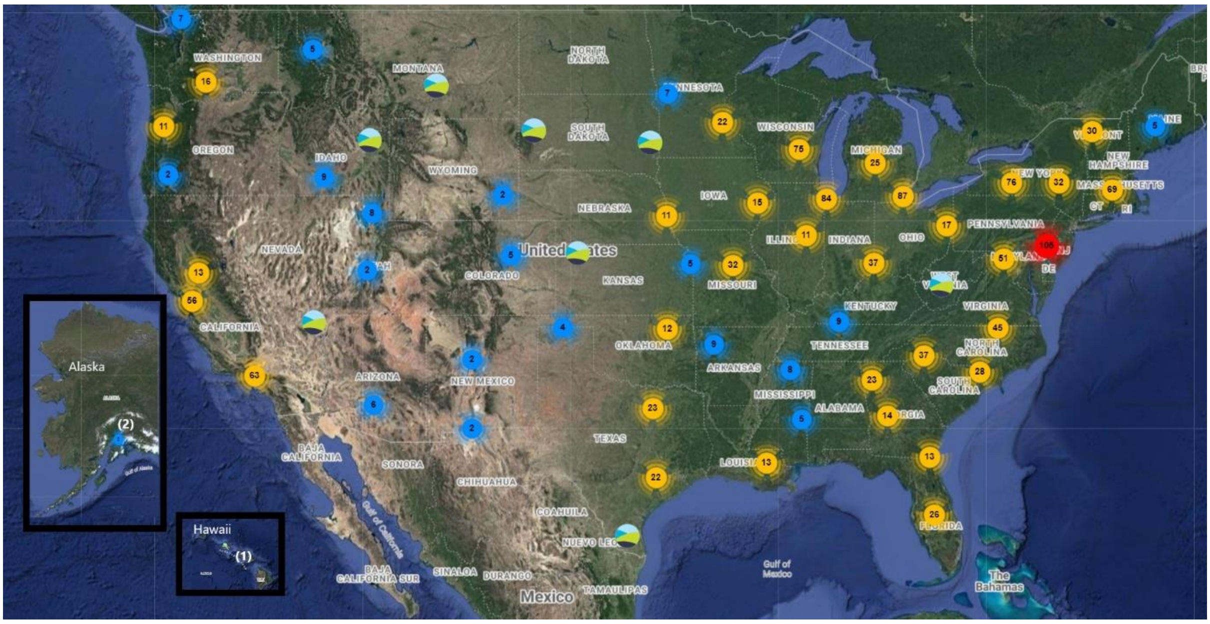

Figure 2.2.1 Biogas plants in the US. Each dot represents a group of plants and states the total number of plants in that area. A single ABC logo represent one plant, blue dots represent 2-9 plants in the vicinity, yellow dots represent 10-99 plants in the vicinity, and red dots represent 100+ plants in the vicinity. (26)

Much like in Europe, different regions are comprised of different types of biogas producing plants. Some areas have large dairy or swine farms and are more suitable for manure digesters while other areas can process wastewater, food scraps, or collect landfill gas. The US biogas production plants are comprised of 1,200 water resource recovery plants, 650 landfills, 317 farms, and 66 stand-alone systems that digest food scraps. (27 , 28)

Some major differences can be seen between the US and Germany in the ways biogas is produced. While Germany relies heavily on energy crops, the US focuses more on water resource recovery plants and landfills. Another significant difference seen between the US and EU countries is that of food scrap digesters. Besides in California, a waste sorting program lacks in most communities in most states, meaning food waste digesters are only suitable in unique cases. Countries like Italy have well established waste sorting programs which allow for the proper sorting of organic digestible waste from inorganic waste which is carried out by the general population.

Biomethane production in the US is steadily increasing and has become the leading final product for newly built or under construction anaerobic digesters. Biomethane, or RNG as it is referred to in the US is most commonly injected into the natural gas grid and used in homes and industries.

3 EU vs US Carbon Credit Systems

3.1 Introduction to Credit Systems

Today there are numerous factors that drive the biogas markets in the US and Europe ranging from incentives, credit systems, taxes, and policies. These factors have driven the biogas markets in both locations at different rates. Some of these factors overlap between the two locations of interest and some are unique to each. For example, the Paris Agreement is one treaty shared by both European countries and the US. On the other hand, only Europe has an international carbon credit trading system in place, known as the European Union Emissions Trading System (EU ETS). (29) While only some states in the US have carbon credit or emissions trading systems in place. These include California, Oregon, Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New York, Rhode Island, Virginia, New Jersey, and Vermont. (30) The state of Washington is also in the process of adopting a clean fuels program by way of legislative action. (31)

3.2 Paris Agreement

The Paris Agreement is a legally binding international treaty under the UNFCCC concerning climate change, which was adopted in Paris on December 12, 2015, at the COP 21 convention. A total of 196 Parties signed the treaty which went into effect on November 4, 2016. The aim of the treaty is to limit global warming by decreasing GHG emissions. The goal is to limit the global warming to well below 2, but preferably 1.5 degrees Celsius with respect to pre-industrial levels. Checks will be carried out every five years to ensure that countries are achieving the required social and economic changes in order to meet their individual goals. In 2020 all members were required to submit their national determined contributions (NDCs). Within these NDCs each country outlines the actions they plan to implement in order to reduce their GHG emissions as well as how they plan to adapt to rising temperatures. Participating Parties were also invited to submit long-term low greenhouse gas emission development strategies (LT-LEDs) to

Figure 3.2.1 UN's Paris Agreement/Sustainable Development Goals Logo (32) describe their long-term plan, albeit this was not a requirement. The Paris Agreement also provides a framework for financial, technical, and capacity building. (33)

Concerning **finances**, countries can support one another, particularly, well established countries can provide financial assistance to less developed countries. Climate finance is important for both mitigation and adaptation and significant investments will be required to achieve both. (33)

From a **technology** vantage point, the Paris Agreement has the outlook for fully developing and distributing technologies that decrease GHGs and aid in the adaptation to rising temperatures. In this way the Paris Agreement ties together with another UNFCCC action, the Technology Mechanism. (33) The Technology Mechanism focuses specifically on supporting countries to accelerate, improve, and enhance action on climate change. (33)

The Paris Agreement also highlights the importance of **capacity-building** in developing countries with the help of developed countries to tackle climate change. In this way the challenges faced by some countries due to insufficiencies can be combatted. (33)

Progress is scheduled to be tracked in 2024 when Parties will present their actions taken in an enhanced transparency framework (ETF). The transparently presented actions will then be compiled into the global stocktake which will then look at the overall progress taken towards the long-term goals to prevent global warming and aid against rising temperatures. This process also serves so countries can make changes to their plan and strategically implement new policies and plans to achieve more ambitious results. (33)

3.3 European Union Emission Trading System

Figure 3.3.1 EU ETS logo (37)

The European Union Emission Trading System (EU ETS) has been active since 2005 and is now in its fourth phase concerning years 2021-2030. The system was first pitched by the EU in March 2000 when a green paper was pitched by the European Commission on how to reduce emissions. This initiative was created by the Kyoto Protocol in 1997 when the first legally binding emissions reduction and caps were set for 37 industrialized countries. (37) The system has undergone revisions since its initial release, each phase improving from the proceeding phase.

3.3.1 Phases and Development of EU ETS

Phase 1: 2005-2007

Phase 1 lasted from 2005 to 2007 and was concerned solely with CO_2 emissions from power generators and energy-intensive industries and placed a penalty at €40 per tonne of CO_2 emitted. Each participating country submitted a national allocation plan (NAP) by March 31, 2004 in which they outlined their expected emission levels and were granted allowances for said expectations. The European Commission reviewed the proposed NAPs of participating countries and approved or denied them. In case of denial the country would reassess their NAP and decrease their national allowance cap. (34) One allowance permitted the holder to emit 1 tonne of CO_2. (35) Nearly all allowances were provided to business for free during the first phase. Phase 1 was successful in setting up the needed infrastructure to oversee the emissions of the businesses under their umbrella. Along with the price of carbon, free trade of emission allowances was successfully established across the EU. Phase 1 fell short however in accurately predicting emission levels and thus over-issued allowances. In fact, the allowances issued exceeded the carbon emissions. For this reason, the allowances issued in Phase 1 fell to zero as the supply far exceeded the demand.

Phase 2: 2008-2012

Phase 2 ranged from 2008-2012 and coincided with the first commitment period of the Kyoto Protocol where participating countries were required to reduce their emissions by an average 5% below 1990 values. (36) Thanks to the lessons learned during Phase 1, the EU had more concrete data to rely one and could more accurately base reduction measures. The allowances cap was also reduced to 6.5% lower than they had been in 2005 and nitrous oxide was even added as a emission of concern. The EU ETS even expanded was the likes of Iceland, Liechtenstein, and Norway joining. The carbon price from phase 1 was also more than doubled and now sat at €100 per tonne of CO_2 emitted, however, the economic crisis of 2008 resulted in less emissions and a surplus of allowances and credits again. During Phase 2 businesses were also allowed to buy international credits which totaled 1.4 billion tonnes of CO_2-equivalent. Some countries even held auctions to sell their excess allowances. Other headways included the addition of the aviation sector to the EU ETS system and the creation of the EU Registry in 2012 by the European Commission where all EU ETS operations were centralized. (37)

The Registry records the national implementation measures of each EU country and any free allocation given to sectors, companies, or individuals within the countries. It also records all allowance transactions, annual verified CO_2 emissions from installations and aircraft operators, and an annual reconciliation of allowances and verified emissions. Each country is required to surrender enough allowances to cover all of its verified emissions. (38)

Phase 3: 2013-2020

The original framework of the EU ETS from Phases 1 and 2 was changed greatly for Phase 3 which lasted from 2013-2020. The main change made was the elimination of individual nation caps and the introduction of an EU-wide cap. Doing so led to auctioning becoming the default method for allocating allowances rather than free allocation. Regarding the free allowances issued to deserving sectors, a harmonized set of allocation rules were set in place. Furthermore, more pollutant gases were included in the emission reduction goals as carbon equivalent which lead to the addition of new entrants. (37) The cap for stationary installations was decreased by a linear reduction factor of 1.74% during Phase 3 and the initial cap set in 2013 was based off the average total quantity of annually issued allowances during Phase 2 (2008-20012). (39) By definition, "The linear reduction factor (LRF) defines the annual decrease of allowances provided to the market either via free allocation or via auctions." (40) To prevent any entry to market, 300 million allowances were set aside in the New Entrants Reserve which aided in the deployment of innovative, renewable energy technologies and carbon capture and storage. (37)

During Phase 3 a technique known as back-loading was used to postpone the suctioning of 900 million allowances until 2019-2020. These can from 400 million, 300 million, and 200 million, in the years 2014, 2015, and 2016, respectively. An impact assessment performed by the European Commission showed that by back loading these allowances the EU ETS can rebalance the supply and demand of allowances within the EU ETS in the short term and further reduce price volatility without any significant impacts of competitiveness. (41) The Eu ETS Auctioning Regulation was founded on February 27, 2014. (42)

Phase 4: 2021-2030

Phase 4 has two main goals:

1. Achieve carbon neutrality in the EU by 2050
2. Achieve a 55% net reduction in greenhouse gas emissions by 2030 (compared to 1990)

These goals will be achieved under the European Green Deal which additionally aims to decouple economic growth from resource use and leave no individual or place behind along the way. (43) All 27 EU member states have pledges to these two main goals as well. (44)

The EU-wide cap will continue to be used to set the number of allowances for sectors such as power plants, industry factories, and the aviation sector. The cap will continue to be decreased annually to ensure that total emissions decrease according to goals 1 and 2. The allowances have expanded beyond solely 1 tonne of CO_2 or nitrous oxide to now include other GHGs and perfluorocarbons (PFCs). In Phase 4 a more aggressive linear reduction factor has been selected at 2.2% and the EU-wide cap for 2021 from stationary installations is fixed at 1,571,583,007 allowances. The free allowances given in Phase 4 are aimed away from the electricity production sector; however, some derogations provided by Article 10c of the EU ETS Directive allow for free allowances to the electricity production sector under certain circumstances in lower income member states. These exceptions include diversification of the energy mix and supply sources, plant renovations, environmental upgrades, clean technology installations, and modernization of the production, transmission, and distributions branches of the energy sector. (45)

3.3.2 Biogas within the EU ETS

The EU ETS has finally succeeded in recognizing the biogas industry as a crucial player in their system and allows ETS players to purchase biogas/biomethane as a renewable source of energy. However, the European Biogas Association (EBA) has called for amending of various directives and proposed the following suggestions recently:

"Proposal for a DIRECTIVE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL amending Directive (EU) 1018/2001 of the European Parliament and of the Council, Regulation (EU) 2019/1999 of the European Parliament and of the Council and Directive 90/70/EC of the European Parliament and of the Council as regards the promotion of renewable energy from renewable sources, repealing Council Directive (EU) 2015/652 COM/2021/557 final" (46)

This translates to the EBA calling upon the European Parliament and Council to build an internal market for biomethane to enable the EU Green Deal to achieve its decarbonization goals by 2050. The EBA would like to see a functioning internal market for biomethane built into the new Renewable Energy Directive (RED III) to help the sector reach its full potential of 42bcm of biomethane, approximately 2.34 times its current production of 18bcm. Revisions of RED II are currently taking place by the European Commission. (46)

The EBA has proposed that in addition to the functioning internal market for biomethane, the following five recommendations be met (46):

1. *Decarbonizing the EU gas supply;*
2. *Streamlining cohesion, modernization and just transition principles in the legislation;*
3. *Encouraging the use of the most sustainable and circular feedstock to protect biodiversity;*
4. *Scaling up zero emission and negative emission biomethane in the transport sector;*
5. *Achieving energy security through and integrated energy market;*

Many European countries such as Germany, Austria, Belgium, Denmark, France, Italy, and The Netherlands already have their own Guarantees of Origin (GO) programs that ensures the biomethane purchased by interested consumers is truly a product of biogas. (47)

RED II introduced GO's in Article 19 and required them for renewable gases; however, they did not lay down a solid framework for the GO's to follow and how the purchase of biomethane from a GO could benefit the buyer. For example, RED II failed to explain clearly how the GO's of biogas/biomethane should be recognized within the EU ETS or other support schemes or quotas. (47)

The EBA is in agreement with the European Commission and the EU ETS must be aligned with the Eu Green Deal in order to decarbonize fossil fuel burning sectors. The EBA stated the following on November 8, 2021:

"The new Monitoring and Reporting rules (ETS MRR) facilitated the deployment of biomethane at ETS installations by rightly introducing the emission factor zero for biomethane which, following the ETS extension, will also finally categorize biomethane under the zero emissions fuels in road and maritime transport. Further clarity is however needed on practical implementation. We recommend that guarantees of origin (GOs) continue to be recognized as one way to prove the share of biomethane in the purchased and used gas by the ETS operator." (48)

Recommendations were also made by the EBA that the ETS be implemented along with GO's within the maritime sector to help decarbonize it while also promoting the production of liquid biomethane. The EBA is also in favor of a *"robust and rising explicit price on fossil carbon from shipping through an ETS"* to quickly decarbonize the sector. (48)

3.4 US Carbon Credit Systems

Within the US there is no single emission trading system, instead individual states or regions may implement their own trading system and policies on emissions. These markets include the California Cap and Trade, the Washington Cap and Invest, and the Regional Green Gas Initiative (RGGI). (58)

3.4.1 California Cap and Trade

The California Cap and Trade program was the first of its kind in North America and it covers multiple sectors throughout the entire state of California covering virtually the entire economy. (58)The Cap and Trade program is a key contributor to the California Air Resource Board's responsibility of protecting public health through the improvement and protection of air quality. (49) The program set a GHG emissions cap in 2015 which by designs decreased by 3% annually through 2020 to achieve California's legislated goal of reducing GHG emission to below 1990 levels by 2020. Additionally, a new state law passed in 2017 requires the cap to decrease between 2020-2030 by another 40% to further reduce emissions. The California Cap and Trade program is closely linked with a Canadian program in Québec. (58)

California Air Resource Board

The California Air Resource Board (CARB) operates many programs to combat climate change, improve air quality, protect public health. CARB has a three-tiered approach to improving air quality for its state which involves the United States Environmental Protection Agency (EPA), CARB, and local air pollution control districts. CARB takes the nationwide standards for air quality set by the EPA and elaborates on them, even making them stricter in some cases, for their own state. From there the local control districts regulate emissions of businesses both small and large. These may be large scale industrial sized oil refineries or even small family run businesses. CARB looks further than just CO_2 emissions from power plants, rather they look to identify any pollutant that pose health risks such as exhaust particles from diesel fuels, benzene in gasoline, or even formaldehyde in consumer products. CARB implements state of the art research with the best science and technology available to improve public health standards while also considering the costs/benefits to the most at risk communities. CARB is also the leader in the state for reducing climate-changing emissions and pushing for energy efficiency and resiliency in the economy. (51)

Figure 3.4.1 CARB logo (50)

CARB Offset Projects

There are currently six main offset project types recognized by CARB:

1) Livestock Projects (November 14, 2014)
    a) Livestock Projects (October 20, 2011)
2) Mine Methane Capture (MMC) Projects (April 25, 2014)
3) Ozone Depleting Substances (ODS) Projects (November 14, 2014)
    a) Ozone Depleting Substances (ODS) Projects (October 20, 2011)
4) Rice Cultivation Projects (June 25, 2015)
5) U.S. Forest Projects - June 25, 2015
    a) U.S. Forest Projects - November 14, 2014
    b) U.S. Forest Projects - October 20, 2011
6) Urban Forest Projects

Note that there have been updates made to livestock, ozone, and forestry related projects since their founding in 2011; however, the overall concept that GHGs are captured with some technology or is sequestered by the forests from the atmosphere has remained unchanged.

Concerning anaerobic digesters and biogas, CARB currently recognizes the biogas control capture for only dairy and swine farms, chicken farms and other livestock are excluded from the offset program. (52) Although, an offset project is permitted to conduct cogeneration of other organics the approved swine or dairy manure. However, offset credits are only issued for the methane extracted from the swine or dairy manure. (53) Naturally, the profits from additional methane yield is reaped by the project owner but there will be no additional offset credits issued for the cogeneration of manures not recognized by CARB.

Air Resource Board (ARB) credits represent verified GHG emission reductions or removal enhancements achieved under ARB's Compliance Offset Protocols or even approved early action quantification methodologies and are issued to projects that meet the Cap-and-Trade Regulations. ARB's may be issued to any project in the lower 48 states of the US and may then be traded within the CARB market. Figure 3.4.2 below shows a map of the US with all compliant projects and all projects still under the early action phase. (54)

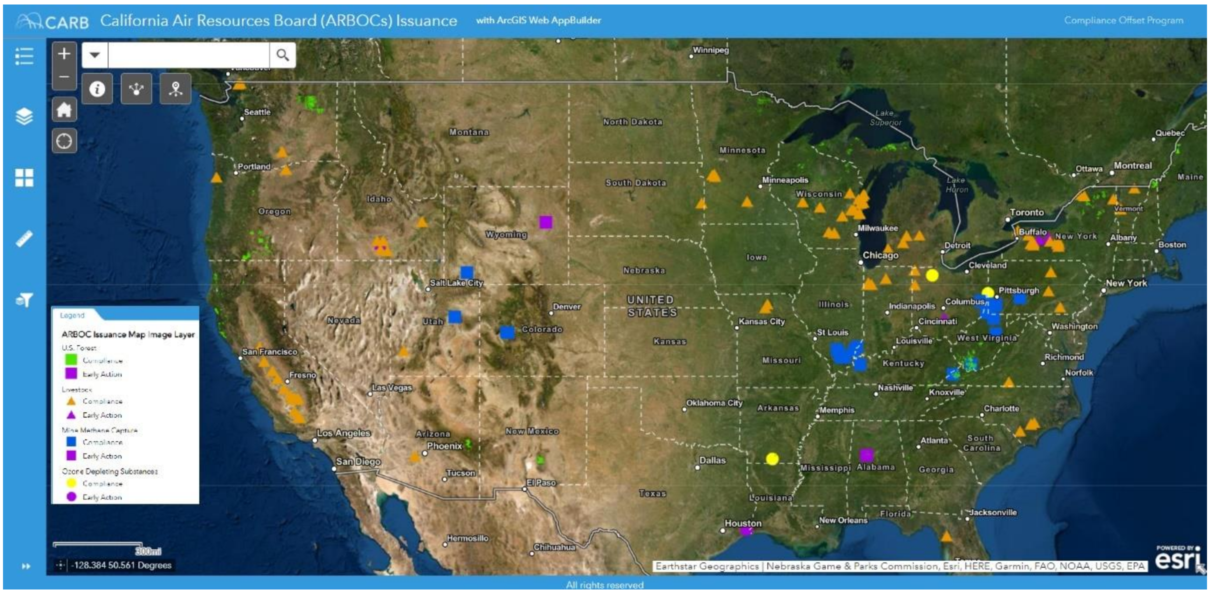

Figure 3.4.2 Map of offset projects in the US recognized by CARB (54)

Interestingly, the state of California recognizes projects occurring in other states far from their borders as qualified offset projects and issues them ARB credits.(54) CARB values the contributions of other states so much that they also provide data on the expected volatile solids of cows for from all 50 states in order to accurately predict GHG reductions from anaerobic digester projects installed at farms. This support system allows for the construction of projects anywhere in the US to benefit the offset credit rewards offered by CARB while operating where the most biogas potential is, not just in California.

CARB Livestock Offset Project

The Compliance Offset Protocol Livestock Projects from CARB is a useful resource for estimating Project Baseline Emissions and Table 3.4.1 below shows the default volatile solids values used when modelling the baseline of expected methane emissions for a proposed offset project for different cow types for each state. The volatile solids potential from a dairy cow herd can be calculated to then estimate the methane captured and reduced GHGs. CARB also requires the calculation of prevented/reduced GHG's of all proposed projects and provides equations based on data sampling to do so. The Compliance Offset Protocol Livestock Projects handbook reviews this procedure. (55)

Table 3.4.1 Volatile solids data for dairy cows in different stages. VS units are kg/day/1000kg mass. (55)

State	VS Dairy Cow	VS Heifer	VS Grazing Heifer	VS Grazing Cow
Alabama	8.62	8.44	19.67	7.82
Alaska	8.71	8.44	30.94	8.89
Arizona	11.64	8.44	22.32	8.89
Arkansas	8.44	8.44	18.38	7.82
California	11.41	8.44	13.96	8.89
Colorado	11.64	8.44	12.28	8.89
Connecticut	10.41	8.44	23.35	7.87
Delaware	10.18	8.44	16.82	7.87
Florida	10.36	8.44	21.99	7.82
Georgia	10.4	8.44	19.17	7.82
Hawaii	8.7	8.44	20.25	8.89
Idaho	11.45	8.44	13.75	8.89
Illinois	10.3	8.44	11.42	7.47
Indiana	10.85	8.44	11.72	7.47
Iowa	10.96	8.44	9.54	7.47
Kansas	10.94	8.44	8.99	7.47
Kentucky	9.2	8.44	14.69	7.82
Louisiana	8.41	8.44	21.36	7.82
Maine	10.01	8.44	15.12	7.87
Maryland	10.2	8.44	17.18	7.87
Massachusetts	9.91	8.44	20.89	7.87
Michigan	11.56	8.44	12.19	7.47
Minnesota	10.29	8.44	11.47	7.47
Mississippi	8.96	8.44	19.31	7.82
Missouri	8.92	8.44	14.84	7.47
Montana	10.85	8.44	18.5	7.82
Nebraska	10.79	8.44	11.97	8.89
Nevada	11.33	8.44	14.77	7.47
New Hampshire	10.34	8.44	23.83	8.92
New Jersey	10.01	8.44	16.56	7.87
New Mexico	11.85	8.44	14.27	7.87
New York	10.93	8.44	16.72	8.89
North Carolina	10.79	8.44	19.93	7.87
North Dakota	10.22	8.44	14.61	7.82
Ohio	10.39	8.44	13.24	7.47
Oklahoma	9.76	8.44	12.67	7.47
Oregon	10.57	8.44	15.75	7.82
Pennsylvania	10.32	8.44	16.19	8.89
Rhode Island	9.93	8.44	20.89	7.87
South Carolina	9.85	8.44	19.71	7.87
South Dakota	10.86	8.44	12.77	7.82
Tennessee	9.49	8.44	16.25	7.47
Texas	11.06	8.44	11.15	7.82
Utah	10.95	8.44	16.65	7.82
Vermont	10.23	8.44	16.08	8.89
Virginia	10.06	8.44	17.93	7.87
Washington	11.58	8.44	12.06	7.82
West Virginia	9.18	8.44	19.13	8.89
Wisconsin	10.87	8.44	17.03	7.47
Wyoming	10.69	8.44	18.18	8.89

Table 3.4.2 below shows the Typical Average Mass (TAM) of each livestock category provided by CARB in for potential projects which must make preliminary calculations regarding biomethane potential and avoided emissions.

Table 3.4.2 Typical Average Mass (TAM) for various livestock categories. (55)

Livestock Category	Livestock Typical Average Mass (kg)
Dairy cows (on feed)	680
Non-milking dairy cows (on feed)	684
Heifers (on feed)	407
Bulls (grazing)	874
Calves (grazing)	118
Heifers (grazing)	351.5
Cows (grazing)	582.5
Nursery swine	12.5
Grow/finish swine	70
Breeding swine	198

Low Carbon Fuel Standard

The Low Carbon Fuel Standard (LCFS) is a program developed by CARB in 2011 to decrease carbon emissions specifically in the transportation sector. The LCFS is implements a benchmark measurement known as Carbon Intensity (CI) to any fuel used in the state of California. Currently, the CI benchmark for 2022 of the two most common fuel sources in the transportation sector, gasoline and diesel, are 89.50 $gCO^2{}_e$/MJ and 90.41 $gCO^2{}_e$/MJ, respectively. Carbon Intensities measured by taking into consideration the complete lifecycle of the fuel which includes emissions involved in crude oil extraction, transportation to the refinery, refining, transportation to fueling stations, and finally the combustion of the fuel by vehicles. Benchmark values are assigned to each fuel source and a reduction in CI for all fuels of 20% from 2011 levels is to be achieved by the year 2030. The benchmark CI level may be achieved by the monitored entities in any way they'd like. Some chose to blend fuels such as corn ethanol with regular gasoline, or biodiesel with regular diesel. These allow the entities to decrease their fuel's CI and stay on track with the LCFS plan of decrease GHG emissions. The CIs previously mentioned are for California Reformulated Gasoline (CaRFG), which is a blend of 90% California Reformulated Gasoline Blendstock for Oxygenate Blending (CARBOB) and 10% Corn Ethanol. Based on 2010 production methods and the crude oil evaluation model, OPGEE, the CI of CARBOB is 101 $gCO^2{}_e$/MJ. The CI of Corn Ethanol is CI 70 $gCO^2{}_e$/MJ, which when blending with CARBOB creates CaRFG. This blended fuel has a lower CI value and with improvements in the aforementioned lifecycle variables can achieve the benchmark

CI score. (56)The blended method is limited by the many car manufacturers who warn that burning fuels with more than 10% corn ethanol voids the vehicles warranty. (57)

However, fuel blending is not the only route entities under the LCFS may take to decrease the CI score of the fuel. Fuel that have a CI above the benchmark value generate deficits, while fuels below the CI benchmark generate credits. Involved entities are allowed to prove decreased emissions through projects involving carbon, renewable fuels, hydrogen, etc. This is where RNG and anaerobic digester projects enter the LCFS system and are implemented to generate credits. They fall under Tier 2 of the LCFS Fuel Pathway Based Crediting system which includes fuel and carbon capture/sequestration projects and implement the GREET model to determine project specific CI scores. (56) In the case of AD projects, each one is unique and a CI score must be calculated for the project. Factors involved in the lifecycle assessment of an AD project involve how the feedstock is delivered to the plant and what happens to the effluent after producing RNG; does it need to be hauled away by a CO_2 emitting truck, or can it be irrigated directly into the crop fields with just pumps and limited/no further CO_2 emissions? In some instances, the plant itself many generate its own electricity from the biogas collected, or the trucks involved in the freight process of feedstock manure and effluent may be equipped to run off biogas/RNG, in these cases the carbon intensity of the project is decreased even further. Because AD projects prevent the methane from escaping into the atmosphere, which is regarding as 25 times more pollutant than CO_2 they are able to have a negative CI score. This can therefore make RNG projects profitable since their projects are generating credits for being below the LCFS benchmark, which can then be traded within the market by involved entities. (56) In addition to other legal requirements and paperwork, the project must only prove that the gas being injected into the grid has a theoretical pathway to California through the pipelines to qualify as a credit generator. The ability to separate the environmental attributes (EA) from the gas itself and sell the credits within the LCFS credit market in California is known as EA Displacement and is critical in the supply chain of RNG in the US. (56)

3.4.2 Washington Cap and Invest

The Washington Cap and Invest program was founded in May 2021 when it was signed into law by Governor Jay Inslee under the Climate Commitment Act. The program is multisectoral and will impose emission limitations of entities emitting over 25,000 ton of CO_2 annually. The program will limit emissions, assign allowances, and establish a climate investment account where revenues from sold allowances will go. Revenues in the investment account will go towards a variety of facets ties to the energy and public health sectors including the deployment of renewables and cleaner technology, GHG and co-pollutant reduction in suffering communities, employment transition for fossil fuel workers, and increased resilience to wildfires. The first compliance period of the program is scheduled to roll-out in 2023 following the rulemaking process of the Climate Commitment Act by the Washington State Department of Ecology. (58)

3.4.3 Regional Greenhouse Gas Initiative

The RGGI was launched and 2009 and was the first program in the US designed to decrease CO_2 emissions from the power sector. The program's current member states are all from the East Coast and New England areas including Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Rhode Island, Vermont, and Virginia. (58) Pennsylvania, a neighboring state in the region, is expected to join in 2022 under the guidance of Governor Tom Wolf and the Pennsylvania Department of Environmental protection. (59) Emissions from power plants within the region are monitored and capped and the power plants are able to trade allowances amongst each other. Allowances are sold in an auction fashion and have generated $3billion in economic values for member states. In addition to the economic benefits, emission levels have decreased by approximately 48% since 2005 and the RGGI has a goal of further reducing emissions such that 2030 levels are 30% lower than 2020. (58)

RGGI Offset Credits

Under the RGGI the possibility for offset credits also exists. Offset credits or allowances come from sectors or industries outside of the capped power generation sector who also emit pollutant GHGs which are converted into equivalent CO_2 emissions, or CO_2e. There are currently five qualifying project types for offset credits which include:

- Landfill methane capture
- Sulfur hexafluoride
- Forestry or afforestation
- End-use efficiency
- Avoided agricultural methane

RGGI member states cooperatively agreed on the regulatory framework for the five project types to ensure that the reduction in the CO_2e emissions or carbon sequestration is real, additional, verifiable, enforceable, and permanent. However, not all member states accept all types of additional project types. In fact, Delaware, Maine, Maryland, New Jersey, New York, and Vermont have removed end use efficiency, sulfur hexafluoride, and afforestation from their lists of qualifying offset credit projects in their respective regulations. Additionally, Massachusetts, New Hampshire, Rhode Island, and Virginia do not allow for any offset projects. Although not all member states support/allow equivalent project types within their state they do allow the power generators within their diction to trade offset credits awarded by a project of another RGGI member state. Table 3.4.3 shown below highlights the trading types and recognized offset projects of each state participating in RGGI. (58)

Table 3.4.3 RGGI member states and accepted trading types and projects

State	Carbon Trading	Offset Projects	Landfill Methane Capture	Forestry or affores-tation	Avoided agricultural methane	Sulfur hexafl-uoride	End-use efficiency	Offset Trading
Connecticut	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Deleware	Yes	Yes	Yes	No	Yes	No	No	Yes
Maine	Yes	Yes	Yes	No	Yes	No	No	Yes
Maryland	Yes	Yes	Yes	No	Yes	No	No	Yes
New Jersey	Yes	Yes	Yes	No	Yes	No	No	Yes
New York	Yes	Yes	Yes	No	Yes	No	No	Yes
Vermont	Yes	Yes	Yes	No	Yes	No	No	Yes
Massachusets	Yes	No	No	No	No	No	No	Yes
New Hampshire	Yes	No	No	No	No	No	No	Yes
Rhode Island	Yes	No	No	No	No	No	No	Yes
Virginia	Yes	No	No	No	No	No	No	Yes

There are also limitations to the quantity of offset credits a power generator is permitted to use under the RGGI Module Rule which sets the rules on the CO_2 Budget Trading Program. (60)Subpart XX-6.5 (3) states the following:

> *"For CO2 offset allowances, the number of CO2 offset allowances that are available to be deducted in order for a CO2 budget source to comply with the CO2 requirements of XX-1.5(c) for a control period or an interim control period may not exceed 3.3 percent of the CO2 budget source's CO2 emissions for that control period, or 3.3 percent of 0.50 times the CO2 budget source's CO2 emissions for an interim control period, as determined in accordance with Subparts XX-6 and XX-8"*(60)

Subparts XX-6 and XX-8 refer to the CO_2 Allowance Tracking System (COATS) and the Monitoring, Reporting, and Recordkeeping, respectively. Nevertheless, the number of offset allowances in the market may not exceed 3.3% of a power plants CO_2 budget for a set control period. (60) This ensures that the power plants are contributing towards decreased emissions in the long run by improving their own operation and not simply purchasing offset allowances. RGGI COATS is used to register offsets projects, track offset project Consistency Application and Monitoring and Verification Report submittals to RGGI member states, track the regulatory status of projects and the award/distribution of CO_2 offset allowances, and lastly, provide public access to offset project documentation. Under RGGI COATS there are three types of reports that must be electronically submitted by offset project sponsors, these include Consistency Applications, Monitoring, and Verification reports. Each member state may also include additional paperwork and procedures for the offset project application process. Upon approval the project may move forward and become a part of the CO_2 Budget Trading Program under RGGI. (60) However, only projects that have a Consistency Application deemed Complete, are available for the public view. (60) Currently only one project is available to view which is the New Beulah Landfill Gas Reconstruction Project with captures and destroys methane in Maryland. As of 2017 the project had been awarded 53506 offset allowances. (61)

The price of RGGI carbon allowances has risen steadily since their conception in 2009 initial price set around $2 per carbon allowance. Currently the price for one carbon allowance, or ton of CO_2e, near $14. Throughout the previous thirteen years the allowances have even been seen trading as high as $34.38 in 2011 and low as $1.25 in 2012 as shown in below Table 3.4.3(61)

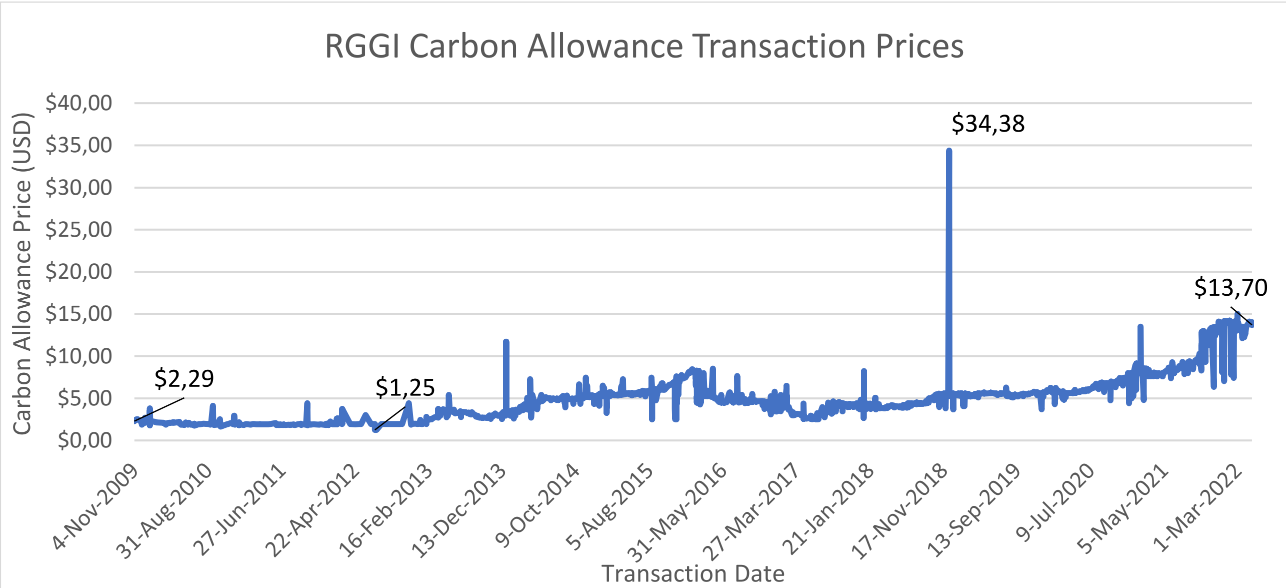

Figure 3.4.3 Fluctuations in RGGI carbon allowance transaction prices

Additionally trading volumes have fluctuated over the years as well. In the 2015-2017 period the trading volume was at its highest with over 608 million carbon allowances being traded during that Control Period. As shown in Figure 3.4.4, current Control Period transaction volumes hints towards a new all-time high from trading volume with over 328 million carbon allowances being traded prior to June 2022, only halfway into the current Control Period. (62)

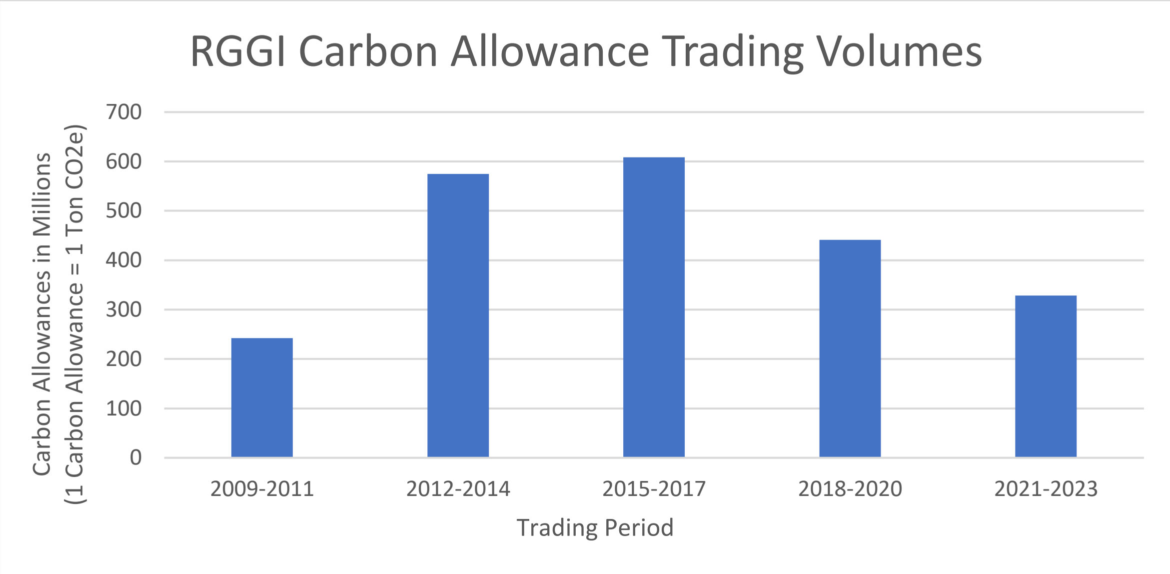

Figure 3.4.4 Fluctuations in RGGI carbon allowance trading volumes.

3.5 Renewable Identification Number

The Renewable Index Number (RIN) is another program found in the US under the Renewable Fuel Standard Program. This nationwide program focuses on the reduction in GHG emissions through the use of renewable fuels. The RNG produced from anaerobic digestors qualifies as a renewable fuel with a D-code of D-3. There are four main categories of D-codes which range include D-3, D-4, D-5, and D-6. A later sub-category was added for D-3 fuels which is D-7, renewable diesel produced from cellulosic. A summary of the RIN fuels is shown below in Table 3.5.1. (63)

Table 3.5.1 D-Codes of RINs

D-Code	Renewable Fuel Type	Additional Information
3	cellulosic biofuel	May be produced from cellulose, hemicellulose, or lignin. Must reduce GHG lifecycle emissions by 60% with respect to petroleum baseline.
7	cellulosic biodiesel	In addition to D-3 requirements D-7 must be specifically cellulosic biodiesel
4	biomass-based diesel	Includes biodiesel and renewable diesel. Must reduce GHG lifecycle emissions by 50% with respect to diesel baseline.
5	advanced biofuel	May be made from any biomass feedstock except corn starch ethanol. Must reduce GHG lifecycle emissions by 50% with respect to petroleum baseline.
6	renewable fuel	May be made from corn starch ethanol and any other renewable fuel. Must reduce GHG lifecycle emissions by 20% with respect to the average 2005 petroleum baseline (Applies to plants commenced after Dec. 19, 2017).

A RIN undertakes a lifecycle shown below in Figure in which it is produced by a qualifying project and then traded within the market. Entities that are required to participate in the market must meet their quota. (63) According to the EPA:

"RINs are the credits that obligated parties use to demonstrate compliance with the standard. Obligated parties must obtain sufficient RINs for each category in order to demonstrate compliance with the annual standard." (64)

RINs are thus used by obliged entities to ensure compliance with the restrictions set upon them by the EPA. Said entities acquire these RINs through the EPA Moderated Transaction System (EMTS) and retire them within one year of the vintage date, i.e. the year in which the RIN was generated. The entities are obliged to use the renewable fuels associated with the RINs and by doing so can retire the acquired RINs to meet compliance by the end of the compliance year which ends on March 31. (63) Figure below shows a general overview of the RIN lifecycle and is accompanied by Figure which shows a more detailed pathway.

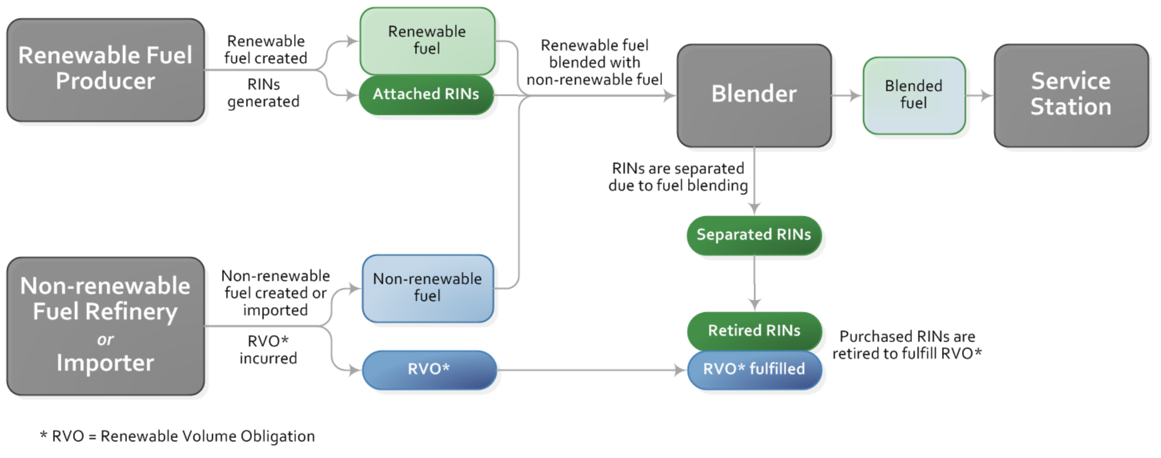

Figure 3.5.1 RIN Lifecycle (63)

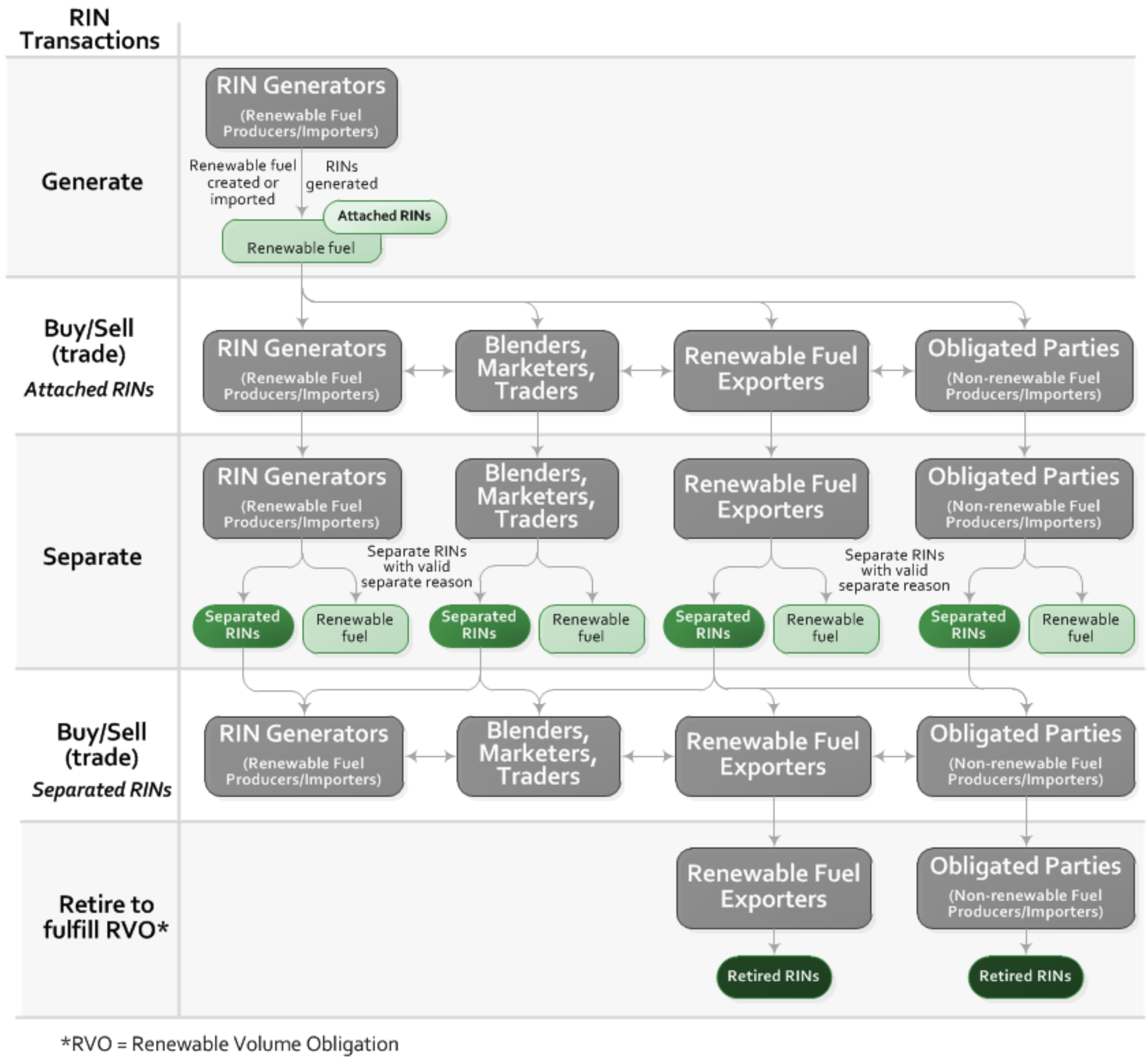

Figure 3.5.2 RIN transaction pathway with EMTS (63)

4 Anaerobic Digester Case Studies

4.1 US Case Studies

As of April 2022 there are 38 AD's under construction in the US. A majority of which are Mixed Plug Flow (13) followed by Complete Mix (11), then Covered Lagoon (5). The AD type of the remaining 9 digesters is unknown or unspecified at this time in the EPA database. (18) Figure 4.1.1 below highlights these figures.

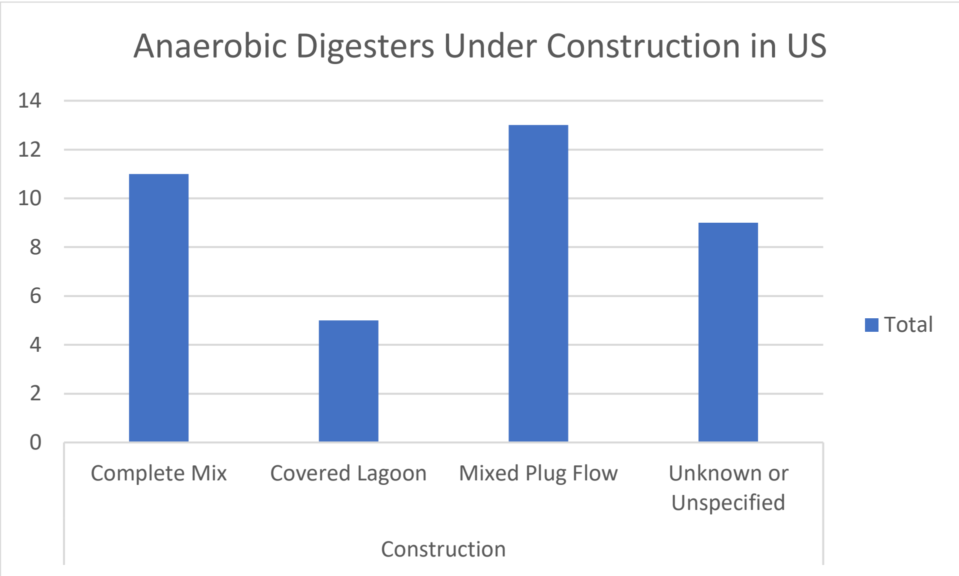

Figure 4.1.1 Anaerobic digesters under construction in the US as of April 2022.

4.1.1 Caballero RNG Project

The Caballero RNG Project is a dairy manure AD located in Eloy, Arizona owned by Brightmark. The project is being realized in conjunction with Venture Engineering & Construction, who has been carrying out the engineering, procurement, and construction (EPC) of the project. Excavation of the plant's 20 million gallon (75,710 m^3) lagoon digester hole began professionally in October, 2021 by Performance Grading and required approximately one month for completion. The plant is still under construction and has been lined with an impermeable liner to protect neighboring ecosystems and underground water tables. Additionally a sand lane has been constructed which will ensure sand/sediment fallout prior to reaching the lagoon. Upon completion the plant will inject 73,000 MMBtu of RNG annually into the nearby natural gas grid, equivalent to 77TJ or 21.4GWh. The plant is currently undergoing mechanical and electrical completion and will be operational 2022. (3, 65)

Table 4.1.1 Caballero RNG Project data (3)

Caballero RNG Project		**Notes**
Construction Start	November 2021	
Commissioning	October 2022	Estimated date
Production of Biomethane	1.9564 Mio. Nm^3/a	Equivalent to 73,000 MMBTU/year
Avoided Emissions	33,000 metric tons/year	Net avoided GHG emissions
Methane Content (CH_4)	>99%	
Heat Supply	None	Subject to changes in ambient temperature
Digester Lagoon	75710 m^3	Double-lined digester (20 million gallons)
Substrates	8,800 dairy cow farm	
OLR	1.65 $kgVS/m^3day$	Supplied by to 500,000-550,000 gallons of dairy cow waste per day
HRT	38-40 days	Approximation
Total Solids Concentration	2%	
Upgrading Method	Membrane	

Figure 4.1.2 below shows an aerial view of the Caballero Dairy Farm where construction began in November 2021. The current lagoons can be seen in the image which have no biogas capture technology and currently allow GHG emissions from 8,800 dairy cows to escape into the atmosphere. The additional Figures show the progress of the project as of May, 2022. (3)

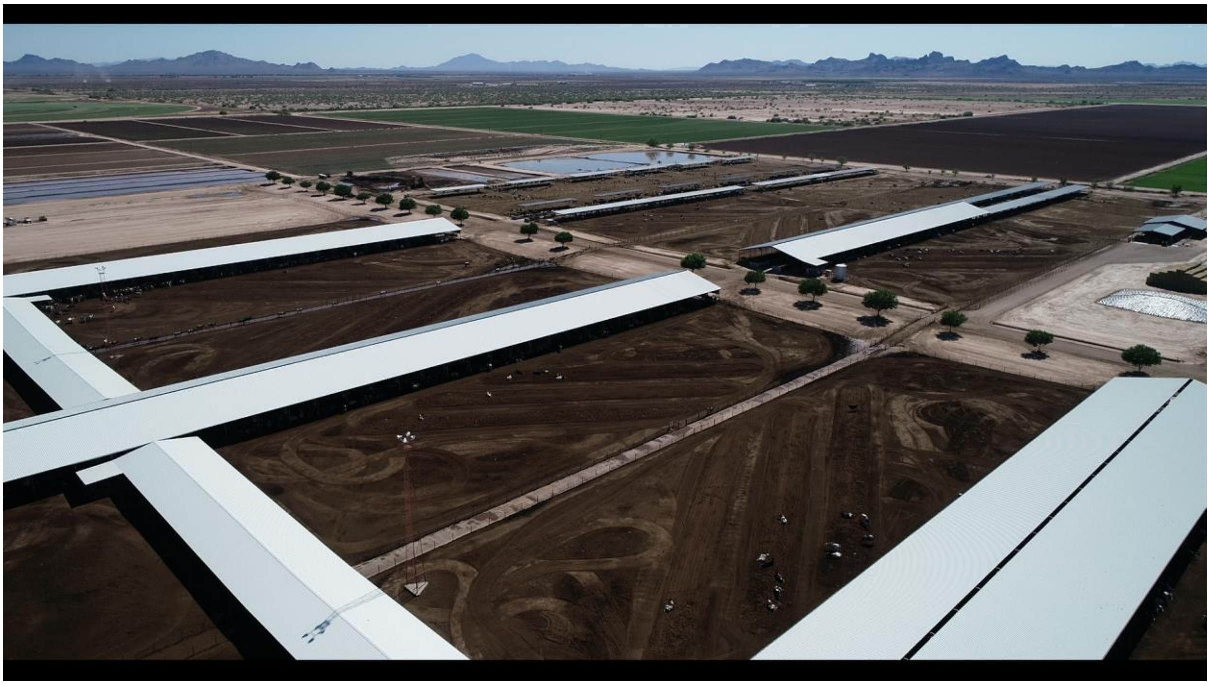

Figure 4.1.2 Aerial view of Caballero Dairy Farm in Eloy, Arizona prior to lagoon excavation

Figure 4.1.3 Lagoon excavation nearing completion

Figure 4.1.4 Double-lined lagoon.

The double lined lagoon was selected by Brightmark as a design criterion with the environment and water table in mind since the digester reaches depths greater than 30ft. (3)

Figure 4.1.5 Sand lane at Caballero RNG Project lagoon

Because the Caballero Dairy uses sand as a bedding source the sand lane was built to removal all sand particles from the feedstock prior to entering the lagoon. Otherwise, the lagoon would fill with sand and drastically change the digesters volume over time and would in turn increase the HRT since the OLR of feedstock from the dairy is constant. This would likely result in expulsion of effluent prematurely that still has biogas producing potential. (3)

Lastly, Figure 4.1.6 shows a 3D model of what the Caballero RNG Project will look like upon completion in October 2022. The plant will feature a covered lagoon (cover not modeled in rendering) accompanied by a upgrading station and flare to be used only when maintenance or other issues require diversion from the upgrading facility or the natural gas grid for injection. (3)

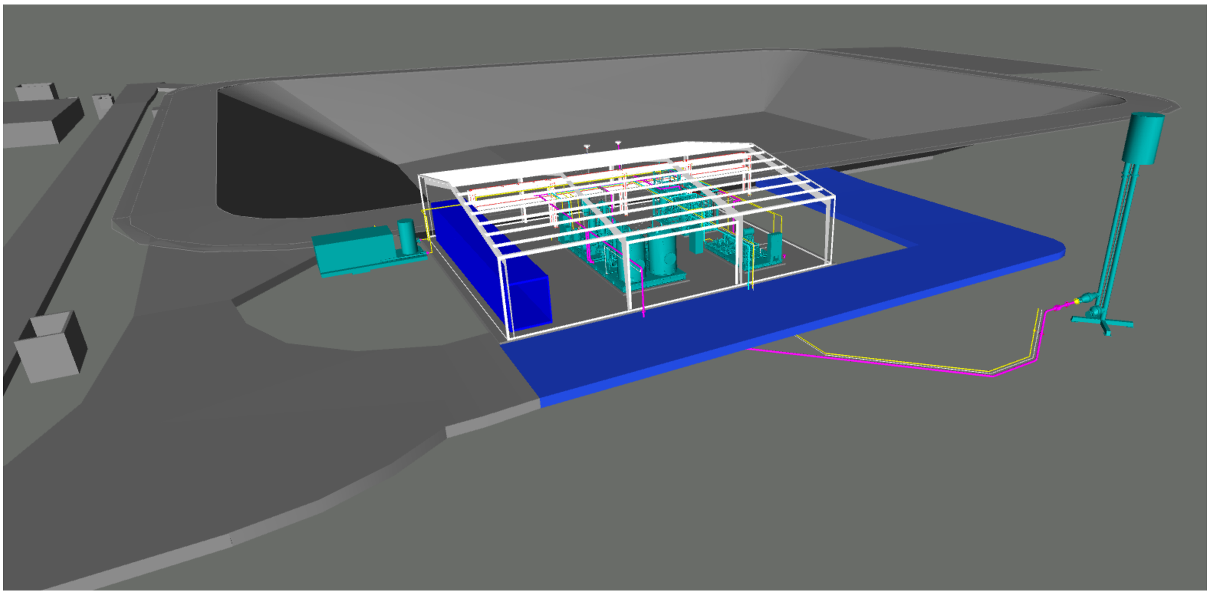

Figure 4.1.6 3D Rendering of Caballero RNG Plant

4.1.2 Castor RNG Project

The Castor RNG Project is located in Coopersville, Michigan and is another AD fed by dairy cow manure owned by Brightmark but followed the EPC guidance of Venture Engineering & Construction. The castor RNG Project has implemented a plug flow digester consisting of four parallel chambers that will handle the feedstock from three dairy farms, Beaver Creek Farm, Den Dulk Farm, and River Ridge Farm to produce approximately 8.8038 Mio. Nm^3/a (328,500 MMBTU/year) of biomethane. The plant is located at the Beaver Creek Farm which will pump its dairy cow manure directly to the digester while the dairy manure from the other two participating farms will be delivered by truck. The RNG will then be injected into the nearby natural gas pipeline. (3)

Table 4.1.2 Castor RNG Project data (3)

Castor RNG Project		Notes
Construction Start	January 2021	
Commissioning	June 2022	Ongoing as of May 2022
Production of Biomethane	8.8038 Mio. Nm^3/a	Equivalent to 328,500 MMBTU/year
Avoided Emissions	98,783 metric tons/year	Net avoided GHG emissions
Methane Content (CH_4)	>99%	
Heat Supply	Hot water boilers	
Plug flow digester	38720 m^3	4 individual plug digesters in parallel (10.2 million gallon capacity)
Substrates	15,000+ dairy cow farm	
OLR	2.84 $kgVS/m^3day$	Equivalent to 3,169,200 lb/day of dairy cow manure
HRT	22 days	
Total Solids Concentration	9%	
Upgrading Method	Membrane	
Solids Separation	Screw press and tumble dryer	Recycles bedding from effluent
Plant's Annual Electricity Consumption	14.95 GWh	Assuming plant power demand of 1797kW with annual operating time of 8760h and load factor of 0.95
Plant's Annual Natural Gas Consumption	3.999 Mio. Nm^3/a	Consumed by Boilers and Bedding Dryer (17MCF)
Plant's Theoretical Electrical Capacity	30.73GWh	Calculated from Equation 4.1
Plant's Theoretical Net Electrical Production	15.78GWH	Found by subtracting the Plant's Annual Electricity Consumption from the Plant's Theoretical Electrical Capacity

Equation 4.1 is used to calculate the plant's theoretical electrical capacity.

$$EE = PE * n \qquad \textit{Equation 4.1}$$

In Equation 4.1 EE represents the Electrical Energy produced from PE, the Primary Energy devoted to electricity production. In this case the PE devoted to producing electricity is equal to the 8.8038 Mio. Nm^3/a produced by the plant deducted by the 3.999 Mio. Nm^3/a consumed by the plant itself. Yielding a PE of 4.8048 Mio. Nm^3/a. An efficiency of 55% was selected for the natural gas Electricity Power Plant to approximate the electricity that could be produced if the biomethane was used directly for electricity production rather than grid injection. The Castor project has a small consumption of natural gas with respect to its annual production. Conversion used included 1ktoe = 1,131,568 Nm^3 of natural gas and 1GWh = 0.086ktoe. (3)

In Figure 4.1.7 are some of the dairy cows consuming mixed grains at Beaver Creek Farm, the diet of the cows with greatly effect the macronutrient content of their manure and later the quality of the biogas produced from the plug flow digester. (3)

Figure 4.1.7 Beaver Creek Dairy's cows consuming grain mixture.

Another crucial piece of equipment in the Castor RNG Project is the boiler house show in Figure 4.1.8. The boiler house is comprised of 2 boilers which run off the gas produced by the plant to heat water and maintain healthy temperatures within the plug flow digester for the anaerobic bacteria. (3)

Figure 4.1.8 Boiler building

Upon extraction the biogas can head in two directions, ideally towards the biogas upgrading facility found in Figure 4.1.10 or in the rare case of maintenance in the facility towards the two flares situated at the end of the partially below grad plug flow digester as shown in Figure 4.1.9. (3)

Within the upgrading facility the biogas undergoes a series of procedures to take it from 50% methane content to >99%. This requires the removal of H_2S and CO_2 through various scrubbers and polishers. The H_2S polishers may be seen in Figure 4.1.11. (3)

Figure 4.1.9 Flare from plug flow digester in case upgrading facility can not receive raw biogas due to maintenance.

Figure 4.1.10 RNG upgrading facility

Figure 4.1.11 H_2S Polishers

The remaining effluent from the digester are pumped into the solids separation facility where they undergo water removal by a screw press to extract a bulk of the liquids followed by the tumble dryer to remove the remaining moisture. Next, the dried effluent is transported outside by a conveyor belt for storage under roof until it is recycled by the farms as bedding for the cows, completing just one portion of the biogas circular economy as discussed in Chapter 1.3. Figure 4.1.12 below shows the solids separation facility with the screw presses in the foreground and the tumble dryer in the background. (3)

Figure 4.1.12 Solids separation facility for recycled bedding.

The revenue streams of the Castor project includes the selling of the natural gas as well as offset credits in the form of RINs and LCFS. The recognition of the project as a RIN is predicted to make up for 26.02% of its revenue. The valuable LCFS offset credits in the California market will contribute 70.64% of the plant's revenue, while the remaining 3.34% will comes from the natural gas itself. This proves that biogas capturing and biomethane production has significantly more value from the offset programs than they do from the RNG itself. Figure 4.1.13 highlights this visually. (3)

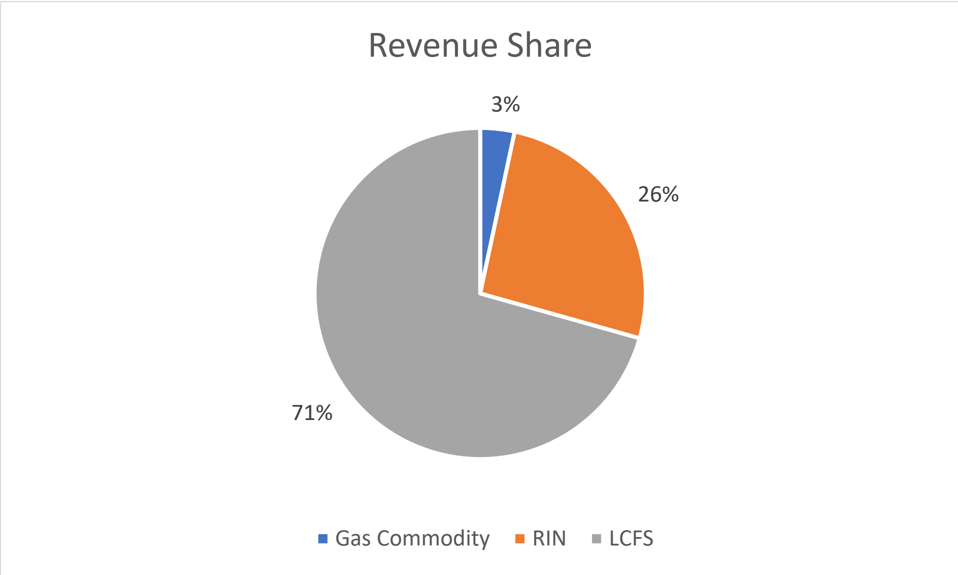

Figure 4.1.13 Revenue Shares

4.2 European Case Studies

Much like in the US, Europe has a wide variety of biogas producing methods, one of the most common methods is from AD's. Europe's biogas production market is dominated by the agriculture residue feedstock but varies from country to country. The biogas producing plants of Germany, Austria, Latvia, Hungary, and Italy, in particular are dominated by energy crops and agricultural residue with over 70% of their production coming from these feedstocks. Germany is Europe's leader in biogas production with over 9,500 operating plants, 200 of which have biomethane upgrading capabilities allowing for injection into the natural gas network. (66)

4.2.1 Arneburg Biomethane Refinery

Germany is the leader in European biogas and is also one of the countries with the most extensive and well documented databases. The Arneburg Biomethane Refinery operated by Weltec Biopower is one of Germany's largest biomethane upgrading plants and relies on energy crops for its production. Located in the Katmark industrial and Commercial Zone, the plant is composed of four digester tanks with a capacity of 4,900 m^3 each and six storage tanks with a capacity of 5,000m^3 each. The plant has an overall biogas production of 1,650 m^3/h of biogas and consumes 200 m^3 of this fuel to meet the heat needs of the plant. Through the amine wash upgrading system 700 m^3/h of biomethane are produced which is supplied to 5,000 homes for power and heating needs. The stainless-steel digester tanks are supplied with approximately 70,000t of substrates per year by the solid matter input system. Table 4.2.1 highlights these points. Photos courtesy of Weltec Bipower are shown below as well in Figure 4.2.1, Figure 4.2.2, and Figure 4.2.3. (67)

Table 4.2.1 Arneburg Biomethane Refinery Data (67)

Arneburg Biomethane Refinery		Notes
Construction Start	2012	
Commissioned	2013	8 months to construct
Production of Raw Biogas	12.2 Mio. Nm^3/a	
Production of Biomethane	5.17 Mio. Nm^3/a	
Biogas Consumption	200 Nm^3/h	Hourly consumption of biogas by the plant for its own heat needs
Methane Content (CH_4)	>99%	
Heat Supply	Biogas boiler	
Digester	4x 4,900m^3	Stainless steel tanks
Digester Temperature	40 °C	Mesophilic/thermophilic boundary temperature
Storage Tank	6x 5,000m^3	
Substrates	70,000 t/a (Maize cereal silage, cereals)	Crop residues
Upgrading Method	Amine Wash	
Plant's Annual Biogas Consumption	1.48 Mio. Nm^3/a	The Arneburg plant uses raw biogas for its heat needs

The German Renewable Energy Act (in German: *Erneuerbare-Energien-Gesetz*) (EEG) no longer incentivizes the use of energy crops and instead has shifted their efforts towards biogas being produced from manure and crop waste residues. The initial incentives in Germany for energy crops and biogas in the 2000s caused it to become a leader in biogas production; however, with the phase outs of these incentives the construction of new plants has stagnated. (68) It can be presumed that due to the policy shifts of RED II and RED III that the Arneburg Biomethane Refinery is generating a majority of its profits through selling the upgraded biomethane to the grid and not from carbon credit schemes like the LCFS and RIN found in the US projects. The European Environmental Bureau has even stated that RED III should see the complete phase out of biogas by 2045, suggesting incentives for biogas in Europe may be on the decline even further. (69)

Figure 4.2.1 Aerial View of Arneburg Biomethane Refinery

Figure 4.2.2 Biomass substrate loading area. The plant receives 70,000tonnes per year

Figure 4.2.3 Mechanical Room of Arneburg Biomethane Refinery

5 Outlook for the Future of Biogas

5.1 The Influence of Geopolitical Events

The war launched by Russia against Ukraine has caused a rippling effect felt throughout the world and Europe. This shock has been particularly strong in the energy sector with the European Union realizing their dependency on Russian natural gas and oil imports and lack of energy security in the fossil fuels sector.

On Wednesday, May 18, 2022 European Commission President Ursula von der Leyen stated in Brussels "We are taking our ambition to yet another level to make sure that we become independent from Russian fossil fuels as quickly as possible, "This statement came during European Union's unveiling of a €300billion package to wean the EU's 27 member states off Russian energy. The package will strive to increase energy security while simultaneously meeting GHG reduction goals set by the EU for 2030 and carbon neutrality by 2050. (70)

These announcements come following the start of the war and the closing of a newly built $11billion pipeline connecting Germany and Russia by way of the Baltic Sea known as Nord Stream 2. (71) The pipeline traversed many underwater obstacles through the Baltic Sea including other pipelines and fiber optic cables which called for extensive engineering and construction methods. These included under-water trench excavations to avoid hydro-dynamic forces, rock bed supports to avoid free spans in rocky areas, and rock mattresses to cross other cables and pipelines. (72)The project construction was completed in September 2021 and was only missing final inspections to be performed by Germany, however, the pipeline may never see Russian gas flowing through it. (73) The pipeline had a total length of 1,230km and would have annually carried 55 billion cubic meters of natural gas from Russia to Germany, doubling the 55bcm already being supplied by the original Nord Stream pipeline which commissioned in 2012. (73)

5.2 Future Potential of Biogas in Europe

The future of biogas in Europe is influenced strongly by both geopolitical factors as previously seen in addition to policies such as the EU Green Deal. Even with a well-established biogas market in place there is still a tremendous amount of room for growth of the biogas market in Europe. The EBA believes the biogas sector will undoubtedly play a role in helping the EU achieve its legally binding target of 32%

renewable energy by 2030. In addition to a greater biogas penetration and renewable penetration as a whole, the EBA has an outlook for the biogas sector to play a bigger role in the circular economy between industry, people, farms, electricity and heat production, and organic fertilizers through the use of AD's. (74)

The EBA also highlights the importance of flexible energy production in today's day and age which biogas and biomethane in particular are excellent candidates for due to their ability to be compressed and stored to help meet seasonal demand. (74) With the ongoing geopolitical issues energy security risks are at an all-time high for Europe, so much so that as of May 2022 the EU has set a mandatory gas storage level at 80% for all EU member states by November in preparation for November. (75)

Harmen Dekker, CEO of the EBA has said the following in response to the need to wean Europe off Russian gas imports:

Europe needs to urgently diversify and reduce its dependence on Russian gas whilst stepping up on the ambition for the climate targets. The sector is ready to deliver the 35 bcm by 2030 proposed by the EU and calls for the inclusion of this target in the recast of the Renewable Energy Directive (REDIII), currently under development. Close cooperation between the European Commission, Members States and the biomethane value chain will be required to ensure immediate action following today's proposals. The biomethane target represents over 20% of the current EU gas imports from Russia. By 2050, this potential can triple, growing well over 100 bcm and covering 30-50% of the future EU gas demand."

If the EU can achieve the EBA's claim of 35bcm by 2030 that would be nearly double today's production of 18bcm annually. Given the current situations and pre-existing goals, the success of the biogas sector seems probable and is linked to many factors, but surely the role of GO's and the EU ETS for traceable and reliable cross-border trade of biomethane will be instrumental. (74)

5.3 Future Potential of Biogas in the US

The biogas industry in the US has an enormous potential and is expected to grow tremendously over the next decade. The ABC estimates that there are 14,958 new sites that show promising potential as future biogas producers. Of these sites, 8,574 are farm related which would feed ADs with dairy, poultry, and swine manure. The ABC identified another 3,748 water recovery facilities that could upgrade their system to include biogas capturing technologies for the facility's own use or distribution. Currently 380 of the water resource facilities are producing biogas but not using it. The food waste sector is another area with huge potential for biogas producing potential with the ABC identifying 2,036 new sites. Lastly, there are 415 landfills that are flaring their landfill gas rather than upgrading it to RNG quality for natural gas grid injection or constructing a CHP plant at the landfill to burn the biogas directly for useful electricity and heat rather than flaring it. (76)

The addition of these nearly 15,000 sites would spell out an electricity production of 103 trillion kilowatt hours annually just from biogas and an emission reduction of approximately 543 million metric tonnes of CO_2e annually, equivalent to the removal of emissions from 117 million passenger vehicles from the road. (76, 77)

The economic impact of the biogas sector development would also be substantial at $45 billion in capital deployment for construction activity alone. Estimations equate this to the creation of 374,000 short term construction jobs and 25,000 permanent jobs for plant operation. The ABC also predicts the impacts on involved supply chains to be even greater, (76)

The US EPA has allocated $1.84 million for food scrap AD projects with 11 different organizations as of March 7, 2022. Beyond aiding in GHG emissions the EPA also ensured that nearly half of the $1.84 million dedicated to the AD projects will go towards underserved communities located near the project locations. Carlton Waterhouse, deputy assistant administrator for the EPA Office of Land and Emergency Management, made the following statements (77):

"Anaerobic digestion is an important way to ensure essential nutrients are recirculated into our ecosystems,"

"This kind of innovation helps communities reduce food waste that could end up in landfills while capturing methane for use, instead of having it go into the atmosphere."

RNG is also a crucial player in decarbonizing individual corporations. UPS announced in 2020 that they made an agreement with Clean Energy Fuels Corp. to purchase 170-million-gallon (644,000 m^3) equivalents of RNG through 2025. UPS has the goal to diversify its fuel usage and aims to have 40% of their makeup from alternative fuel sources by 2025. This shift will aid in their goal to decrease fleet GHG emissions by 12% by 2025. Clean Energy Fuels reported on UPS's purchase and received the following statements from Mike Casteel, UPS director of fleet procurement (79):

"The world has a trash problem. And the world has an emissions problem. Renewable natural gas, produced naturally from bio sources such as landfills and dairy farms, not only turns trash to gas, but it turns it into clean *gas,"*

"Since RNG is supported by existing national infrastructure used to transport natural gas, it's a winning solution that will help UPS to reach our ambitious sustainability goals. At the same time, we hope our unprecedented seven-year commitment serves as a catalyst for wider adoption of RNG by other companies."

The impact of this deal between UPS and Clean Energy Fuels Corp. will not be felt solely in the US. In fact, the UPS fleet is comprised of over 6,100 CNG and LNG vehicles in Argentina, Belgium, Canada, France, Germany, the Netherlands, Thailand, the United Kingdom, and the United States. (79)

However, investments in the US biogas sector don't just come from within. On February 3, 2022, Air Liquide, world leader in gases, technologies and services for Industry and Health, and a major player in the biogas industry announced their plans to construct their largest biomethane facility to date in Rockford, Illinois, US. The plant will have a produce biomethane from a solids waste treatment plant and will have a production capacity of 380GWh and is scheduled to be operational by the end of 2023. Worldwide, Air Liquide currently has 21 biomethane operational production units with a production capacity of 1.4TWh, the production capacity will reach 1.8TWh upon the commissioning of a LFG plant in Delavan Wisconsin at the end of Q2, 2022 and the Rockford plant. This will be a 28.5% increase in the group's production capacity in just 2 years. (80)

Given the great potential of 15,000 untapped sites, the incentivizing programs such as the LCFS and RINs, and the potential adoption of stricter GHG emission policies, the US biogas market is primed for immense expansion and growth in the upcoming years.

6 Conclusion

Anaerobic digesters prove to be a solution to avoiding methane emissions from landfills, wastewater treatment plants, and farms. Anaerobic digesters have also been heavily implemented in Europe from incentive programs, specifically concerned with energy crops however policy shifting under RED III has drastically slowed down the growth of the biogas sector in leading EU countries like Germany. Under RED III biogas will be phased out in the EU by 2045; however, a more appropriate approach would be to phase out energy crop biogas production and expand methane capturing technology to landfills, wastewater treatment plants, and farms. Through this expansion route methane emissions from those industries will be minimized and the land previously used for energy crops can be used for other purposes, such as food production followed by digestors of crop residues and fertilization products from final effluents. Care will need to be taken concerning the sustainability practices of such a biogas value chain and unique assessment should be applied to each case. Better recognition of the benefits of sustainability produced biogas should be recognized by the EU ETS to integrate a better functioning system for biogas with more incentives as criticized by the EBA. Although the European biogas sector is more developed and established than that of the US its current policies are pointing it in a direction of decline. Recent geopolitical events concerning Russia and Ukraine may cause a shift towards more biogas production. The RePowerEU Communication released on March 8, 2022 already called for biomethane to scale up to 35bcm by 2030, 10% of current natural gas demand in Europe. (81)

Within the US the biogas industry shows promising growth thanks greatly to the LCFS and RIN programs but also shows promising room for growth into other carbon crediting systems such as RGGI and groups forming in other states. Growth in the US is very promising with nearly 15,000 potential sites identified for biogas production in the US, a majority of which are manure based (8,574). As more projects come online one could expect the value of offset credits may decrease due to a greater supply; however, polices controlling the penalties for non-compliance will greatly dictate the demand for the offset credits. Additionally, policies focused on the transport sector will greatly affect the growth of biogas, and specifically biomethane (RNG) in the US if further restrictions are set on freight vehicles. (77)

In conclusion, more anaerobic digesters are expected to be constructed in the US accompanied by the promising growth of the biomethane markets. Lastly, US and European biomethane growth is greatly dependent on the adoption of proper policies.

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