Hacettepe University Graduate School of Social Sciences
Department of Economics

ECONOMIC ANALYSES OF UTILIZATION OF BIOMETHANE IN TURKEY

Batuhan GÜRLER

Master's Thesis

Ankara, 2024

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The jury finds that Batuhan Gürler has on the date of 06/06/2024 successfully passed the defense examination and approves his Master's Thesis titled "Economic Analyses of Utilization of Biomethane in Turkey".

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ETİK BEYAN

Bu çalışmadaki bütün bilgi ve belgeleri akademik kurallar çerçevesinde elde ettiğimi, görsel, işitsel ve yazılı tüm bilgi ve sonuçları bilimsel ahlak kurallarına uygun olarak sunduğumu, kullandığım verilerde herhangi bir tahrifat yapmadığımı, yararlandığım kaynaklara bilimsel normlara uygun olarak atıfta bulunduğumu, tezimin kaynak gösterilen durumlar dışında özgün olduğunu, **Dr. Öğr. Üyesi Shihomi ARA AKSOY** danışmanlığında tarafımdan üretildiğini ve Hacettepe Üniversitesi Sosyal Bilimler Enstitüsü Tez Yazım Yönergesine göre yazıldığını beyan ederim.

Batuhan GÜRLER

ABSTRACT

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Biomethane is a globally flourishing, renewable, and sustainable fuel and is considered to have the potential to be a promising solution in the future because of its benefits in terms of waste management, carbon reduction potential, and cost competitiveness. The study analyzes to determine the economical feasibility conditions of a prospective biomethane facility for Turkey as well as the carbon reduction potential of the facility. Because the raw material to produce biomethane is biogas, the study analyses the main determinants of the total cost of biogas firms producing electricity. Our findings include (1) repair maintenance costs, labor force costs, and raw material cost are the main determinants of the total cost of the firms. In addition, biogas production cost value is calculated hypothetically to utilize in the hypothetic biomethane facility as raw material as a cost component. The feasibility analysis of the hypothetic facility compares different biomethane production technologies on different scales. It is resulted that the unique feasible technology is the Pressurized Water Scrubbing method. Moreover, Hotspot fields are produced for biogas potential for layer chicken manure and cattle manure to suggest a province for the potential biomethane facility. In this respect, Çorum and Kars are considered as favorable places. Lastly, it is concluded that the mentioned biomethane facility production would cause 81,952 tons yearly net carbon savings which is equal to $15,161,094 social benefits yearly.

Keywords

Sustainability, Waste Management, Renewable Energy, Biomethane, Feasible Technology, Carbon-Neutral

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BIP : Biomethane Industrial Partnership
BımSchG : Federal Emission Control Act
Bio-LNG : Bio-liquefied natural gas
Biokraft-NachV : Biofuel Sustainability Regulation
BOTAŞ : Petroleum Pipeline Corporation
CBA : Canadian Biogas Association
CBAM : Carbon Border Adjustment Mechanism
CFA : Central Financial Assistance
CNG : Compressed Natural Gas
CO2 : Carbon dioxide
EBA : European Biogas Association
EEG : Renewable Energy Sources Act
EMRA : The Republic of Turkey Energy Market Regulatory Authority
EPA : Environmental Protection Agency
ETS : The EU Emission Trading System
EU : European Union
FiP : Feed-in Premium
FiTs : Feed-in Tariffs
GGSS : Green Gas Support Scheme
GHG : Greenhouse gas
HPWS : High-pressure water scrubbing
IEA : International Energy Agency
IMO : International Maritime Organization
LCFS : Low Carbon Fuels Standard
LNG : Liquefied natural gas
OECD : Organisation for Economic Co-operation and Development
OLS : Ordinary Least Squares
Nm3 : Normal Cubic Meter
RES : Renewable Energy Directive
RFS : Renewable Fuel Standards

SDS : Sustainable Development Scenario
Sm3 : Standard Cubic Meter
U.N. : United Nations
USA : United States of America

INTRODUCTION

Biomethane is a promising fuel that is a perfect substitute for natural gas. It is categorized as a carbon-neutral fuel because it is a type of biofuel (Solakivi, Paimander, Ojala, 2022). The net zero emission target cannot be reached unless biogas, and hence biomethane, which can be produced by recycling different kinds of waste such as municipal, agricultural and industrial waste, is widely deployed via its wide range usage in different purposes such as heating, electricity production, and vehicle fuel (Anaerobic Digestion and Bioresources Association,2020). The utilization of biomethane affects the economy directly due to its cost efficiency compared to other fuels (EBA, 2022) and indirectly via positive externalities (D'Adamo et al., 2019; Franco et al., 2021) through waste management which converts waste to fuel (Ahmed et al., 2021). The usage of the fuel supports energy security, which is a key driver of the economy, as domestic production reduces the risks associated with international supply restrictions. (Ahmed et al., 2021). These characteristics suggest that the adoption of biomethane is motivated by considerations such as environmental concerns, economic feasibility, and energy security.

Biomethane results in decarbonizing different sectors, such as manufacturing (Ahlström et al., 2020), electricity production and heating, and transportation (Anaerobic Digestion and Bioresources Association, 2020) in which fossil fuels are used. It is thought that it might be an important fuel to reach the International Maritime Organization’s (IMO) emission reduction goal by 2050 which was declared in 2018 (Mallouppas et al., 2023). With environmental concerns, as of 2024, many organizations and 195 countries including the European Union (EU), United States of America (USA), China, and India have announced carbon reduction policies, targets, and schemes (ENERGY & CLIMATE INTELLIGENCE UNIT, 2024; United Nations Climate Change, 2024). The current EU legislation derived from “Fit for 55” promotes the use of biomethane source (Mallouppas et al., 2023). In addition, the “Carbon Border Adjustment Mechanism” (CBAM) takes this fuel as a zero-emission category (EUROPEAN COMMISSION, 2023) and the EU views this fuel as a green fuel to back up and raise its share in energy composition. On the other hand, because of the difficulty of electrifying aviation and maritime modes of transportation, biomethane will seek opportunities in these areas as well (Lawson et al., 2021).

To make an investment decision for biomethane, its viability should be proven (Lauer et al., 2018). In this regard, biomethane can demonstrate its economic feasibility through the price mechanism by competing with other fuels in the market. Alternatively, incentives with environmental concerns may be needed to support biomethane production (Gupta et al.,2022). Its cost-competitiveness analyses compared with other fuels are conducted in the literature and it is found that biomethane has a cost advantage against hydrogen and electricity (Giocoli et al., 2023). Furthermore, to substitute fossil fuels, it remains competitive across different historical price scenarios (Pääkkönen et al., 2019). While biomethane is becoming increasingly price-competitive and economically viable (Waste Management World magazine, 2023), it is predicted that biomethane production cost will be lower by around 25% than the current production cost by 2040 (Luo et al, 2023).

In terms of waste management, there would be positive externalities and extra revenue for biomethane production facilities because people would be willing to pay fees for their waste to be collected (Kinnaman, 2009). This creates a waste management economy that brings additional revenues through the recycling of waste. Moreover, in the biomethane production process, valuable co-products such as liquified CO2 (Vernersson, 2022) can be obtained. This CO2 is commercially useful for the food industry and contributes to lower emissions through carbon capture. Additionally, digestate can be obtained, providing a sustainable source of nutrients in agriculture by displacing conventional mineral fertilizers (Balcioglu et al., 2022). Hence, this fuel will enhance sustainability in our economy, and promote rural development and waste management.

For the energy security, raw material potential for biomethane production takes a vital role because high biomethane production potential can help to reduce energy import dependence and more domestic energy production when it is realized. However, because biomethane can be produced from various raw materials, predicting the production potential is very difficult. It can be produced by using animal manure, vegetable, slaughter wastes (Balcioglu et al., 2022), or industrial refuse such as wastes from the chemical industry, wood industry, or catering industry (Lawson et al., 2021). It can be thought that Turkey has an important biomethane production potential and this implies a domestic substitution opportunity for import fuels. For example, manure-based biomethane potential is assumed about 3.163 billion m^3 in 2019 (Şenol et al., 2021) and it is equal to 5% of the annual natural gas consumption of Turkey which equals to 60 billion cubic meters (bcm) (EMRA, 2022). Despite this fact, there is only one biomethane production facility in Turkey. Although there are no exact explanations for reasons why biomethane production does not exist in Turkey, we might list the possible reasons as: (i) insufficient knowledge regarding biomethane, (ii) absence of encouraging financial conditions and government policies (natural gas price-biomethane production cost differences and lack of feed-in tariffs (Yalcinkaya & Ruhbas, 2022)) for biomethane production. The high surge in natural gas prices made biomethane a price-competitive fuel against natural gas, and some restrictions such as halting natural gas flow downstream from upstream promote the idea that biomethane can be a vital fuel for energy security.

For a decade, biomethane fuel has been ascending as a leading renewable fuel across the world. Because its technical features are almost the same as natural gas, biomethane fuel is often compared with natural gas. However because it is a renewable resource and contributable to waste management, biomethane may be a prospective common fuel in the future. For example, storage of animal manure in uncontrolled conditions causes greenhouse gas emissions, odor, and hygiene problems (Melikoglu & Menekse, 2020). The utilization of biomethane could be a remarkable solution for multiple problems in developing countries such as Turkey.

The rest of the sections are organized as follows. Given the overview of biomethane in the world, literature with multiple aspects of biomethane is reviewed. Feasibility study of biomethane facility based on the data from biofuel facilities is conducted. Given the cattle and layer chicken data taken from TurkStat (Turkish Statistical Institue), the ideal location for biomethane facility is determined. Carbon reduction potential is also calculated, followed by policy implications and conclusions.

CHAPTER 1

BACKGROUND

A niche management approach offers a sustainable economy with policies on the environment, energy, and climate change topics and thus can be viewed as an innovation for social-technical dimensions (Wang et al., 2023).

The case for biomethane is important against two challenges of modern life: (i) ensure waste management and (ii) GHG emissions reduction (IEA, 2020). The cost-based competitiveness of biomethane as a fuel source is another important factor in its preference (Birman et al., 2021). Biomethane production from animal wastes can contribute to rural development and national energy security as well (World Bioenergy Association, 2022; European Biogas Association, n.d.). The EU Emission Trading System (ETS) provides a common carbon price for large carbon emitters because of fossil-deprived fuels use in electricity production and industrial production (OECD, 2022). The programs such as REPowerEU aims to take decisive steps to flourish the biomethane industry in the EU (European Commission, n.d.). Biomethane production rises in Europe from 3.5 billion cubic meters (bcm) in 2021 to 4.2 bcm in 2022 at a percent of 20 while Denmark covers almost 40% of its natural gas demand from biomethane with a target to reach 100% of its natural gas demand (EBA, 2023). Moreover, Europe reached to 1,322 of biomethane facilities as of April 2023 (EBA, n.d.). When we take a glance at facility numbers across the world, we come across 1,484 upgrading facilities as of 2021 (CEDIGAZ, 2023).

Biomethane has a strong potential to support the International Energy Agency's (IEA) Sustainable Development Scenario (SDS) meeting the requirements necessary to prevent climate change, improve air quality, and provide access to modern energy. It also aligns with the goals of the Paris Agreement, which aims to keep the rise in global temperatures to below 2 degrees and limit to 1.5 degrees (IEA, 2020).

Total biomethane production is around 5.9 bcm worldwide (CEDIGAZ, 2023) while the potential is around 848.8 bcm which amounts to 20% of the worldwide natural gas demand. It points out that there is still a strong way to go to reach the full potential of biomethane. In this context, due to carbon-neutral policies worldwide, there is a significant increase in interest in biomethane investments. This implies that there will likely be a strong relationship and market for a mixture of natural gas and biomethane in the future. This section presents the different and emerging biomethane industry conditions across Europe, North America, and Asia, respectively.

1.1. OVERVIEW OF BIOMETHANE CONDITIONS IN EUROPE

Currently, producers and suppliers of biomethane are rewarded via employing policies such as financial support or market-based mechanisms, such as Feed-in Tariffs (FiTs) or Feed-in Premium (FiP) due to their contribution to renewable energy targets in Europe. Although positive externalities stemming from biomethane production are neither fully rewarded nor comprehensively recognized by society, it is estimated that in 2030 the full benefits of biomethane production in the European Union and United Kingdom will range between €38-78 billion per year, and reaching to €133-283 billion by 2050 (Gandolphe, 2023). Many countries have established carbon certificate systems for various industries. These certificates can be traded in a market setting. Notably, biomethane is exempted from these certificates. Despite being a natural gas-producing country, Britain has adopted a green gas levy mechanism for natural gas suppliers as of the end of November 2021 to fund the Green Gas Support Scheme (GGSS) providing tariff incentives for upgrading plants that produce biomethane (UK Government, 2021). The mechanism is designed to calculate the necessary incentives for biomethane producers to offset new investment costs and alleviate operational expenses.

Exemptions from the green gas levy can be granted to suppliers whose total gas supply comprises at least 95% certified biomethane during a scheme year. To qualify for this exemption, suppliers must demonstrate their biomethane supply levels by submitting retired green gas certificates. These certificates represent a net calculation that deducts green gas produced from any fossil fuel used in the production process, such as natural gas usage (GreenGas, n.d.). They also indicate that the fuel is allocated to an end-user as per the period specified on the approved biomethane certification scheme list (GreenGas, n.d.). According to GreenGas (n.d.), the certification fee for a trader account is 500 Pound per year, whereas the annual membership fee for a producer is 250 Pound. This implies that the system can be operated with only a registration fee. As of April 1, 2021, Austria implemented taxes on energy use and greenhouse gases, targeting petrol, medium heavy oils, gasoil, and natural gas. This tax, known as the mineral oil tax, varies based on the content of fossil fuels, including sulfur and other harmful substances. Notably, biogases are exempted from these taxes (OECD, 2022). On the other hand, the Austrian government gives tax exemption and indirect subsidies for biomethane usage and production to reach the Paris target and imposes certificates on biomethane suppliers (Wolf, 2019; Federal Ministry of Austria, 2019).

Germany is the ideal market for biomethane suppliers with clean-fuel certificates for renewable usage to maximize their revenue potential (IEA, 2023). The country has conducted a feed-in tariff (FIT) scheme since 2004 as part of its energy law, which subsidizes electricity generated from biogas or biomethane. In addition, it offers an upgrading bonus that provides an advantage to biomethane over biogas (Biomethane Industrial Partnership (BIP), 2023). It is considered that the scheme caused the largest biomethane producers to come out in Germany (BIP, 2023). In the country, out of 238 biomethane facilities in 2021, 199 facilities use agricultural waste as raw material, as the main part of the German biomethane industry (European Commission, 2021). With 821 Comprassed Natural Gas (CNG) stations in Germany, 60% of biomethane is allocated to transportation fuel in 2020 while there are 3810 CNG stations in Europe (gmobility, 2022). However, Biomethane utilization in the transportation sector is unmatured because of the limited vehicle fleet (European Commission, 2021). On the contrary, through the Federal Emission Control Act (BImSchG), which establishes emission quotas for vehicle fuels, and the Biofuel Sustainability Regulation (Biokraft-NachV), which ensures that biofuels achieve a minimum of 35% greenhouse gas (GHG) savings compared to fossil fuels (Federal Ministry for Economic Affairs and Energy, n.d.), biomethane can be promoted to meet the requirements outlined in these legislations. Additionally, the main driver of biomethane in transportation is the obligation for retailers to reduce GHG emissions (Cornot-Gandolphe, 2023).

From a different perspective, the biomethane potential in the country is estimated at 8.1 billion cubic meters (bcm), composed of 2.16 bcm from grassland-based sources, 1.7 bcm from animal manure, and 1.5 bcm from agricultural residuals-based sources. In comparison, the country's annual natural gas consumption is 86.8 bcm, indicating that almost 10% of the country's gas needs can potentially be met by biomethane (European Commission, 2021). However, only 25% of animal manure in Germany is currently utilized in the industry (Dirk, 2021).

Germany is the leader of Europe in biomethane production with almost 1.116 bcm production in 2022, which covers 30% of total production in Europe, although France has the largest number of biomethane facilities with 514 plants (Guidehouse, 2023). Furthermore, it is considered that with decreased support for electricity generation through the Renewable Energy Sources Act (EEG), the transformation from biogas to biomethane and the construction of new upgrading plants could accelerate, because biogas firms can prefer to upgrade biogas rather than producing electricity (Jain, 2019).

Germany has middle-size plants with an average capacity of 582 m^3/h, which equals to around 5 million m^3 yearly production capacity, while France has small-size plants with 184 m^3/h around 1.6 million m^3 annual capacity, which is the second smallest average capacity following Switzerland. On the other hand, Denmark has the largest average size plant capacity with 1,431 m^3/h equals around 12.5 million m^3 annual capacity.

Germany, like other European countries, clings to the Renewable Energy Directive (RED) II as the directive aims to raise renewable energy sources (European Commission, n.d.). The Directive points out the significance of biomethane utilization in transportation, including road and railway transportation. It suggests that biomethane produced from manure and organic waste can be particularly effective in reducing greenhouse gas emissions (Official Journal of the European Union, 2018). In this regard, it is considered that the promotion of biomethane and utilization from it as a mixture of natural gas and cross-border trade of the fuel is needed (Official Journal of the European Union, 2018).

EU published the REPower Plan as an action plan to achieve biomethane targets and speed up hydrogen deployment and investment needs for renewable gases (European Commission, 2022). According to the plan, it is considered to pave the way to boost the conversion of the production of biogas to biomethane to achieve yearly 35 bcm production by 2030 as set in REPowerEU communication in March 2022. In addition, it is planned to ramp up its production potential by 2050 while the union's biomethane potential is estimated to be around 100 bcm, which is mostly based on manure (IEA, 2022). The plan brings strict environmental criteria, and aims the integration of the fuel to the EU system, and seeks to foster cooperation between national and provincial levels. Moreover, the plan highlights the importance of diversifying import gas sources via LNG including bio-LNG, sustainable domestic production of biomethane, and hydrogen utilization. It intends to promote stakeholder partnerships and public acceptance via forums and cooperation between organizations and to form national strategies with local-level authorities' development strategies. The plan also aims to set up rural community hubs, which prioritize sustainable waste management methods and develop innovative technologies and solutions for biomethane use and integration into the system under The National Energy and Climate Plans. Moreover, it targets to broaden the fuel supply obligations. It is considered to detect potential and regional network studies to match each other via action plans. In this regard, the European Commission, EU members, and gas industry leading firms have begun to foster partnerships to support the progress in the biomethane field (Englund, 2023).

The plan aims to alleviate economic obstacles for biogas to upgrade to biomethane. This includes supporting individual operators to produce biomethane with incentives for the operational costs of its production. It is expected that these incentives are encouraging for biogas facilities generating electricity to transition into upgrading facilities for biomethane production and for new biomethane facility investments with long-term benefits. In addition, in the scope of the action plan, it is considered to conduct potential and regional network analyses to match each other and to determine bottlenecks relating to biomethane facilities. Furthermore, it proposes to ease access to EU funds and grants which are provided via rural development funds, to create resilience and horizon plans developed with state aid funds, and to increase these funds mechanisms in terms of content and diversity.

In addition, it is planned to fund innovative production solutions and existing biomethane technology to invest in innovative pre-commercial projects by applying the Innovation Fund financing mechanism with competitive bidding. In line with REPowerEU's aims, private funds are considered to be scaled up and diversified. These funds will be allocated to green investments to share risks under the European Investment Bank and InvestEU. They are regarded to finance increasing targets for green investments.

In the scope of the fit for 55 packages, which is introduced in December 2021, the EU aims to reach decarbonization in the gas sector and flourish the gas market with biomethane and hydrogen consumption (European Council, n.d.). Via this package, the EU Council projects to reach 55% less GHG emission compared with 1990 level and 100% carbon reduction for new cars and vans. In the context of the package, the emission trading system is set to be expanded with a mechanism of trade of emission allowance certificates that take zero accounting of CO2 emissions for biomethane (Hofmeier,2021). This expansion is intended for energy-intensive sectors and the power generation industry (European Council, n.d.). This is because burning biogas does not add new carbon to the climate (Holta & Ruelas, 2023). This mechanism also addresses emissions stemming from maritime transportation and the aviation sector. Moreover, the mechanism is supported by the innovation fund to mitigate carbon emissions in these sectors, and carbon emission from foreign trade goods is considered to be monitored (European Council, 2022). Under the Carbon Border Adjustment Mechanism (CBAM), current legislation implies that there might be an exemption or a privileged status for biomethane. On the other hand, because of the difficulty of electrifying aviation and maritime transportation, biomethane will seek opportunities in these areas (Lawson, Morales, Tsapekos, 2021).

The mechanism obliges import goods to be registered by CBAM declarants as from 2026, otherwise, the goods will be rejected in the customs (KPMG, n.d.). In this context, it is considered that the certification will be an additional cost for exporters to Europe. However, if this cost is incurred in the exporter country, the goods will be exempted from the cost in the EU territories.

For the biomethane market, a certificate of origin gives opportunity for customers to pay a voluntary premium (Ricardo,2021) for buying biomethane in the European transmission system. This is considered a crucial factor in fostering the growth of the biomethane industry (CEPCONSULT, 2022). Via these certificates, the origin of the gas injected into the natural gas system and its features can be described and seen detailedly (AGCS Biomethan Register Austria, n.d.; Vylupek et al., 2023). This includes its raw material which is converted into biomethane, greenhouse savings level, and the location where the fuel is produced with year. These suppliers will be awarded by incentives. In addition, these certificates, issued in the United Kingdom, Denmark, Germany, the Netherlands, and Austria, can be transferred cross-border between these countries (Ecohz, n.d.). The certificates are used in many European Countries such as Germany, Netherlands, Austria, and Sweden on a voluntary basis, while in France, they are mandatory (Ricardo, 2021).

Denmark meets around 40% of its natural gas demand from biomethane production with 58 upgrading facilities (Energy Ireland, 2023) and it targets to achieve coverage of complete natural gas demand with biomethane (EBA, 2023). The country views that biomethane reduces CO2 and CH4 emissions while backing up rural development (Energinet, 2022). It has around 2 bcm of biomethane production potential (IEA, 2022) while almost with 40% shares of the potential is separately composed of animal manure and agriculture plant residuals (European Commission, 2023). The upgrading process for biomethane production is incentivized by the Danish government (Danish Energy Agency, n.d.). In addition, energy crops are backed up by the government as raw material because it has favorable effects on climate and fosters the biomethane potential (Danish Energy Agency, n.d.).

France is the country that has the most biomethane facilities with 543 facilities which amounts to 41% of the total biomethane facilities in Europe (Guidehouse, 2023). It is thought that its biomethane potential is around 4 bcm (European Commission, 2023), which equals almost 10% of the natural gas consumption of the country (Statista, 2023), while the production level of biomethane is around 0.41 bcm in 2022 (Guidehouse, 2023). The composition of the biomethane potential is predominantly based on crops with 34.5% of the total potential, followed by manure composed of the total potential (European Commision, 2023). In France, support for biomethane industry include investment and research and development subsidies along with guaranteed prices (Bridging European&Local Climate Action, 2018; Guidehouse, 2022). In addition, the country aims to convert all bus fleet in Paris to biomethane and electricity-powered buses (Guidehouse, 2022).

Netherland biomethane production is at the level of 0.237 bcm (bioGemexpress, n.d.). The biomethane potential of the country amounts to 1.3 bcm, which is composed of 0.8 bcm of manure equaling to 61.5% of the total potential (European Commission, 2021). The country has a target to reach 2 bcm yearly biomethane production by 2030. The goal is supported via financial policies such as a feed-in-tariff system by rating emission reduction and feedstock management along with investment funds (Guide House, 2022).

Italy has currently 85 upgrading plants (ABetterway,2023). The country produces over 0.2 bcm in 2022 (Guidehouse,2023) while it has a production capacity at the level of 5.8 bcm, which equals to almost 9% of the country’s natural gas consumption (Statista,2023). The production capacity is based on crops at a rate of 55% and animal manure at a rate of 17% of the total capacity (European Commission, 2023). The country introduces a plan in 2022 to back up the biomethane industry to reach to 2.3 bcm production by 2026 (Guide House, 2022). The plan includes 4.3 billion EURO financial support for biogas firms to convert their facilities into biomethane production as well as new upgrading facilities to be planted with guaranteed tariffs for 15 years (Investment Policy Hub, 2022). In addition, it comprises incentives for the end-use sectors such as the biomethane fuel industry and heating sector. The accompanying policy is directed to lead the agricultural sector to support the biomethane industry, along with promoting municipal waste management initiatives in urban areas to facilitate waste-to-energy production (Guidehouse, 2022).

Although there is important progress in the biogas field in Turkey, there is only one biomethane facility which is opened in the latter part of 2023 (Presidency of the Republic of Türkiye, 2023). The facility aims to meet 30% of the natural gas need of a linked manufacturing facility with 1.26 million Sm^3 production capacity with 10,000 ton waste which avoids 1,237 ton GHG emissions equaling to 566,000 m^3 natural gas-based emissions (Bloomberg, 2023).

1.2 A GRAPHICAL OVERVIEW OF EUROPEAN BIOMETHANE INDUSTRY

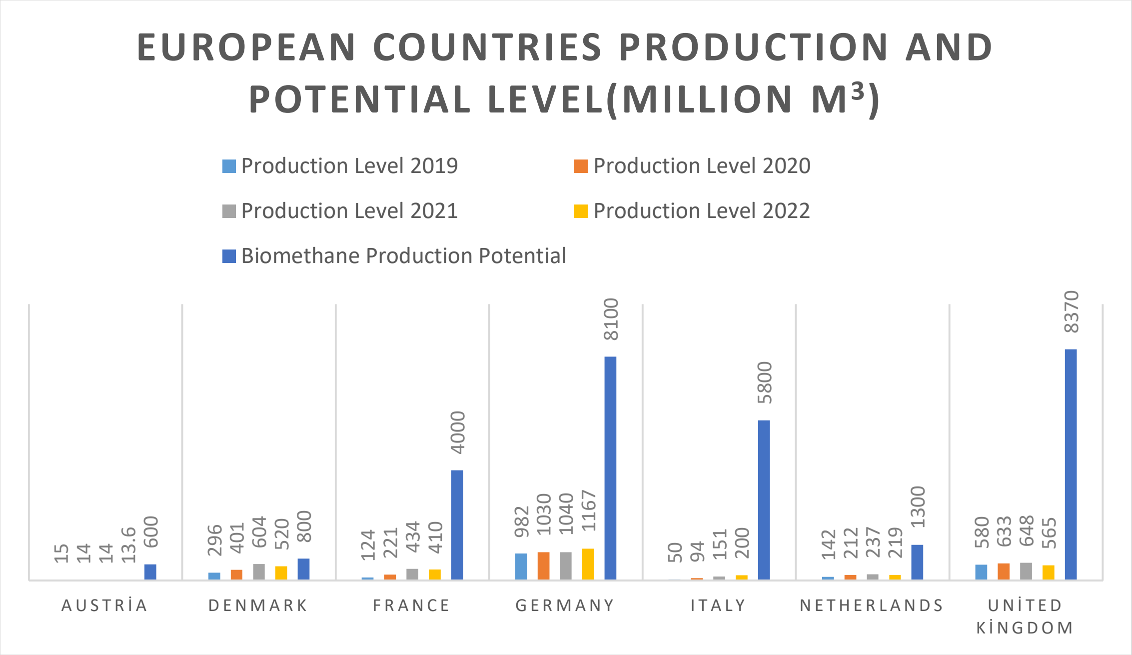


Figure 1: European Countries Production and Potentıal Level(million m3)(Source:Cedigaz,2023)

Figure 1 shows that the most significant production level exists in Germany with levels over 1,000 million m^3 (1 bcm) while the highest potential is in England, followed by Germany. An increasing trend line over the years is evident in almost all countries, with the most significant percentage increase occurring in Italy, where biomethane production experienced a four-fold increase from 2019 to 2022. Although the other countries fulfill at most 12% of their potential, Denmark covers almost 65% of its biomethane production potential.

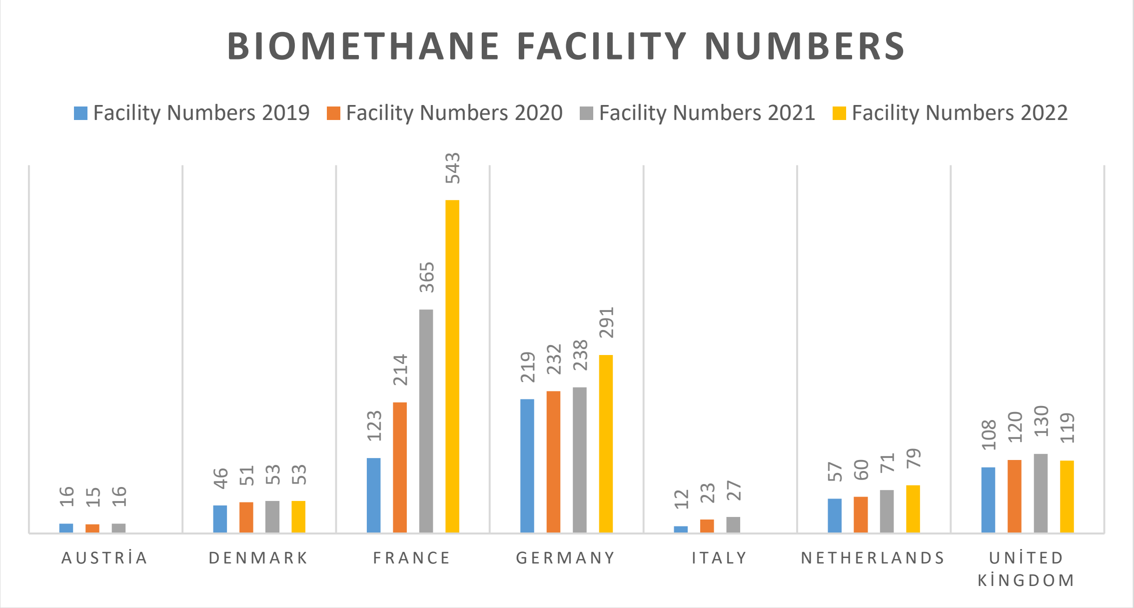


Figure 2: Biomethane Facility Numbers(Source:Cedigaz, 2023)

As can be seen in Figure 2, another upsurge in biomethane production occurs in France, accompanied by sharp rises in the biomethane facility numbers over the years, climbing to 543 facilities in 2022 from 123 in 2019. The increase goes up steadily every year in the period. In this period, there is a generally rising trend in facility numbers, except for England. This can imply the results of the EU steps for biomethane production.

1.3 OVERVIEW OF THE BIOMETHANE INDUSTRY IN NORTH AMERICA

Although natural gas and petroleum production are important in the country, Canada imposes a carbon tax on the usage and purchase of fossil fuels such as diesel, gasoline, natural gas, and coal (Government of Canada, n.d.). The country has a target to reduce one of a third of the carbon pollution in the country by 2030 (Government of Canada, n.d.). Canada views biomethane as a carbon-neutral renewable fuel produced from agricultural wastes and not distinguishable when mixed with natural gas. In this regard, Canada provides tax exemptions for biomethane when it is used either in its pure form or when blended with natural gas. Moreover, the fuel is seen as an important instrument to keep 1.5 degrees under the Paris Agreement. The country's goal is to reduce emissions by 45% below the 2005 level by 2030 and achieve carbon neutrality by 2050 (Canadian Biogas Association (CBA), 2022). In addition, according to CBA, agricultural waste, which is composed of animal manure and crop residuals, causes 9.3 million tons of CO2 emissions out of a total of 26.7 million tons of CO2. This composes almost 34% of the emissions in the country. As of 2022, the carbon reduction achieved from the treatment of agricultural waste through biogas and biomethane facilities in the country amounts to 0.8 million tons of CO2. Furthermore, according to the association, a mixture of emission offset credits and biomethane mandates policies such as the Québec Renewable Gas Mandate, which is a provincial step, are crucial to foster the biomethane industry (Government of Canada, 2024). With this policy, The Quebec Government requires Natural gas suppliers to mix a minimum rate of 5% of their supply with biomethane between 2025-2026 and plan to reach 10% in 2030 (Quebec Government, 2023). It is considered that it will bring important benefits to reaching climate targets. Moreover, according to the Canada Energy Regulator, it is estimated that with 17 new projects, in addition to 22 existing facilities, the production capacity will reach over 447 million m^3 in 2025 while the country's biomethane production potential equals to 4.079 bcm (Stephen et al., 2020). Furthermore, distribution companies in the country give options for their customers to pay a little more for biomethane than natural gas to fund their biomethane investments (Canada Energy Regulator, 2023).

The Transportation sector is the leading factor in developing the biomethane industry in the USA. Support mechanisms are introduced such as the Renewable Fuel Standards (RFS), which entails all biomethane facilities to register in it, and California’s Low Carbon Fuels Standard (LCFS), which is mandatory only for fuels sold in California borders (IEA, 2024). The "Set" rule under the Renewable Fuel Standards (RFS) in 2023 mandates an increase of over 33% in the renewable volume of a fuel compared to its 2022 level for the years between 2023 and 2025. It stimulates higher volume biomethane production during the period along with a simplified credit program for raw material procurement (The Coalition for Renewable Natural Gas, n.d.). According to the rule, the biomethane volume in CNG and LNG form will increase by 25% from 2023 to 2024, and this level will be maintained between 2024 and 2025. Additionally, there is a projected 56% increase in biomethane volume in 2025 compared to 2023. This situation gives biogas producers a strong opportunity to enjoy high gains, leading many biogas firms to convert their systems into biomethane production facilities (World Biogas Association, 2018). In addition, with the Organics recycling requirements law, the amount of waste reaching a landfill is limited, instead, waste is led to energy production while under this mechanism, there are grants and credits for producers as financial assistance (Commercial Recycling, n.d.). Moreover, the United States' goal, which is enforced in 2015 to reduce waste by 50% by 2050 to avoid harmful effects on climate and the environment (United States Environmental Protection Agency (EPA), 2024), is considered as an important solution for biogas production in USA (United States Environmental Protection Agency,2023). Rural utilities and environmental quality initiatives programs can provide financial assistance for biogas production (World Biogas Association, 2018).

The country’s biomethane potential is at the level of 11 bcm (National Renewable Energy Laboratory, 2013). In 2022, the USA produces 2 bcm of biomethane with 250 upgrading facilities, with an additional 220 upgrading facilities either planned or under construction (IEA, 2023). According to the International Energy Agency (IEA), the production composition consists of 70% municipal waste, and 20 % agricultural waste, and the remaining 10% is made up of garbage and wastewater.

1.4 A GRAPHICAL OVERVIEW OF NORTH AMERICA

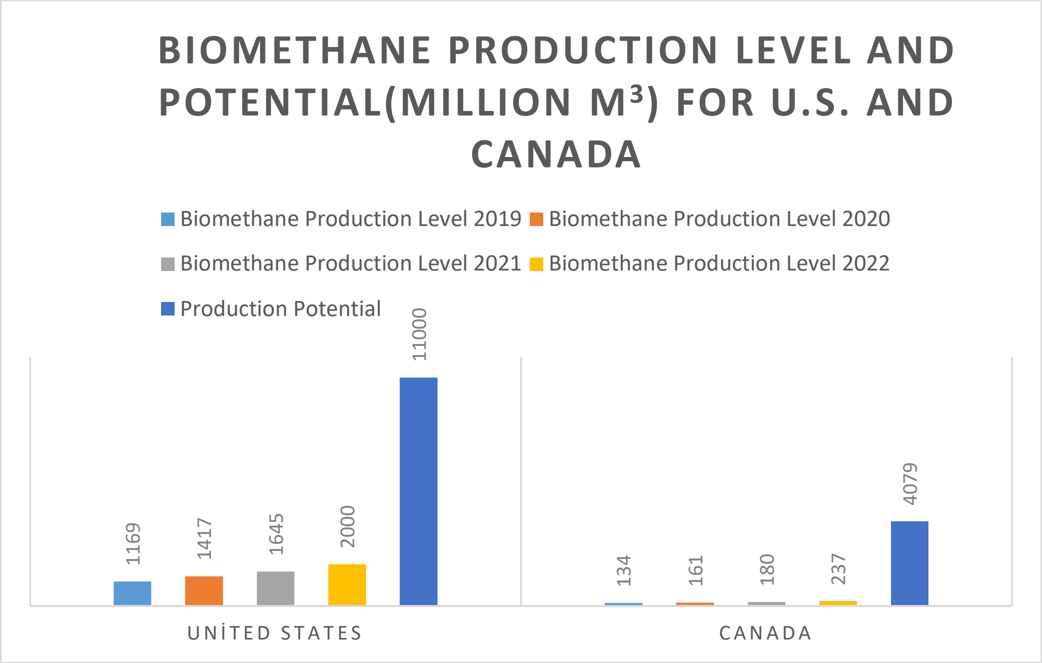


Figure 3: Biomethane Production Level and Potential (Million m3) for U.S. And Canada (Source: Cedigaz,2023)

Figure 3 points out that biomethane production has increased over the years in both countries. In 2021, the United States achieved the world's highest biomethane production level at 1.645 billion cubic meters (bcm), and 2 bcm in 2022, which still falls short of its biomethane potential, fulfilling nearly 20% of it. Additionally, the change in volume between 2019 and 2020 exceeds 200 million m^3, and between 2020 and 2021, it is also over 200 million m^3. The increase between 2021 and 2022 surpasses 300 million m^3, while the difference between 2019 and 2022 is more than 800 million m^3. This difference exceeds the annual production levels of many countries, indicating a significant rise.

Alternatively, Canada's biomethane production levels see a modest rise, hitting 237 million cubic meters in 2022. This figure represents approximately 6% of the country's total biomethane potential, suggesting that Canada is slowly advancing towards its full potential.

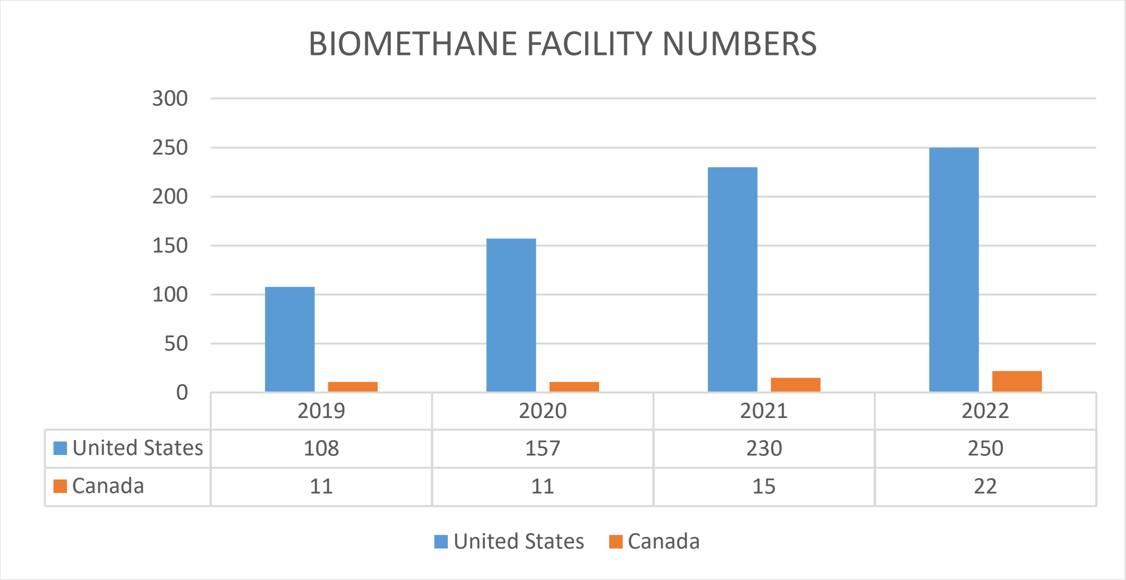


Figure 4: Biomethane Facility Numbers in U.S. and Canada(Source: Cedigaz,2023)

Figure 4 illustrates a significant increase in the number of biomethane facilities in the U.S. accompanied by the rise in production levels, while in Canada, the growth in facility numbers is comparatively modest. That is, the count of biomethane facilities in the U.S. sees an addition of 49 units from 2019 to 2020, 73 units from 2020 to 2021, and 20 units from 2021 to 2022. The cumulative increase from 2019 to 2022 more than doubled, with a total of 142 new facilities. This suggests a robust inclination towards biomethane production, likely reflecting heightened environmental awareness and the attainment of economic viability.

1.5 ASIA BIOMETHANE MARKET SNAPSHOT

China and India have been emerging biomethane markets in Asia in terms of Facility number and production level. In this section, conditions in China and Indian markets will be explained.

According to the environmental Kuznets curve, it is thought that China will hit a peak for emissions and later will start to emit less, like what happened in other countries but at a lower level (U.N., 2023). China targets to reach 20 bcm of green gas production by 2030 (IEA,2023). In this regard, the China Natural Energy Administration released Guidelines to promote the industrial progress of biomethane and to accelerate the increase in production level and reach the targeted level (Giwa et al., 2020). The guidelines for this target mention to aim to keep coal and natural gas under pollution control, and with a fast increase in production of the biofuel, and the consumption of these fuels will be decreased incrementally via the rural revitalization strategy (Giwa et al., 2020). On the other hand, Yeng et al. (2012) stress that although high potential to produce biomethane from agriculture-based raw materials such as manure although its utilization only amounted to less than %0.5 of the total capacity. Moreover, biomethane production potential for the country is calculated over 888 billion m^3 while yearly natural gas consumption which is estimated to reach 480 billion cubic meters by 2030 of the country (Zheng et al., 2020). The value amounts to around 45% of its potential, while 147 bcm of this total is composed of animal manure, which is available for rural development (Liu et al., 2016). It is expected that in 2050, as China's energy transition scenario denotes, biomass production will reach 7.6% of the total power generation which is larger than natural gas consumption at the level of 7.1% of the total power generation. Hence, biomass is seen as a crucial option for a low-emission scenario instead of coal and natural gas because of carbon capture and storage mechanism (United Nations (U.N.), 2023). Additionally, the Chinese government launched the Chinese Rural Household Biogas State Debt Project in 2003, a subsidy scheme aimed at fostering rural growth and autonomy. The project offered financial incentives and a feed-in tariff mechanism, leading to the establishment of biogas digesters in 42 million households by the year 2015 (IEA, 2023).

With investment plans, in 2019, the biomethane facility number was 44, increased to 48 in 2020, and reached to 63 in 2021 (CEDIGAZ, 2023). According to Cedigaz, biomethane production levels amount to 0.25 million cubic meters in 2021 while 0.18 million cubic meters, and 0.13 million cubic meters respectively in 2019 and 2020. This development is a consequence of the Chinese government’s directive to transition the biogas sector towards substantial biomethane production investments. These investments are intended to utilize biomethane produced from waste from urban and rural sources to blend with natural gas and facilitate power generation (IEA, 2023). The 14th Five-Year Renewable Development Plan, published in 2022, sets forth an agenda for new high-capacity biomethane initiatives that utilize livestock-derived materials (Climate Change of Laws of The World, 2022). These initiatives are pivotal to the country’s low-carbon transition efforts, which aspire to achieve carbon neutrality by 2060. Additionally, the plan focuses on enhancing the robustness of the energy network, ensuring energy security, and improving network management and adaptability. Moreover, it is expected that both national and international giants of fossil fuel and energy production will channel investments into the biogas field, as policy backing is intensified to achieve China’s ambitious goals (IEA, 2023). On the other hand, it is considered that the Chinese transition process needs long-run full achievements of biogas solutions with the medium-term goal to obtain multi-functional coexistence. In the short term, it is crucial to analyze and identify the most market-suitable multifunctional model. It is suggested that the nation provides support and investment in both pilot projects and essential biogas technologies (Wang et al., 2023).

It is projected that the utilization of pure biomethane derived from manure as a biofuel for road transport results in a significant decrease in GHG, with 5 g CO2-eq per km. This represents a 97% reduction compared to gasoline and is equivalent to the emissions from electric mobility powered entirely by wind energy (Sino-German Energy Partnership, 2020).

India has old practices to promote the deployment of biogas technology. India has a household digester system for self-sufficiency for households to help to fulfill their primitive needs such as cooking and lighting as from 1981 when the National Biogas and Manure Management Programme was introduced. The country also plans to blend biomethane to natural gas as usage for vehicle fuel and injecting into the pipeline by rising at a rate of %1 each year until 2028. Hence, large-size biogas plants are covered with the Waste to Energy program to promote energy recovery from municipal wastes to transform bio-CNG or power and thermal via gasification to use in gas form in industries (Jain, 2023).

Within the framework of the program, through the Central Financial Assistance (CFA) scheme, the government provides financial incentives that vary based on the scale and type of fuel, such as bio-CNG and biogas (Government of India, 2022). In addition, The government secures relevant taxes with an adjustable base price to maintain a surplus that supports the biomass industry. Furthermore, it offers an incentive of approximately 206 million USD through 2026 for plants of all sizes that use cattle manure as the primary raw material. This initiative promotes the country's Waste to Energy, Biomass, and Biogas programs, providing extra income for rural households, contributing to the reduction of greenhouse gases, enhancing environmental quality, and encouraging the recruitment of women (Ministry of New and Renewable Energy of India, 2022). Aligned with the commitment to green energy and the "net zero" carbon goal by 2070, the Indian government has released an interim budget for its 2024 vision. This budget mandates the blending of biomethane with natural gas and encourages its use in transportation as compressed biomethane. Additionally, it gives incentives for biomass raw material collection (Government of India, 2024). The government targets the construction of new 15,205 small biogas plants for the Financial Year 2023-2024 (Ministry of New and Renewable Energy of India, n.d.). In the scope of the Sustainable Alternative Towards Affordable Transportation (SATAT) scheme which aims to encourage producers to set up compressed biomethane plants (SATAT, n.d.) while Indian Oil Corporation Limited company adjusts the price for allocated compressed biomethane according to compressed natural gas price to supply road vehicles to keep surplus (Indian Oil Corporation Limited, 2023).

The government aims to promote the sector by encouraging its co-product as organic fertilizer from biogas plants by giving stimulus to its demander farmers (Cabinet Committee on Economic Affairs of India,2023). In this regard, the country encourages cooperation between different authorities and associations (Ministry of New and Renewable Energy of India, n.d.).

The projection is that utilizing pure biomethane derived from manure as a biofuel for road transport leads to the most significant decrease in greenhouse gas emissions, down to 5 g of CO2-equivalent per kilometer. This equates to a 97% reduction when compared to the emissions from gasoline, and it matches the emissions from electric vehicles that are powered entirely by wind energy. (Sino-German Energy Partnership, 2020).

While the biomethane production level in the country is estimated at 57.8 million m^3 (CEDIGAZ,2023), the country's production Potential is assessed at the level of 125 bcm (Rey&Thomson, 2023).

1.6 A GRAPHICAL OVERVIEW OF THE ASIAN COUNTRIES

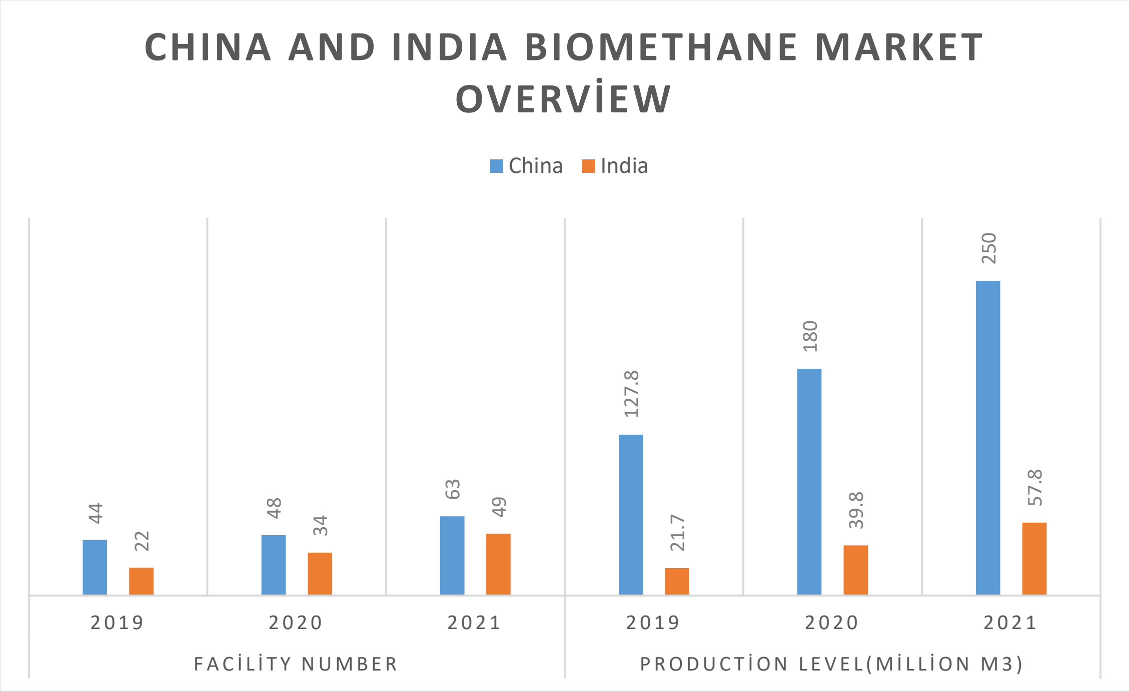


Figure 5: China and India Biomethane Market Overview (Source: Cedigaz,2023)

In Figure 5, it can be seen that there is a significant increase in the number of facilities in China, rising by 31% from 48 to 63 between 2020 and 2021. Concurrently, there is a 38% surge in production levels during the same period. Furthermore, comparing 2021 to 2019, there is an expansion of 19 facilities, amounting to a 43% growth. Analyzing the growth between 2019 and 2021, the increase is 95%, indicating that each additional facility contributes to a production boost of over 6 million m^3. Moreover, a 1% rise in the number of facilities leads to a 2.21% increase in production levels. Despite the advancements in the biomethane industry, Figure 6 indicates that China is utilizing less than 1% of its potential capacity for biomethane production.

While India has demonstrated a robust percentage increase in both the number of facilities and production levels—doubling in 2021 compared to 2019—the country still remains significantly below its potential capacity. This suggests that the industry is currently thriving and undergoing a phase of discovery and expansion.

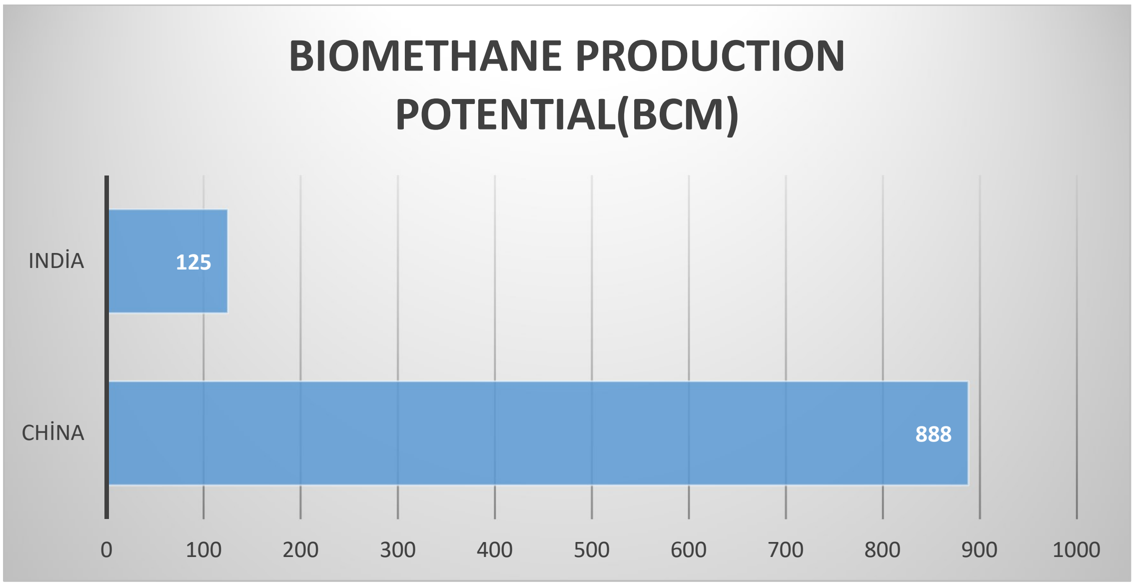


Figure 6: Biomethane Production Potential(BCM) for China And India

This section discusses the global expansion of biomethane industries, highlighting significant growth in regions such as Europe, North America, and Asia. It suggests that biomethane is an emerging fuel source experiencing rapid development, bolstered by industry incentives.

The following section stresses that the conclusions drawn from biomethane research in the existing literature.

CHAPTER 2

LITERATURE REVIEW

The rise in organic waste requires governments to convert them into value such as biogas which can be produced in heat-power generation (Gupta et al., 2022). Biogas solutions establish circular economies and promote waste valorization in a widespread sector range, such as agriculture (Cuccehiellla et al., 2019). While many feasibility studies have been conducted for different regions over time, different conclusions are reached in those studies. Although progress has been achieved in the area of biomethane production, the economic feasibility of the technology is still ambiguous (Sulewski et al., 2023).

Several technologies have been developed in years, including pressure swing adsorption, organic physical and chemical scrubbing, and membrane separation. While the cryogenic process for liquefaction is less commonly implemented, the most prevalent technique is high-pressure water scrubbing (HPWS), which is a physical process (Ferella et al., 2019). These methods are commercially available and analyzed in literature while their cost-competitive and environmental effects are appreciated by different key variables like energy consumption of the upgrading systems. In this regard, pressured water scrubbing has been seen as one of the most preferable technologies in terms of cost-competitive standards and environmental effects and it is used widely at the global level (Patrizio et al., 2015). These technology's capital expenditures are differentiated according to scale and technology types (Gupta et al., 2022). In terms of running operational costs, there is a diversity occurring in different kinds of upgrading technologies (Thrän et al., 2014). In addition, many studies stress how different biomass residue types as raw materials can change the final cost of biomethane (Rotunno et al., 2017). For example, a mixture of food waste and sewage sludge might have more advantages than pig slurry because gate fee which is paid for food waste and sewage sludge provides additional revenue for the facility (Chan Gutiérrez et al., 2018).

Patrizio et. al.(2015) analyzed biomethane solutions for transportation and grid injection into the north of Italy and compare these applications with biogas co-generation via using

Mixed Integer Linear Programming (MILP) to find economical optimization. They found that with low carbon prices, there is no additional biogas plant for settlement. In addition, it is assessed that raw material availability leads to an expansion in biogas plants. However, for Bio-compressed natural gas (CNG), a form of biomethane and the primary focus of this study, an incentive-based approach is deemed necessary rather than relying on carbon tax mechanisms.

Starr et. al.(2015) analyzed the economic feasibility of alkaline with regeneration (AwR) technology as a new biogas upgrading technology via a net present value approach by using data collected from literature and interviews with relevant companies and sector experts. General operational costs such as electricity cost, labor force cost, and annual maintenance costs are used along with specific operational costs because of the technology's features such as air pollution control (APS) disposal, cost of NaOH (principal reagent), wastewater treatment costs because of municipal refuse. It is observed that these specific costs for wastewater treatment cost (49%) and NaOH (25%) costs comprise the main items of the cost. Therefore, the biomethane cost for this upgrading technology is around 2.8 €/m^3 while for other upgrading technologies, the biomethane production cost is between 0.11-0.4 €/m^3. for the utilization of CNG in vehicles, the production cost should remain below 1.23 €/m^3. Hence, they state despite high GHG savings, the AwR technology is not economical under the conditions of the study.

Biomethane is the most lucrative biogas-derived product and as scale increases, profits increase whereas biomethane is analyzed as the most profitable bioenergy. Hence it is more profitable than biohydrogen, biobutanol, and algal biodiesel (Lee, 2017). In addition, it is assumed that the efficiency of this technology will reach its technical limit by 2030.

While the total cost of biomethane production includes biogas production cost in addition to upgrading cost, it is composed of upgrading unit investment costs as CAPEX and operating costs, OPEX. The unit cost of upgrading is ranged by depending on the upgrading treatment technology and the size of the facility (Sulewski, Ignaciuk, Szymańska, et.al.).

Through life cycle assessment (LCA) for environmental performance analysis and net present value (NPV) approaches for economic assessment, it has been determined that carbon taxes are necessary to render biomethane upgrading systems economically viable in the Glasgow region (Gupta et al., 2022). As cost items, CAPEX of biogas and biomethane facilities, operational costs, maintenance, transportation, and collection costs are taken. Revenue streams such as heat recovery, gate fees for raw materials, and income generated from biomethane price are considered. Data for these variables are compiled from literature and authority reports. It is concluded that without carbon taxes at a level of 31.3 pound per tonne of CO2 saved, because of high transportation cost and capital costs biomethane technology for membrane separation-based technology is economically unfavorable.

Using a case study of techno-economic assessment focused on Denmark, the profitability of a biomethane facility is analyzed (Lawson et al., 2021). This analysis aims to inform policy considerations and steps, assisting shareholders in making informed decisions regarding the installation of biomethane technology. In this study economic evaluation shows that for economic viability to be achieved, the sale price of biomethane needs to fall within the range of at least 0.66 to 0.79 $\$/m^3$. Although operational costs are divided into subgroups, it is pointed out that the raw material cost constitutes a significant portion of the operational expenses, accounting for 27% of the yearly operational costs.

Three upgrading technologies are studied and compared in terms of economical performance, by regarding a sewage sludge treatment plant as a raw material source in Stuttgart (Cappiello et al., 2022). It is found that when the the selling price of biomethane is 0.55 Euro/m^3, the payback period for the water scrubbing solution is less than 10 years, making it the most favorable option.

In their study, Hoo et al. (2020) utilize the net present value (NPV) approach to estimate the biomethane selling rate by determining the levelized cost of energy of biomethane, considering various raw material types, specifically for Malaysia. Data is collected via international sources, literature review, and personal communications. They analyze palm oil waste ,which is exported from mill, and compare it with food refuse, chicken manure, and cattle manure as raw material sources. They find palm oil mill effluent and food trash show more competitive costs due to the fact that they are more productive sources. While they take maintenance, electricity, and raw material costs as operational costs, they find under the current natural gas selling prices, the feed-in-tariff mechanism is incompetent for biomethane without government intervention as policy or institutional support.

A study employing the NPV and financial internal rate of return (FIRR) approaches is conducted to assess the financial feasibility of producing biomethane as a compressed fuel for vehicles in Thailand (Tonrangklang et al., 2022). This study focuses on water scrubbing technology as the reference technology. It comprises a cost analysis based on technical features, including the installation and maintenance costs of the technology, along with technical energy and monetary indicators. It is concluded that without government support, a biogas facility producing less than 6 tons per day experiences payback periods ranging between 8 and 9 years, however, with a 30% subsidy of the total cost, the payback period shortens to 5-6 years. In addition, for the Netherlands biomethane sector, with data taken from the Central Bureau of Statistics (CBS) of the Netherlands, Eker and Van Daalen (2015) conclude subsidies play an important role in economic analyses. They utilize Exploratory Modeling and Analysis (EMA) which analyzes the effects of uncertainties and System Dynamics (SD) modeling to capture the dynamic behavior of outcome indicators and assess the effectiveness of policies.

Koido et. al (2018) analyze small-scale biomethane facility for Thailand by using NPV and LCA (Life Cycle Analysis) for environmental effects. Data for the research is collected via personal communications with plant operators and researchers at Srinakharinwirot University and Nagoya University and taken from literature and other online public data sources. It is revealed that the biomethane production level is the most important parameter for the sustainability of the plant operation.

Rotunno et al. (2017) assess different final usage cases for a 120 m^3/h capacity biogas plant upgraded by a pressured water scrubber in purpose for injection grid and as car fuel use. In these cases, it is found that the production cost for injection into the gas grid is 0.54 €/m^3, whereas it amounts to 0.73 €/m^3 for utilization as a transportation fuel (Rotunno et al., 2017).

Economic analysis for the upgrading production chain produced from manure for Italy is carried out (Cucchiella et al., 2019). In this study, Alongside various operational cost components like labor, maintenance, transportation, and insurance, operational costs also include interest payments. Technical features are outlined in addition to subsidy in the form of the Certificate of Emission of biofuel consumption (CIC) against carbon foot print. It is concluded that for 0.25 EURO/m^3 biomethane, 350 m^3/h is the minimum plant production capacity to stay in economical viability range. But this result is available in case of use of sheep/goats, agricultural by-products which include crop silage, fruit pulp, pomace oil, and poultry manure-type raw materials. NPV value ranges from 169,000 EURO and 279,000 EURO. For the other plant sizes of 150 m^3/h and 250 m^3/h, NPV value takes negative values.

Chan Gutiérrez et. al. (2018) apply the net present value (NPV) approach to find economically feasible raw material scenarios from different options. The base technology is taken as pressure water scrubbing (PWS) with 250 m^3/h capacity. Various scenarios are generated based on the energy contents of raw materials. Using these base scenarios, upgraded biogas is converted into compressed form as equal to compressed natural gas (CNG) for its application as vehicle fuel. All revenues and cost data used in the study are drawn from the literature and from reviews with industry experts and relevant government officials. In conclusion, they say that the use of biomethane as a transportation fuel might reduce GHG emission targets for Mexico. Scenario 1, which includes plant proceeding 60.000 t/year capacity for food waste and sewage sludge raw material type, can result in a positive NPV. Nevertheless, in scenario 2 where pig manure is combined with food waste, despite achieving higher methane yields, the net present value (NPV) becomes negative due to the absence of gate fees for collecting pig manure from the field. Hence, it is pointed out that food waste and sewage sludge is preferable. However, for the second scenario, with subsidies, positive cash flows occur, in addition, subsidies and gate fees are the main factors in terms of the emergence of the industry.

Jaikrishna Jagtap et.al. (2021) conduct a technical and economic feasibility analysis for biomethane usage in India according to current conditions by using cash flow and internal rate of return (IRR) approach. Operational items such as raw material cost, operation and maintenance costs, and labor force are analyzed, in addition to capital expenditures for facilities from data acquired from the literature. While different upgrading systems are compared in the study, the high-pressure water scrubbing system is found more economically feasible than other options. They prefer to take agricultural wastes and manure because the study focuses on the development in the rural economy, and mentioning this material are procurement at a price in rural fields. The reduction of international energy dependency and environmental effects are commented on by the authors of the paper. They take the revenue as only compressed natural gas (CNG) price as 44.3 ₹/kg (Indian rupee per kg) which is drawn from the Indian local market to determine the competitiveness according to this fuel. They determine a biomethane cost of approximately 24.7 ₹/kg, with an internal rate of return (IRR) standing at 9.5%. In addition, they identify a payback period of 10.3 years without government subsidy, which decreases to 6.26 years with subsidy.

Vernersson (2022) aims to assess the economical feasibility of investment in biomethane and CO2 liquefication for a 350 Nm^3/h production potential facility along with greenhouse gas saving potential so that it can affect the price of bio-LNG as a form of biomethane. The study's financial quantitive data for biogas, upgrading, and liquefaction plants is collected from scientific reports, literature reviews, and interviews with personnel at the Institute for Biogas, Waste Management, and Energy. In addition, for the calculation of environmental effects, greenhouse gas data is drawn from literature and Renewable Energy Directive II. For financial calculation, the study conducts NPV and the life cycle cost (LCC) approaches while for emission analyses, LCA analyses is utilized. The study takes cost items such as electricity cost, maintenance cost, and raw material cost as operational costs. The chemical scrubber method is taken as upgrading technology in addition to cryogenic systems to liquefy biomethane and CO2. In this paper, the cost of biomethane is taken as a raw material cost and calculated as 0.66 Euro/m^3 while NPV calculation for bio-LNG as a liquified form of biomethane with 1.18 Euro/kg takes zero value around a %5 discount rate. However, when liquified CO2 (LCO2) as extra revenue as a by-product is invested and sold with bio-LNG, NPV value is 2 million EURO at a 5% discount rate and the payback period occurs as 5 years in 10 years life-span.

Ardolino et. al. (2021) assess and compare different upgrading technologies by regarding economic efficiency and environmental aspects by employing LCC which is utilized to analyze economic efficiency throughout the entire life scale and Life Scale Analyses (LSA). They use maintenance costs, energy costs, and required consumables (raw material) costs as operational costs obtained from the literature, and the biomethane selling price is taken from the decree of the Italian government to promote the use of biomethane. They state that the life cycle costs take negative values for all upgrading solutions. It denotes biomethane revenues are higher than direct and indirect costs in all solutions and provides positive savings. It is mentioned in the study that this result occurs because of high incentives via CIC (tradable emission certificates) which covers 80% of total revenues (160 EURO/FU incentives while 200 EURO/FU is total revenue).
Table 1 Summarizes the existing literature.

Table 1: Previous Studies

Author	**Remarks**
Gupta et al., 2022	Net present value (NPV) approaches for economic assessment, it has been determined that carbon taxes are necessary to render biomethane upgrading systems economically viable in the Glasgow region
Lawson et al., 2021	Using a case study of techno-economic assessment focused on Denmark, the profitability of a biomethane facility is analyzed. The sale price of biomethane needs to fall within the range of at least 0.66 $/m3 .
Cappiello et al., 2022	Three upgrading technologies are studied and compared in terms of economical performance, by regarding a sewage sludge treatment plant as a raw material source in Stuttgart . The water scrubbing solution is the most favorable solution.
Hoo et al., 2020	Utilizing the net present value (NPV) for Malaysia. palm oil waste, and compare it with food refuse, chicken manure, and cattle manure. under the current natural gas selling prices, for biomethane without government intervention as policy or institutional support

Koido et. al, 2018	Analyzing small-scale biomethane facility for Thailand by using NPV. Data for the research is collected via personal communications with plant operators and researchers at Srinakharinwirot University and Nagoya University. The biomethane production level is the most important parameter for the sustainability of the plant operation
Cucchiella et al., 2019	Economic analysis for the upgrading production chain produced from manure for Italy is carried out. It is concluded that for 0.25 EURO/m3 biomethane, 350 m3/h is the minimum plant production capacity to stay in economical viability range
Chan Gutiérrez et. al., 2018	Applying the net present value (NPV) approach to find economically feasible raw material scenarios from different options for Mexico. The base technology is taken as pressure water scrubbing (PWS) with 250 m3/h capacity. pig manure is combined with food waste, despite achieving higher methane yields, the net present value (NPV) becomes negative due to the absence of gate fees for collecting pig manure from the field. Hence, it is pointed out that food waste and sewage sludge is preferable.
Jaikrishna Jagtap et.al., 2021	Conducting a technical and economic feasibility analysis for biomethane usage in India according to current conditions by using cash flow for India. The high-pressure water scrubbing system is found more economically feasible than other options.

Although there are several studies on biogas investment, along with hybrid systems, in terms of economic feasibility analysis, there aren't any economic analyses for biomethane investment in Turkey. However, several papers have been published to assess the biomethane potential in the country. This gap in economic analysis could be attributed to the prevailing higher production cost compared to fossil fuels, particularly natural gas, which serves as an ideal substitute. The ongoing Ukraine-Russia war caused the natural gas fuel crisis, further underscoring the importance of exploring alternatives such as biomethane. Therefore, the European Biogas Community (EBA) stresses that the deployment of biomethane could alleviate disruptions in the natural gas supply from third parties, which cover over 85% of the European Union's natural gas needs. EBA highlights that biomethane is priced at around 55 euros per megawatt-hour (MWh), whereas natural gas costs approximately 80 euros per MWh, excluding carbon prices during this period (EBA, 2022). Moreover, CBAM and prospective carbon tax mechanism entails reforms in the fossil fuels field. Moreover, natural gas supply restrictions and energy safety importance requires this fuel.

When we mention biogas economic feasibility and environmental analysis for Turkey, we come across a strong literature. Balcioglu et al. (2022) conducted an assessment of anaerobic digestion (AD) using the life cycle assessment (LCA) methodology to evaluate environmental impacts. Additionally, they employed life cycle cost analysis, net present value (NPV), and payback time analysis for economic evaluations across four different plants. Data for analysis is drawn from literature, authority reports, and citing from websites. They use cattle and chicken manure as the main raw material types for all plants along with other kinds of wastes as a mixture with manure while utilizing operating-maintenance costs, and waste collection costs as operational costs. Electricity and digestate selling prices are taken revenues along with incentives. As a result of LCA, it is detected that there are net savings in terms of environmental impact. On the other hand, the life cycle cost (LCC) analysis reveals negative values, suggesting net profits for the biogas plants. Electricity production cost for plants ranging between 0.061 USD/ Kwh - 0.093 USD/kwh, while the selling price is taken as 0.133 USD/kwh. Their findings indicate that all plants generated positive net present values ranging from $4.7 million to 6.2 million USD. Additionally, they observed payback periods ranging between 1.6 to 2.1 years, with the plant utilizing only cattle manure waste exhibiting the shortest payback period.

Tufaner et.al. (2019) conduct a cost-benefit analysis for low-capacity biogas facilities based on cattle manure as raw material and determine net profit and payback periods for different capacity levels by using 20 years lifespan for facilities. Operational costs encompass repair and maintenance expenses, electricity usage, labor expenditures, and waste management expenses. They conclude that establishing biogas plants for farms with over 50 cattle can be advantageous. Their findings indicate that as the capacity increases, the payback period decreases and the net profit expands.

Odabaş et. al. (2022) examine the economic benefits of biogas and solar photovoltaic (PV) as a hybrid model based on urban wastewater treatment plants (WWTPs). The study utilizes the NPV and payback period methodologies, employing the Hybrid Optimization Models for Energy Resources (HOMER) tool for analysis. They collect the cost and technical data via interview with sector experts and open literature for 456 urban WWTPs operated by metropolitan municipalities (MMs). During their analysis of various scenarios involving carbon penalties and fluctuating electricity prices, they observe that higher carbon penalties and diverse electricity price structures lead to a shorter payback period. Moreover, they determine that facilities with a capacity exceeding 1 million m^3 become cost-effective under these conditions.

Kirim et. al (2022) investigate a renewable model which integrates biogas with solar energy based on cattle manure located in Konya, Erzurum, and İzmir provinces. They utilize net present cost (NPC) and life cycle cost (LCC) via HOMER software programming. Their findings reveal that NPC results are consistent for three provinces and hybrid models are more feasible than only biomass systems in terms of economic indicators. The study shows that larger plants give fewer payback periods and higher IRR rates.

Although there is no study, to the best of our knowledge, conducting financial feasibility analysis for biomethane, there are several papers existing in the literature to study on biomethane potential of Turkey. Meanwhile, biomethane is a derivation of biogas, biogas potential can be seen as a biomethane potential via a conversion factor.

Şenol et. al. (2021) estimate biomethane potential and its distribution across the country to 2030 based on bovine manure by using an artificial neural network (ANN) model which employs regression models. For visualization of the biomethane potential, ArcGIS as a Geographical Information Systems program is used in the study with data sourced from the Turkish Statistical Institute (TurkStat) for all provinces for the 2013-2019 years. The biomethane potential of bovine manure is calculated in the laboratory. It is estimated that while bovine manure-based biomethane potential in 2002 is 1.757 billion m^3, it reaches 3.163 billion m^3 in 2019. By 2030, it's estimated to reach 5.45 billion m^3, which would cover approximately 7.1% of the natural gas demand, estimated at 76.8 billion m^3. Mapping the potential points out that there is concentrated accumulation in specific parts of the country, instead it is spread sparsely throughout the nation. They stress that the districts with the highest biomethane potential per capita (BPPC) include Ardahan, Kastamonu, Karaman, and Erzurum.

Melikoglu et. al. (2020) explore biomethane potential which can be obtained from cattle and sheep manure in Turkey. The required data for the study is obtained from literature and TurkStat. Their estimate suggests that 2.14 billion m^3 of biomethane produced from cattle and sheep manure is probably to be produced in 2026.

Karaca (2018) studies to determine the energy value of biogas based on animal manure in Turkey, as well as analyzing GHG emission abatement effects stemming from the usage of biogas. The study which utilizes cattle manure and laying hens manure to estimate biogas potential uses 2015 year animal statics from the Turkish Statistical Institution as the data source. Distribution of the calculated biogas potential data is mapped by using a GIS program. The study shows that the highest biogas potential, accordingly biomethane potential, is in Konya followed by İzmir, Erzurum, Balıkesir, Afyon, and Kars. The biogas potential based on cattle manure and hens manure is estimated at around 1,616.4 million/m^3 for 2015. In terms of CO2 emission based on animal manure, the study indicates that the majority of emissions caused by manure are concentrated in these districts.

Ersoy et. al. (2020) investigate biomethane potential based on animal manure, animal-based GHG emission, and how the emission would be mitigated via manure management. In this regard, they gather data from Turkstat to calculate the biomethane potential on different kinds of animals such as cattle, sheep, geese, chickens, and horse manure. Moreover, they conduct personal communications with scholars in universities and sector experts along with an internet search for the study. The study estimate 2.51 billion m^3 biomethane potential based on animal manure for 2015. It is found that Konya, having the highest number of cattle, possesses the greatest biogas potential among the regions studied. Additionally, Balıkesir, İzmir, Afyon Erzurum, and Kars are important places for the potential. These cities are assumed to be locations with significant GHG emissions based on animal manure. The study points out that animal manure management via biomethane production could result in a reduction in GHG emissions, accounting for 1.13% of the total emissions.

Yalcinkaya et. al. (2022) conduct spatial analysis for biogas potential based on livestock manure to determine district-intense hot spot fields throughout Turkey. They obtain livestock population data, which includes cattle, sheep goats, and poultry, from the TurkStat for 2013-2019. Yet, the data regarding manure production capacity is sourced from published reports, serving as a guideline from the Ministry of Food, Agriculture, and Livestock.. Based on the available data, spatial analysis using ArcGIS Pro software is conducted in the study. It is observed that hotspot fields around Konya, İzmir, Balıkesir, Çorum, and Afyon are intensifying districts while the Kars and Ardahan districts are sorted as persistent hotspot fields on the map. In addition, the study highlights that out of 72 districts ,which encompass Aksaray, the southeast, central and south parts of Turkey and Odemis (Izmir) as the highest biogas potential areas, 63 plants utilize manure as a raw material among 72 biogas plants. It is determined that 66 districts are emerging hot spots and among these, 44 districts lack biogas facilities entirely. These districts covers 28% of total theoretical capacity while only 16% of this capacity is used by existing biogas plants in these districts.

During the literature review process, various topics related to biomethane and biogas are encountered. While numerous economic analyses on biomethane fuel exist for different regions worldwide in the global literature, there is no economic study for biomethane conducted either from Turkey or for the country. However, economic analyses of biomethane production have been conducted for Italy, the Netherlands, Mexico, India, Malaysia, and Thailand. Instead, several economic analysis studies have been conducted for biogas in Turkey, along with numerous studies assessing the biomethane potential specifically for Turkey. This might be due to that there was no economic opportunity for biomethane such as carbon taxes and high natural gas prices, which could make biomethane production more financially viable, despite natural gas supply restrictions bringing the country to an energy crisis (Saglam, 2022).

In the frame of this thesis literature review chapter, economic analysis of biomethane on a global scale is highlighted. In this study Economic feasibility study for biomethane based on the collected data of opearting biogas facilities is conducted.In this context, because there is a lack of econometrical application in the existing literature, OLS method is settled in additon to NPV analysis. Furthermore, environmental analyses for biogas, as well as assessments of biomethane and biogas potential for Turkey, have been completed. The assessment of biogas potential, distinct from existing literature, involves utilizing raw material data sourced from operational biogas firms. Moreover, The evaluation of environmental impacts of the biomethane facility and its economical value are examined in the study. Following the literature review, the next part includes data and methodology for empirical analyses of biogas and biomethane.

CHAPTER 3

METHODOLOGY

The analysis is divided into two parts to assess the economic analysis of prospective biomethane production in Turkey. In the first part, The study employs the Ordinary Least Square (OLS) model via cross-sectional data from the survey to find the main determinants of total cost and total profits of the biogas facilities producing electricity. Linear and logarithmic regression models are settled. These models examine the effect of various combinations of independent variables which include electricity cost, labor cost, repair maintenance cost, heating cost, and raw material cost, derived from the conducted survey. They are analyzed to determine their impact on total cost and total profits. The model specifications are summarized in Table 2.

Table 2: OLS Model Types

Model Types	**Dependent Variables**	**Independent Variables**	
		Model 1	**Model 2**
Linear Regression Mode	Total Cost	Repair	Labor
		Heat	Heat
		Raw Material	Raw Material
		Electricity	Electricity
Logarithmic Regression Models	lncost	lnlabor	Lnrepair
		lnelectricity	Lnelectricity
		lnheat	Lnheat
		lnraw	lnraw

Secondly, the study develops theoretical biogas facilities based on data from electricity-producing firms. These facilities are designed to exclusively produce biogas as a raw material for biomethane. A hypothetical approach is undertaken due to the absence of existing biogas facilities solely dedicated to solely producing biogas. Hypothetical values are formulated by consulting sector expert comments and employed as inputs for a theoretical biomethane facility. Various upgrading methods with different capacities are compared by regarding operational costs, as biogas cost as raw material, electricity cost, repair maintenance cost, labor force cost, and heating cost while the selling price is taken as the natural gas price to find the most profitable method. These costs are derived from different technical features as described in Table 8. In this context, the suitable method is determined, followed by the calculation of the NPV. Cash flows are assessed using various discount rates and Internal Rate of Return (IRR) to ascertain the profitability of the system, mirroring methodologies found in existing literature (Gupta et al. , 2022; Cucchiella et al., 2019). C_{Biogas} implies biogas purchasing cost while C_{Repair}, $C_{Electricity}$, C_{Heat}, C_{Labor}, and R represent repair maintenance cost, electricity cost, heat cost, labor force cost, and revenue, respectively. The project is considered economically viable if the NPV is positive.

$$NPV = \text{-}Investment\ Cost + \sum_{t=0}^{n}(R - (C_{Biogas}+C_{Repair}+C_{Electricity}+C_{Heat}+C_{Labor}))/(1+i)^{t}) \quad (1)$$

In addition, to ensure procurement, hotspot fields for layer chicken manure and cattle manure are generated via mapping. This calculation utilizes biogas production potential derived from raw material data in the survey, differing from the literature. This approach is adopted because it is realized that the main raw material sources in the survey concept are layer chicken manure and cattle manure. These manure values are calculated for their biogas potential as raw material for biomethane facilities.

In the last part of the analysis, the carbon emissions effects of prospective biomethane facilities are analyzed to identify the environmental effects of biomethane production. it is considered that carbon saving calculation includes: (i) CO2 emissions from the raw material collection and transportation to the plant, (ii) Avoided carbon emissions due to raw material collection, (iii) Emission in Anaerobic Process, (iv) CO2 emissions during the upgrading process and (v) Avoided emissions resulting from substituting natural gas with biomethane.

CHAPTER 4

DATA COLLECTION

A survey was conducted to collect data on the specific costs associated with the operating biogas facilities in Turkey. The financial data collected from 17 different electricity-generating biogas facilities include raw material cost, electricity cost, repair maintenance cost, heating cost, and labor cost. The survey was conducted in 2024, in-person by vising the facilities as well as through phone-inverviews and e-mails. The survey was answered by facility managers for 8 facilities, engineers in facilities for 7 facilities, and high-ranked personnel from two facilities.

According to the Renewable Energy Resources (RES) List for 2024 (EMRA,2023), the total number of facilities utilizing animal, agricultural, and plant waste either separately or in combination is 76 in Turkey. Our sample size accounts for approximately 22% of total biogas facilities. Furthermore, this sample size constitutes 13.3% of the total biogas production capacity in Turkey.

The survey includes questions regarding daily and yearly production capacity, raw material components and raw material costs, raw material collection and procurement costs (USD), repair maintenance cost (USD), electricity cost (USD), heating cost (USD), labor force cost (USD) for the second half of 2023. The expectations of the respondents regarding a rise in the demand for biomethane due to CBAM, as well as their perceptions for biomethane are asked as well. Facilities' total cost and profit are calculated based on the collected data.

Because essential raw materials are chicken manure and cattle manure, raw materials maps are produced at the level of province, both separately and combined, according to the biogas production potential in m^3. Hotspot fields are generated via the Tableau program for biogas production potential. Data for cattle numbers and layer chicken numbers for the year 2022 is drawn from the Turkish Statistical Institute (TUIK). Firstly, daily manure production capacity is calculated for biogas potential production capacity.

Secondly, this potential capacity is multiplied by the coefficient of biogas potential in m^3 which is calculated using the collected data. Furthermore, distance information regarding the proximity of prospective districts to their borders is obtained from an online mapping platform for both the Çorum and Kars districts (Haritamap, n.d.).

CHAPTER 5

DATA ANALYSIS

5.1 SUMMARY STATISTICS OF EXISTING BIOGAS FACILITIES

In this section, the summary statistics of the collected variables are presented. To preserve the anonymity of each facility, it is not possible to report raw data or information that leads to the identification of individual firms.

Table 3 presents a numerical summary featuring generalized values under various statistical categories, while Figure 7 categorizes electricity-producing biogas facilities based on different size groups. Figure 8 illustrates hypothetical biogas facilities. To conclude, selected cost items for the chosen biomethane solution are identified.

5.1.1 Numerical Summary of Existing Biogas Facilities

Table 3: Descriptive Statistics in USD (n = 17)

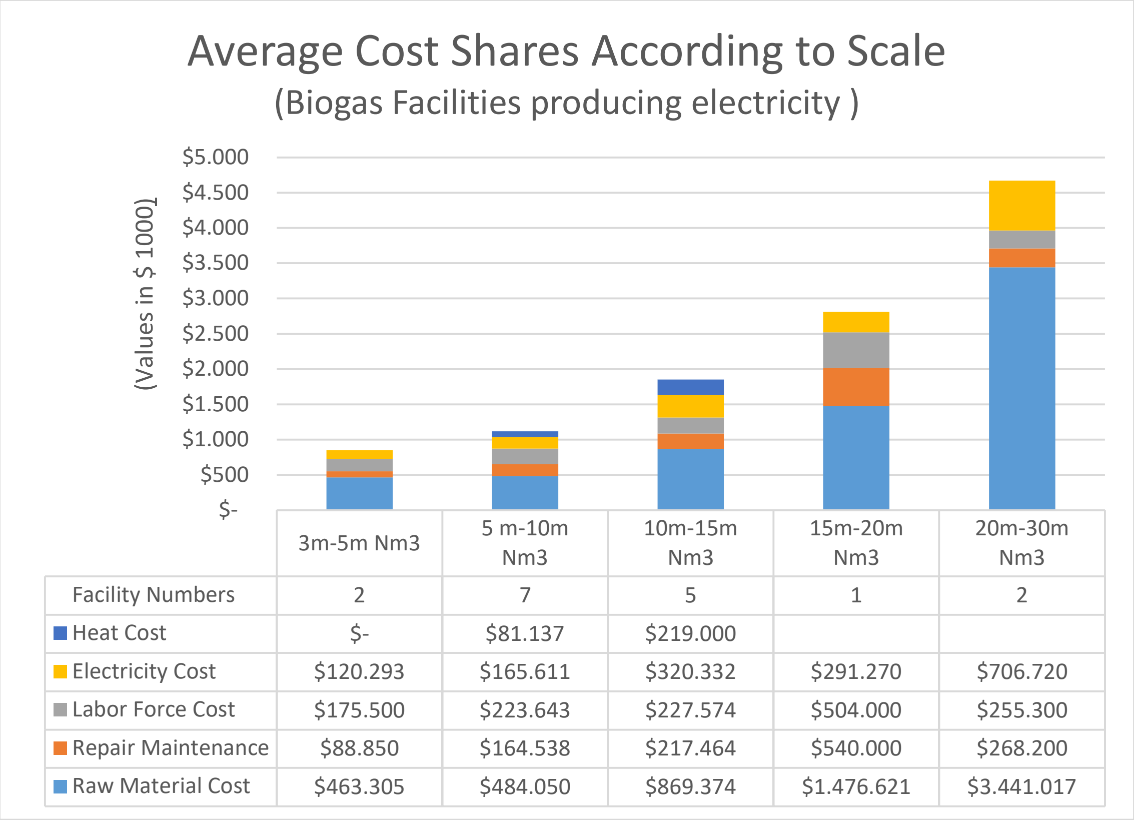
Variables (USD)	***Mean***	***Median***	***Standard Deviation***	***Range***	***Min***	***Max***
Profit	*1,158,447*	*871,713*	*1,100,268*	*4,911,975*	*-265,377*	*4,646,598*
Total Cost	*1,856,577*	*1,415,863*	*1,358,976*	*5,484,399*	*509,002*	*5,993,402*
Electricity Cost	*277,368*	*182,500*	*221,282*	*980,000*	*84,000*	*1,064,000*
Labor Force	*244,742*	*228,000*	*94,058*	*372,000*	*132,000*	*504,000*
Heat Cost	*102,594*	*0*	*300,147*	*1,095,000*	*0*	*1,095,000*
Repair Maintenance	*211,631*	*180,000*	*145,140*	*480,000*	*60,000*	*540,000*
Raw Material Cost	*1,020,242*	*509,143*	*1,055,227*	*4,108,984*	*160,417*	*4,269,402*
Capacity(Nm3)	10,508,482	8,640,000	6,706,717	24,862,000	-	-

Data collected from 17 facilities via the survey is summarized in Table 3. The widest ranges in values are seen in profit and total cost items, followed by raw material cost. However, the narrowest range in statistics can be seen in low-cost values embedded items such as labor force cost, electricity cost, and repair maintenance cost. Two facilities reported bearing heat costs. Median is the middle value of the dataset when it is ordered from the least to the greatest. It's a measure of central tendency that is less influenced by extreme values (outliers) compared to the mean. Range is the difference between the maximum and minimum values in the dataset, providing an idea of the spread of the data. In order not to expose the facilities, capacity values for both maximum and minimum values are not added to the table. Standard deviation measures the dispersion or spread of the values around the mean. A higher standard deviation indicates greater variability in the data.

The greatest amounts are in mean, in profit and total cost, as well as capacity items, because of the differences in facility size. The highest mean in cost items appear in the raw material cost item as it is the major part of the total cost by composing 55% of the total cost and has huge values with respect to other cost components. However, heat cost has higher standard deviation value because there are differences between values due to only two firms announcing heating cost, although it has the lowest mean.

5.1.2 Graphical Summary

Error! Reference source not found. summarises the cost structures of 17 facilities according to their production capacity. It can be observed that the greater the production capacity is, the higher the total cost. Raw material cost accounts for the highest share in the total cost, and increases as the capacity increases. Two firms fall into the 3 million (m) to 5 million (m) Nm3 capacity category, whereas there are seven firms in the 5 m to 10 m capacity range, five in the 10 m to 15 m category, one in the 15 m to 20 m range, and two in the 20 m to 30 m Nm3 capacity range. Electricity costs and repair maintenance costs increase as the capacity increases, however, an irregular pattern is observed for 15 million (m)-20m Nm^3 capacity. Labor cost is doubled for 15m-20m Nm^3 as compared with 10-15m or 20-30m Nm^3. This irregular pattern might be because there is only one observation in this group and it is a specific case. Because only two respondents reported that their facilities have heating costs, their values are excluded from the cost shares calculations.



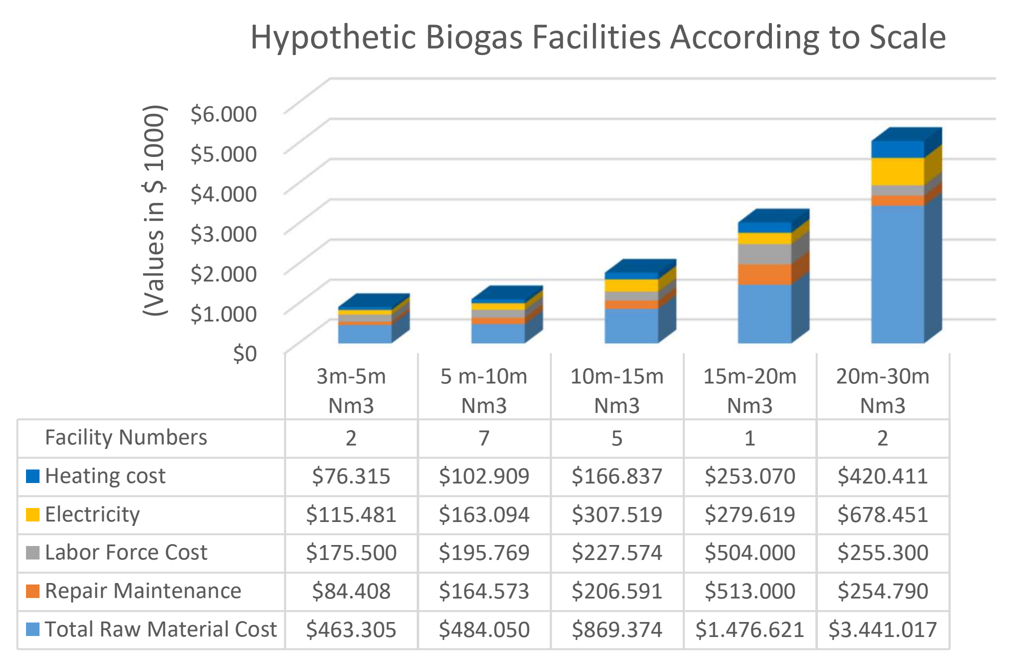
	3m-5m Nm3	5 m-10m Nm3	10m-15m Nm3	15m-20m Nm3	20m-30m Nm3
Facility Numbers	2	7	5	1	2
🟦 Heat Cost	$-	$81.137	$219.000		
🟨 Electricity Cost	$120.293	$165.611	$320.332	$291.270	$706.720
⬜ Labor Force Cost	$175.500	$223.643	$227.574	$504.000	$255.300
🟧 Repair Maintenance	$88.850	$164.538	$217.464	$540.000	$268.200
🟦 Raw Material Cost	$463.305	$484.050	$869.374	$1.476.621	$3.441.017

Figure 7: Average Cost Shares of Biogas Facilities Producing Electricity According to Scale

Based on expert comments from the biogas sector, existing facilities are hypothetically being redesigned with the goal of generating biogas to serve as the raw material for biomethane production. In this respect, labor force cost and total raw material cost are taken as the same values as the values in biogas facilities producing electricity. Changes in the other three items are adjusted to the graphics.

Hypothetic facilities are sorted concerning their scale. It is clear in the graphics that raw material cost, electricity cost, and heating cost items move in the same direction with the production capacity scale, while repair maintenance and labor force cost are the highest values in the 15m-20m Nm^3 range. However, when this group is omitted, both repair maintenance and labor force costs increase as production capacity increases. This different trend can be explained by only one observation included in that group.

Here, it is seen that the largest portion of the total cost is raw material cost, followed in sequence by electricity, labor force, repair maintenance, and heating costs. It is counted that the average total cost for the 3m-5m Nm^3 range is 915,009 USD, for 5m-10m Nm^3 is 1,206,291 USD and for 10m-15m Nm^3, for 20m-30m Nm^3, is respectively 1,777,894 USD, 3,026,310.05 USD, 5,049,969 USD.

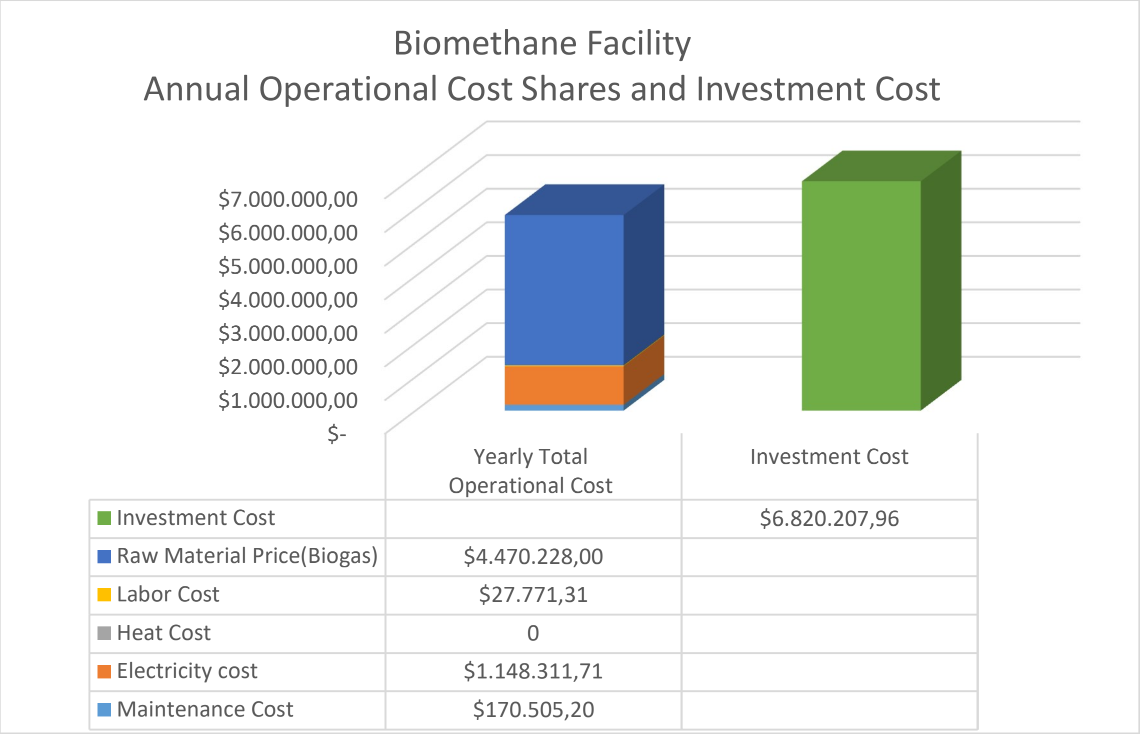


	3m-5m Nm3	5 m-10m Nm3	10m-15m Nm3	15m-20m Nm3	20m-30m Nm3
Facility Numbers	2	7	5	1	2
■ Heating cost	$76.315	$102.909	$166.837	$253.070	$420.411
■ Electricity	$115.481	$163.094	$307.519	$279.619	$678.451
■ Labor Force Cost	$175.500	$195.769	$227.574	$504.000	$255.300
■ Repair Maintenance	$84.408	$164.573	$206.591	$513.000	$254.790
■ Total Raw Material Cost	$463.305	$484.050	$869.374	$1.476.621	$3.441.017

Figure 8: Hypothetically Calculated Cost of Only Biogas Producer Facilities

In Figure 9, annual operational costs are sorted out as raw material cost (biogas), labor force cost, heating cost, electricity cost, and repair maintenance cost. It is shown that the largest part of the operational cost is seen as biogas price. This item is followed by electricity, repair maintenance, and labor force costs.

In the second column of Figure 9, the investment cost is settled for water scrubbing upgrading technology for 18,396,000 Sm^3 biomethane production capacity.



	Yearly Total Operational Cost	Investment Cost
🟩 Investment Cost		$6.820.207,96
🟦 Raw Material Price(Biogas)	$4.470.228,00	
🟨 Labor Cost	$27.771,31	
◼ Heat Cost	0	
🟧 Electricity cost	$1.148.311,71	
🟦 Maintenance Cost	$170.505,20	

Figure 9: Biomethane Facility Annual Operational Cost Shares and Investment Cost

5.2 REGRESSION ANALYSIS

OLS (Ordinary Least Squares) regression is a commonly used statistical method to estimate the relationship between one or more independent variables and a dependent variable. It's often used to analyze and understand the relationship between variables in data sets. OLS allows us to determine which factors have a statistically significant impact on the outcome variable.

OLS regression is a valuable tool in research as it helps to uncover relationships between variables, make predictions, identify significant factors, compare models, and inform policy decisions. In the context of biogas research, it can provide insights into cost drivers and efficiency improvements for biomethane production.

Table 4: Linear Variables Correlation Results

Variables	Labor Force Cost	Electricity Cost	Heat Cost	Total Raw Material Cost	Repair Maintenance	Total Cost	Capacity
labor Force Cost	1						
Electricity Cost	0.188	1					
Heat Cost	-0.184	-0.057	1				
Total Raw Material Cost	0.250	0.854	-0.095	1			
Repair Maintenance	0.576	0.338	0.322	0.393	1		
Total Cost	0.315	0.863	0.160	0.954	0.578	1	
Capacity	0.336	0.860	0.074	0.877	0.561	0.920	1

In Table 4, the correlation coefficients are presented. The table points out that except for between electricity and raw material cost, and labor force and repair maintenance cost, there is not any correlation between variables. The labor force and repair maintenance are modeled separately because when included together in a model, p-values consistently remain insignificant. Electricity and raw material cost are modeled together because there is no significant value presence in models. The assessment for multicollinearity utilizes the Variance Inflation Factor (VIF), where values below 5 signify that modeling raw material cost and electricity cost together is appropriate and acceptable. Consequently, our models exhibit no serial multicollinearity, making them suitable for analysis.

Table 5: Linear Regression Models Results

Variables	Model 1			Model 2		
	Coefficient	**T**	**Sig.**	**Coefficient**	**T**	**Sig.**
Repair	1.486	9	.000			
Heat	0.865	12.252	.000	1.221	1.358	.000
Raw Material	0.997	27.122	.000	1.037	2.11	.000
Electricity	0.973	5.772	.000	1.016	4.401	.000
Labor				1.908	6.464	.000
N	17			17		
R²	.998			.995		
Adjusted R²	.997			.994		
F	1227.88			655.24		
Confidence Level	.95			.95		
Dependent Variable	Total Cost			Total Cost		

Estimated results are presented in Table 5. All the estimated coefficients are statistically sigifnicant at 5% significance level. In the first model, It is seen that the because R square value is 0.998, it means that 99.8% of the variability in the dependent variable is accounted for by the independent variables in the model. This indicates the model well fits the observed data. The F test is significant. In this model, because Repair's coefficient value is 1.486, an increase in repair maintenance cost raises the total cost by almost 1.486 USD. A USD increase in heat cost, in raw material cost, and in electricity cost cause a rise of 0.865 USD, 0.997 USD, and 0.973 USD in total cost, respectively.

In the second model, the R squared value of 0.995 indicates the model is a good fit for the data. F test is significant and P-values are significant for all variables. Here, a USD rise in heat cost leads to a 1.221 USD rise in total cost as a mean. Similarly raw material cost, electricity cost, and labor force cost result in mean rises of 1.037 USD, 1.016 USD, and 1.908 USD, respectively, in the total cost. The different coefficient estimates between the two models can be related to the different additional independent variables (repair maintenance cost in the first model and labor cost in the second model). They may have different impacts on the dependent variable (total cost) compared to each other. Even if the shared independent variables are the same, the presence of different additional variables can affect the coefficient estimates of the shared independent variables.

Table 6: Logarithmic Variables Regression Analysis

Variables	Model 1			Model 2		
	Coefficient	T	Sig.	Coefficient	T	Sig.
lnlabor	0.356	3.365	0.006			
lnelectricity	0.295	3.946	0.002	0.243	3.640	0.003
lnheat	0.048	6.696	0.000	0.030	4.261	0.001
lnraw	0.486	9.479	.000	0.451	9.318	0.000
lnrepair				0.243	4.201	0.001
N	17			17		
R^2	0.971			0.978		
Adjusted R^2	0.962			0.97		
F	102.001			130.448		
Confidence Level	0.95			0.95		
Dependent Variable	lncost			Lncost		

In Table 6, the logarithmic regression models are presented. As can be seen in Table 6, two models comprise four different independent variables because, in the five independent variable model, lnlabor variable becomes statistically insignificant. The decision to model "lnlabor" and "lnrepair" separately is due to the consistent insignificance of p-values when included together in a single model. All values are produced by taking logarithmic values of linear variables.

In the first model, as can be seen in Table 6, the R squared is high, indicating a strong fit of the model, whereas all estimated coefficients are statistically significant at one percent significance level with expected signs. In this regard, a one percent rise in labor force cost (lnlabor) causes a 0.356% rise in total cost (lncost), while a one percent increase in electricity cost, heat cost, and in raw material cost, result in 0.295%, 0.048%, and 0.486% rise, respectively, in total cost.

The second model values in Table 7 point out a good fit feature for the R square value, significant F-test value for the model, and significant P-test values for all independent variables. In this respect, a 1 percent increase in electricity cost causes a 0.243% rise in total cost while a percent increase in heat cost, raw material cost, and repair maintenance cost push-up total cost by 0.03%, 0.451%, and 0.243%, respectively. The different coefficient estimates can be linked to the effect of the different additional variable on the dependent variable.

Table 7: Logarithmic Variables Correlation Results

Variables	lnlabor	lnelectricity	lnheat	lnraw	lnrepair	lncost	lncap
lnlabor	1						
lnelectricity	0,253	1					
lnheat	-0,154	-0,016	1				
lnraw	0,434	0,656	-0,010	1			
lnrepair	0,603	0,466	0,361	0,603	1		
lncost	0,486	0,731	0,292	0,905	0,802	1	
lncap	0,438	0,870	0,100	0,781	0,709	0,896	1

Table 7 denotes that there is a relatively high correlation between lnelectricity and lnraw, and between lnlabor and lnrepair, as 0.656 and 0.603, respectively. The evaluation for multicollinearity indicates that the Variance Inflation Factor (VIF) values are below 5 for the independent variables, it suggests that the models do not suffer from significant multicollinearity issues and modeling them together is considered appropriate and acceptable..

5.3 FEASIBILITY ANALYSIS

In Turkey, existing biogas facilities produce electricity by using biogas produced from municipal wastes including trash and industrial wastes, forest waste, agricultural waste such as plant residuals, and animal manure (Renewable Energy Resources(RES) List for 2024 (EMRA,2023)). However, no facilities are producing only biogas as raw material and selling it as raw material. The biogas produced in the anaerobic digesters contains primarily methane along with other gases such as carbon dioxide and trace impurities. Biogas upgrading technologies are used to remove impurities and increase the methane concentration to produce biomethane. Various technologies are employed for upgrading biogas to biomethane, such as Pressured Water Scrubbing, Pressure Swing Adsorption, Membrane Separation, Chemical Scrubbing, and Organic Physical Scrubbing. In this section, we conduct a feasibility analysis for a potential biomethane facility that uses biogas as input. Currently, there is only one biomethane facility in Turkey. We are going to explore the potential of an ideal biomethane facility in Turkey.

Because we need biogas cost as raw material for the biomethane facility and there are not any facilities producing only biogas at the time of our study, we consulted an expert to estimate the hypothetical cost for biogas. According to the expert, the electricity cost of the biogas facility would decrease by 4% if the facility produces only biogas, not electricity.

Additionally, the repair maintenance cost would be 95% of the repair maintenance cost of a biogas facility that produces electricity. Heating costs would constitute 9% of the total cost of the biogas facility generating electricity, while raw material and labor force expenses would remain at the same level as those of the facility producing electricity. Given these estimates, electricity and repair maintenance costs are recalculated to hypothetically transform from electricity production to exclusive a biogas-producing facility.

Biomethane investment data is drawn from the study of Gupta et. al. (2022). For operational cost calculation, labor force need is taken from the assumption of Gupta et. al.(2022), and calculated via investigating domestic conditions by consulting sector experts. The electricity cost, repair maintenance and heat cost technical data are taken from the assumptions of Bilig et. al. (2014). The cost value is determined by regarding the technical value mentioned in the study of Bilig et. al.(2014) and computed using the electricity selling prices set by the Republic of Turkey Energy Market Regulatory Authority (EMRA) effective from October 2023 (EMRA, 2023). Heat cost is assumed as zero and the maintenance cost is taken as 2.5% of the total investment cost (Bilig et al., 2014).

The operational cost which is composed of electricity cost, maintenance cost, heat cost, labor force cost, and raw material cost as hypothetical biogas cost per Sm^3 is calculated as per Sm^3. The finding is compared with domestic natural gas price taken from BOTAŞ (Petroleum Pipeline Corporation) February 2024 Natural Gas Retail Natural Gas Selling

Price Publishment (BOTAŞ, 2024) , because there has not been any change in natural gas selling price for the industrial sector since October, 2023. This comparison helps to identify economically feasible upgrading technology and its period for capital recovery. In this context, biomethane cost data and graphics are produced to exhibit cost shares according to scales.

5.4 FEASIBLE UPGRADING TECHNOLOGY

Analyzing different upgrading technologies is essential for economic reasons because it directly impacts financial viability through diverse technical characteristics affecting operational expenses, and initial expenses.

Table 8: Technical Features of Different Upgrading Technologies (Source:Bilig et. all, 2014)

Upgrading System/Items	Pressured Water Scrubbing	Pressure Swing Adsorption	Membrane Separation	Chemical Scrubbing	Organic Physical Scrubbing
Methane Yield	97%	97%	97%	97,5%	97%
Annual Repair Maintenance Cost (% of investment)	2.5%	2.5%	3,5%	2.5%	2.5%
Electricity consumption(kwh/Nm^3 biogas)	0.25	0.25	0.25	0.125	0.25
Heat Consumption(kwh/Nm^3 biogas)	None	None	None	0.55	None

Four different upgrading technologies with different production capacities are taken as a base for a hypothetical upgrading facility. Here, operational costs for different technologies are counted based on technical values shown in table 8.

None of the Upgrading facilities techniques have any bias for technical viability of installation in considering environmental factors. Thus, technical details are ignored and techniques are compared only in terms of economical features.

In this context, operational costs and profits are calculated based on the highest BOTAŞ natural gas selling price, which is determined to be 0.447 USD per standard cubic meter as of October 1, 2023. This determination is based on the exchange rate observed on September 9, 2023. Insights were gathered from interviews with a sector expert who deems this date suitable for initiating the calculation for price determination analysis. Biogas cost as a raw material must be at most at a level of 0.21 USD per Sm^3 biogas because for per biomethane Sm^3 generation, 1.62 Sm^3 is needed. Hence, its price per Sm^3 biomethane is determined as 0.34 USD. In other words, the operational cost of producing biomethane is deducted from the selling price of natural gas. Upon analysis, it's determined that the threshold is $0.21 USD Sm^3 of biogas. Consequently, it's revealed that three facilities fulfill this price requirement.

When annual profit based on operational cost is calculated, and only one facility type is seen as an economically viable because of the usable span of upgrading facilities as 20 years (Gupta, Miller, Sloan, at. al.,2022). It is concluded that an economically viable facility should have an 18,396,000 Sm^3 annual capacity in the pressurized water scrubbing (PWS) technique. Its economical profile can be seen in Table 9.

It is considered that the PWS method which is a simple and technically reliable and effective technology (Miltner et al., 2017) is the most common technology in the biomethane production industry (Ammenberg et al., 2021). From a technical standpoint, the technology demonstrates high efficiency and exhibits good tolerance for impurities like sulfur and ammonia (Ammenberg et al., 2021). It is regarded to be cost competitive, specifically in large-scale production capacities, and well-tested, flexible, and reliable technology (THE ORGANICS RECYCLING AUTHORITY, 2018). Moreover, it showcases environmentally friendly feature by efficiently reducing pollutant emissions through effective gas cleaning processes (Wylock & Budzianowski, 2017).

Investment Cost:

Investment cost refers to the expenses for constructing a new biomethane facility. The costs are drawn from literature because there is no biomethane facility with significant product capacity in in Turkey. After comparing the operating costs of various upgrading technologies with the selling price of natural gas as biomethane price, it becomes evident that all options lead to financial losses due to operational costs exceeding revenue, with the exception of the Pressured Scrubbing Method. As a result of the cost analysis, only the Pressured Water Scrubbing Method is taken as the technology.

Maintenance Cost:

The maintenance cost is taken as yearly as a share of the investment cost as mentioned in Table 8 as 2.5 % (Bilig et. all, 2014). This value is based on information from upgrading technology manufacturers.

Electricity Cost:

The cost is calculated by the technical value mentioned in Table 8 and calculated with electricity selling prices of 0.15 USD per kWh, enforced from 2023 October (EMRA, 2023). The electricity consumption varies based on numerous factors, including, system pressure, particular design, and, in certain instances, outdoor temperature (especially relevant for physical scrubbers), as well as the methane concentration in the raw biogas (Bilig et. all, 2014).

Labor Cost:

Labor cost is determined based on the wage of two engineers as technical needs (Gupta et al., 2022). These wages are derived from real wage data for two engineers working in a biogas facility in Turkey in the second half of 2023, according to expert opinion from the biogas sector.

Heating Cost:

Heating cost is taken from as a technical feature from Table 8.

Raw Material Cost (Biogas):

The hypothetical raw material cost is calculated using the survey data. The total cost of hypothetical biogas firms, along with the profit generated by the 17 electricity-generating biogas facilities considered as an opportunity cost, is calculated per cubic meter (m3) of biogas. The operational cost of producing biomethane is subtracted from the selling price of natural gas. After setting the threshold at \$0.21 USD Sm^3 of biogas, it is found that only three facilities meet this pricing requirement. Due to only three firms having hypothetical biogas prices that meet feasibility for the sale price, only three values are selected as base raw material cost per Sm^3 and then multiplied by total production capacity. Section 5.5 provides a detailed explanation of how biogas prices are calculated. By using this cost item, the yearly operational cost screen is settled for a feasible solution as below in Table 9.

Table 9: The Selected Technology Cost Screen

Project Life	20 years		
Investment Cost	$6,820,207		
Annual Maintenance Cost	$170,505		
Yearly Electricity Costs	$1,148,311		
Heat Cost	0		
Yearly Labor Cost	$27,771		
Yearly Raw Material Cost	$4,470,228		
Raw Material Price(Biogas per Sm^3 biomethane)*	$0.15**	$0.24***	$0.34****
Sale Price	$0.447		
Capacity(Sm3)	18,396,000		
*The price calculated for per Sm3 biomethane, which is 1.62 (methane rate for biomethane=0.97/methane rate in biogas)xPrice for biogas Sm3			
**Price by Facility C=$0.08 Sm3 biogas			
*** Price by Facility B=$0.15 Sm3 biogas			
**** Price by Facility A=$0.21 Sm3 biogas			

5.5 NPV CALCULATION

Table 10: Feasibility Analyses Results in Different Price Scenarios

	Biogas Facility A	Biogas Facility B	Biogas Facility C
Price for Sm3 Biogas	$0.21	$0.15	$0.08
NPV(%5)	$32,721	$23,166,309	$49,163,806
NPV(%10)	$-2,138,626	$13,665,093	$31,425,292
NPV(%15)	$-3,378,221	$8,240,969	$21,298,600

The price of Biogas Facility A corresponds to a facility with a production capacity ranging between 15 million and 20 million Nm^3. Biogas Facility B's price is attributed to a facility within a group with production capacities ranging from 5 million to 10 million Nm3. Biogas Facility C's price is associated with a facility with a production capacity ranging from 10 million to 15 million Nm^3. Each of these three prices is determined by dividing the sum of the hypothetical total cost of a facility and its profits earned from electricity production (considered as an opportunity cost) by the facility's biogas production. The equation is as shown below:

$$\frac{\text{Hypothetical Total Cost}_{\text{Facility i}} + \text{Profit}_{\text{Facility i}}}{\text{Biogas Production Capacity}_{\text{Facility i}}} = \text{Biogas Price}_{\text{Facility i}} \qquad (2)$$

According to the three prices allowing positive profit, different internal rate of return values, 5% (Gupta et al., 2022), 10% (Yorucu et al., 2018; Balcioglu et al., 2022; Bulut et al., 2021), and 15% (Balcioglu et al., 2022), respectively, are utilized for the net present value calculations. Over the past five years, the 20-year yield TR EUROBOND rates have varied between 5.94% and 11.18% (Bloomberg, 2024). This range suggests that these rates could be considered suitable discount rates for incorporation into net present value calculations concerning investments denominated in foreign currencies. All prices yield positive net present values at a 5% discount rate. However, at discount rates of 10% and 15%, the \$0.21 price per Sm^3 for biogas results in negative values, whereas the \$0.15 and \$0.08 prices yield positive but decreasing values as the rate of return increases.

The internal rate of return is calculated to identify the discount rate with which the net present value becomes zero. Accordingly, for a price of \$0.21, a 5% internal rate of return is calculated, while for \$0.15, it is 35%, and for \$0.08, it is 66%. These figures provide insights into the project's financial viability and its ability to generate profits relative to the initial investment, with higher rates indicating greater profitability.

5.6 SUGGESTED BIOMETHANE FACILITY

5.6.1 Map Analyses

The responses to our survey revealed that cattle manure or layer chicken manure are used together or separately in all facilities. To determine the ideal location for a new biomethane facility, we identify provinces that have enough raw materials to support profitable operations. As the first step, cattle and layer chicken numbers in 2022 are drawn from province-level statistics published by TÜİK. The compiled data is adjusted based on the daily manure production capacity of cattle and layer chickens, utilizing coefficient data sourced from the Agriculture and Forest Ministry of Turkey's open-source reports[1]. The data announces a layer chicken can produce 175 g of manure daily (Şekeroğlu, et.al., 2013) while a cattle can generate 48 kg of manure daily (MINISTRY OF AGRICULTURE AND FORESTRY, n.d.). These values are multiplied by coefficients obtained from the survey data, representing the biogas production potential for various types of raw materials. As a result, it has been determined that the average biogas potential for cattle manure is 42.85 Nm3 per ton, while the average biogas potential for layer chicken manure is 116.13 Nm3 per ton, as indicated in Table 11.

Table 11: Biogas Potentials of Raw Materials

Raw Material Type	**Biogas Potential (Nm^3 per ton)**
Chicken Manure	116.13
Cattle Manure	42.85

By considering the values mentioned above, the biogas potential according to raw materials was calculated at the provincial level. Consequently, 32 hotspot fields are produced and colored on maps, intensifying their potential ranks separately and combined. Table 12 presents the total daily biogas potential, as well as the daily biogas potential from cattle manure and layer chicken manure, for these 32 hotspot fields.

Table 12: 32 Hotspot Fields

Rank	**Districts**	**Total Daily Biogas Potential (Nm3)**	**Daily Cattle Manure Biogas Potential(Nm3)**	**Daily Layer Chicken Manure Biogas Potential (Nm3)**
1	Ödemiş	266769	266044	725
2	Aksaray	256632	253393	3239
3	Eregli	197522	193661	3861
4	Meram	162419	106068	56352
5	Kars	156442	154281	2160
6	Kiraz	152314	151996	318
7	Tire	149316	149112	203
8	Çorum	135556	61377	74179
9	Çine	134501	133281	1219
10	Eskil	129393	129314	79
11	Bayındır	121947	121666	281

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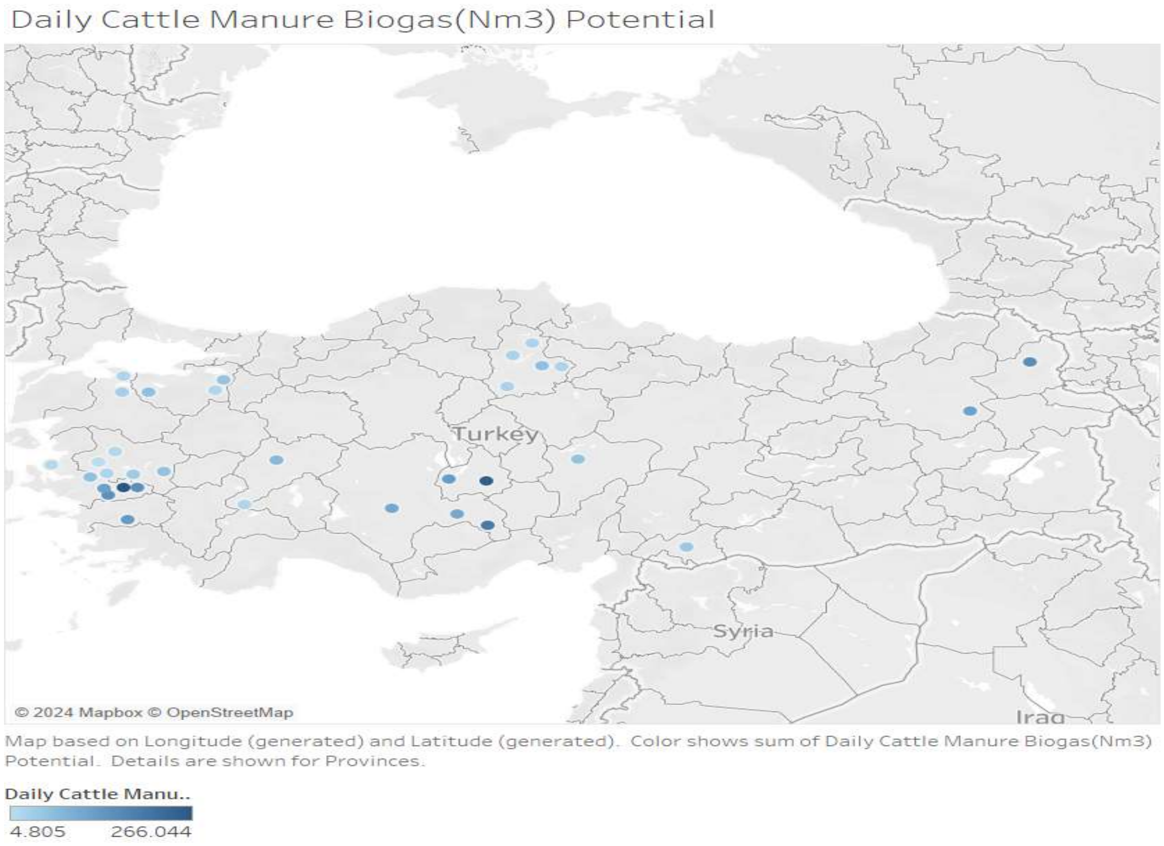
[1] MINISTRY OF AGRICULTURE AND FORESTRY”BÜYÜKBAŞ HAYVANCILIK (SIĞIRCILIK)”

12	Karayazı	118206	118032	174
13	Karapınar	104009	103653	356
14	Afyonkarahisar	82358	75781	6576
15	Mustafakemalpaşa	65448	61069	4380
16	Kemalpaşa	63206	61069	2137
17	Yenişehir	61299	53471	7828
18	Kocasinan	58183	56414	1769
19	Kula	55505	55357	148
20	Şehitkamil	50708	44312	6396
21	Salihli	44423	42041	2381
22	Manyas	32636	31167	1470
23	Turgutlu	32519	22072	10447
24	İskilip	26742	25856	886
25	Sungurlu	26466	26060	406
26	Mecitözü	23392	22884	508
27	Bandırma	23267	21539	1728
28	Osmancık	23040	22962	78
29	Başmakçı	22425	20453	1972
30	İnegöl	21134	20854	280
31	Akhisar	17103	14799	2305
32	Foça	13471	11757	1714

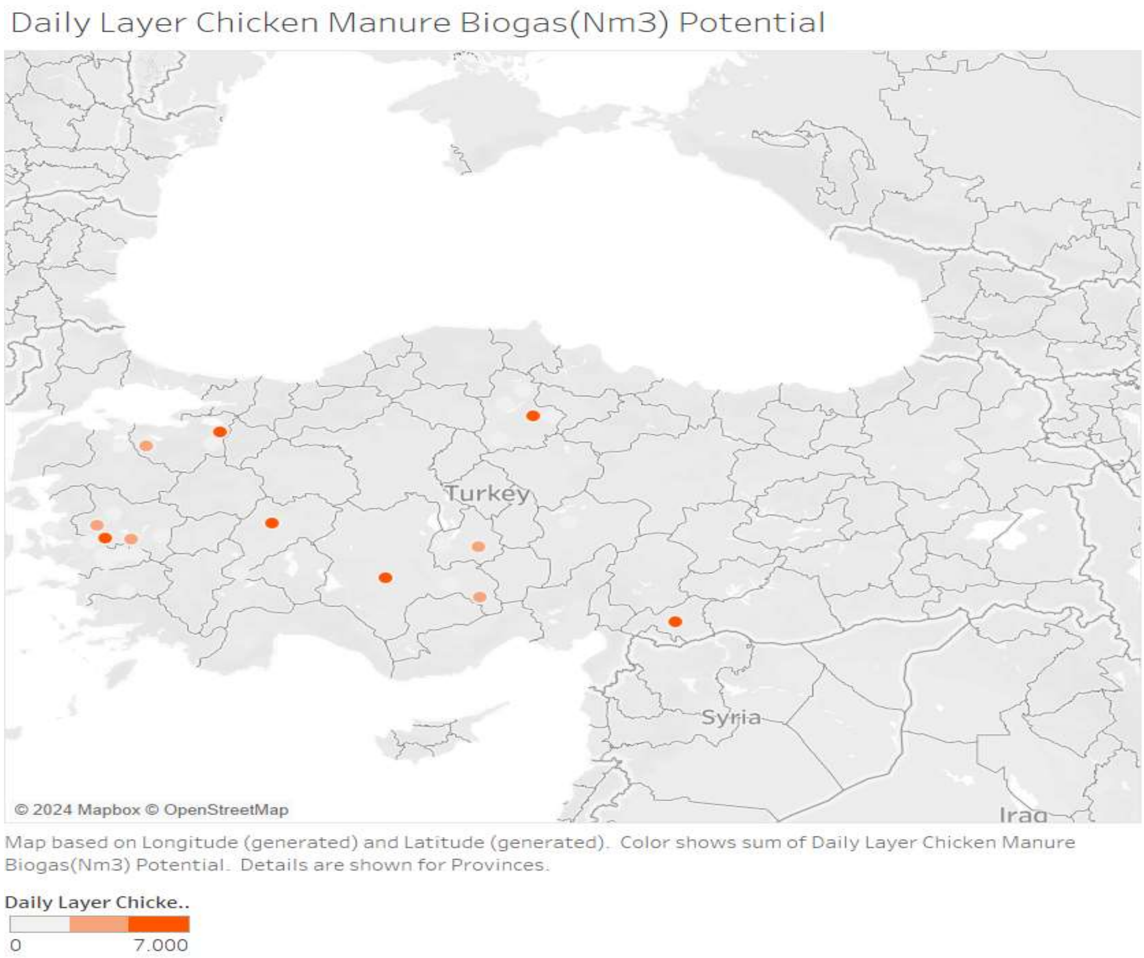
As illustrated in Figure 10, for daily biogas production from cattle manure, the areas with the highest potential are concentrated in western Anatolia, particularly between the cities of Izmir, Manisa, and Aydın. This region is followed by Aksaray and the southeastern part of Konya. Additionally, Kars district shows strong potential. However, in Kars, cattle manure is currently used as solid fuel and fertilizer, so ensuring an adequate supply for local residents would be necessary before utilizing it for biogas production (Demir, 2017).



Map based on Longitude (generated) and Latitude (generated). Color shows sum of Daily Cattle Manure Biogas(Nm3) Potential. Details are shown for Provinces.

Figure 10: Daily Cattle Manure Biogas Potential According to Province Level

For daily layer chicken manure biogas potential is ranked first in Çorum (Center), followed by Meram (Konya), Turgutlu (Manisa), Yenişehir (Bursa), Afyonkarahisar (Merkez), and Şehitkamil (Gaziantep). As depicted in Figure 11, the distribution of biogas potential from this raw material seems to be less concentrated compared to the biogas potential from cattle manure.



Map based on Longitude (generated) and Latitude (generated). Color shows sum of Daily Layer Chicken Manure Biogas(Nm3) Potential. Details are shown for Provinces.

Figure 11: Daily Layer Chicken Manure Biogas Potential According to Province Level

As daily total biogas potential is the sum of these two total raw materials' daily biogas potential, Figure 12 is produced with intensified colors. Here, it is drawn that the total biogas potential is concentrated on the western side of Anatolia. It is followed by Aksaray, Eregli, and Meram (Konya provinces), Kars (Center), and Çorum (Center).

The potential is primarily dominated by cattle manure material, with sparse distribution across the country. In this regard, we can conclude that there are many potential centers for prospective facilities.

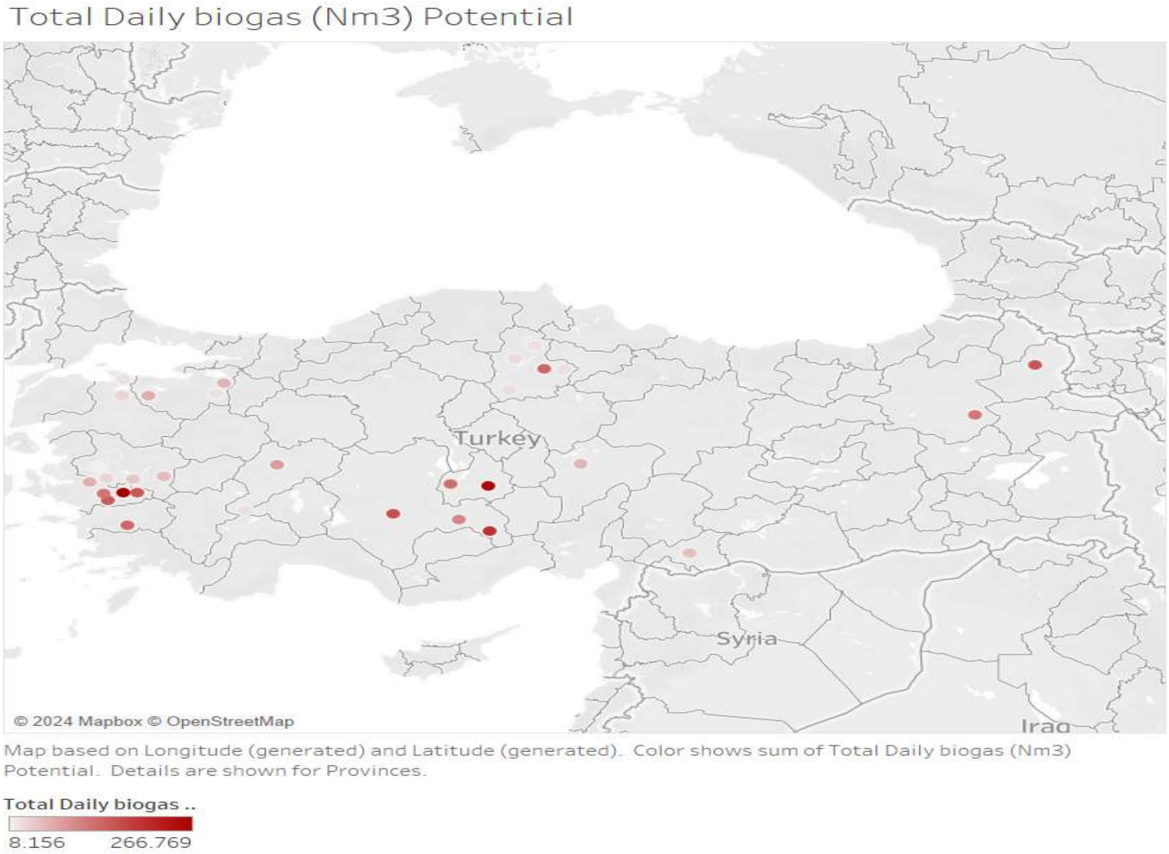


Figure 12: Total Daily Biogas Potential According to Province Level

5.6.2 Prospective Biomethane Facility Features in An Exact Place

Up to this point, it has been observed that in the three hypothetical biogas facilities calculated to produce only biogas, the selling price of biogas is sufficient to achieve a positive operational profit (Income-Operational Cost) or positive cash flow. Therefore, these prices should be considered as the raw material cost necessary to achieve a positive profit for prospective biomethane facilities. It has been concluded that only a biomethane production capacity of 18,396,000 Sm3 would yield a positive operational profit with the analyzed data, as the operational costs per Sm3 for other options exceed the natural gas price per Sm3, which is set as the biomethane price. This value stipulates 28,311,444 Nm^3 annual biogas production potential with a 1.539 conversion coefficient (1 Sm^3 biogas=0.95 Nm^3 biogas= 0.62 Sm^3 biomethane) while 77,566 Nm^3 is daily biogas needed potentially. Because the main source of the biomethane is biogas, the location, where the prospective biomethane facility is projected, requires to meet this potential.

The first step in the prospective area selection process involves assessing the availability of raw materials that can be used to produce biogas. Biogas is typically produced through the anaerobic digestion of organic materials such as agricultural residues, animal manure, municipal solid waste, and organic industrial waste. Therefore, the first consideration is to identify areas where these raw materials are abundant and easily accessible. The second step is available existing facilities in the area to feed the prospective biomethane facility. In this situation, there may be a pool of local expertise including operators, technicians, and engineers who are experienced in biogas production, which can be valuable for the operation of a biomethane facility. Communities with existing biogas facilities may already be familiar with the benefits of renewable energy production and may be more accepting of a biomethane facility. However, If multiple facilities in the area rely on the same feedstock sources, there may already be an existing competition and potential conflicts over resource availability. Existing biogas facilities with significant potential in the region might already be procuring organic waste from nearby raw material sources. Competition for feedstock could drive up prices or lead to shortages, affecting the profitability and operational stability of the prospective biomethane facility. However, in areas where biogas facilities are absent, there isn't an established market for raw materials, potentially resulting in lower costs and easier procurement of these materials. Furthermore, selecting regions without existing biogas facilities can lead to enhanced environmental quality, as waste left in the environment can be repurposed into energy, thereby capitalizing on this resource. This approach also opens up opportunities to improve waste management practices in these areas. Therefore, districts with multiple biogas facilities, single biogas facility, and districts lacking biogas facilities have been selected. However, it's crucial that the biogas prices in these districts align with the three biogas price conditions mentioned earlier.

We have selected city’s central district as potential locations for biomethane facilities based on the abundance of raw material sources, as indicated in the hotspot provinces table. Additionally, these provinces are within a feasible distance of 60-80 km to provincial borders, facilitating transportation and logistics. Central district of Çorum already hosts one existing biogas facility, while Aksaray (Center) boasts three such facilities. Furthermore, Building biomethane facilities in city’s central district provides opportunities for community engagement and public education about renewable energy and sustainable waste management practices. It allows residents to witness firsthand the benefits of converting organic waste into clean energy, fostering support for renewable energy initiatives and environmental stewardship.

According to daily biogas potential, the first eight hotspots are listed below. As can be seen in Table 13, these districts contain strong potentials, and for Kars (Center) two facilities can be supported given its high potential.

Table 13: First 8 hotspot Districts

District	**Daily Biogas Potential (km)**
Ödemiş	266,769
Aksaray(Center)	256,632
Eregli	197,522
Meram	162,419
Kars(Center)	156,441
Kiraz	152,314
Tire	149,316
Çorum(Center)	135,556

Another important aspect to consider is the absence of multiple biogas facilities fed by raw materials from surrounding districts, leading to the absence of a raw material market within a district, which can raise raw material costs. Hence, Kars and Çorum can lack the raw material market because, in Çorum, there is currently only one biogas facility in operation, while in Kars, no biogas facility exists. In addition, this prospective facility can value waste in those districts, create a clean environment, and raise environmental quality because of the collection and capitalization of waste as energy.

Given that manure serves as both an energy source and fertilizer in agriculture, biogas plants are compelled to provide either fertilizer or energy to farmers engaged in animal husbandry, as they utilize this manure as a raw material for biogas production. Additionally, domestic firms make use of this method for procuring raw materials.

It is mentioned by a sector expert that heating cost is related to the average temperature in the district. However, the analysis process did not reveal any correlation or relationship between average temperature and heat cost. Hence, average temperature is ignored for a cost determinant in our study. It is assumed that Çorum, Aksaray, and Kars, with lower average temperatures, are considered to have similar heat cost features.

Excluding heating costs, all other expenses are unrelated to location and instead are associated with the internal processes of facilities, with the exception of raw material transportation costs. Hence it is told that the optimal distance from the accumulation place to the facility must be an averagely 60-80 km according to expert comments from the sector. The distance between Kars (Center) and central area of Kars's distance to its borders is 30-40 km on average. Table 14 illustrates the distances of the city's districts from the city's central district. It can be drawn that a facility which is built in the city center can procure its raw material at a feasible distance. It can be considered that collecting raw materials in Kars, where sources may be scattered across a large area, poses logistics challenges. Encouraging partnerships and cooperative arrangements among farmers to pool resources in a specific location can significantly enhance efficiency and lighten the burden on individual farmers. Policy makers can develop incentive programs that reward farmers for collective action and collaboration. This could include bonuses or preferential treatment for farmers who participate in cooperative ventures, such as priority access to markets or additional financial incentives. Collecting and properly managing manure reduces these emissions, mitigating climate change. Moreover, collecting manure helps prevent nutrient runoff, improving water quality. Additionally, it reduces odors and air pollutants associated with untreated manure, benefiting both local ecosystems and nearby communities. Instead of incurring costs associated with traditional manure disposal methods like land spreading or storage, farmers can save money by diverting manure to biogas facilities. This reduces the financial burden of waste management. Biogas produced from manure can be used to provide a renewable and reliable energy source. The digestate produced during biomethane production serves as a nutrient-rich fertilizer, enhancing soil health and diminishing the necessity for chemical fertilizers.

Table 14: Distance to Kars(Center) from Districts

District	Distance to Kars(Center) km
Akyaka	46.3
Digor	37.9
Selim	31.6
Arpaçay	32.3
Kağızman	52.9
Sarıkamış	53.2
Susuz	18.1
Average Distance	38.9

There is only one biogas facility existing in Çorum. Hence, a new facility that could be constructed in the city center could potentially be supplied with sufficient raw materials to meet their needs. In addition, as can be seen in Table 15, because the city center is a 40.6 km average distance from the district's border, a facility can be seen as a feasible location in terms of transportation distance. Moreover, there are some potential districts on the Çorum city border. Hence the city center facility might be fed further by this potential.

Table 15: Distance to Çorum(Center) from Districts

District	Distance to Çorum(Center) km
Alaca	43.6
Mecitözü	29.3
Ortaköy	39.7
Sungurlu	65.4
Uğurludağ	44.1
İskilip	46
Oğuzlar	30.8
Laçin	25.6
Average Distance	40.6

With three existing biogas facilities already operational in Aksaray (Center), there is an opportunity to repurpose these facilities to feed a prospective biomethane facility. There is enough raw material potential here to feed the facility. In addition, as can be seen in Table 16, because the city center is a 44.7 km average distance from the district's border, it meets the feasibility criteria for transportation distance. Additionally, Eskil district presents significant potential as a location with abundant raw material resources on the border of Aksaray city. Therefore, the city center facility could potentially be supplied by this resource-rich area. However, the presence of existing biogas facilities suggests the existence of a raw material market in this province, potentially leading to higher raw material prices.

Table 16: Distance to Aksaray(Center) from Districts

Districts	Distance to Aksaray(Center)
Ağaçören	56.9
Gülağaç	26.9
Sarıyahşi	70.1
Eskil	54.5
Güzelyurt	31.3
Sarıkamış	40.9
Average Distance	44.7

In this regard, due to raw material availability, low average transportation distance, the absence of existing facilities, and advantage of waste management, these provinces can be considered as potential places for the prospective facility.

5.7 REDUCED CARBON CALCULATION

This section discusses the benefits of a biomethane facility from a carbon reduction perspective. The carbon emission factors encompass various components, including (i) CO2 emissions from the raw material collection and transportation to the plant, (ii) Avoided carbon emissions due to raw material collection, (iii) Emission in Anaerobic Process, (iv) CO2 emissions during the upgrading process and (v) Avoided emissions resulting from substituting natural gas with biomethane. Each component is discussed and calculated within the framework of this project below.

CO2 Emission from raw material collection and transportation to the plant (RMT): This group can include CO2 emissions which fuel consumption causes during the raw material transportation to the plant as well as avoidance of emissions because of production of the fossil fuel. The carbon footprint of gasoline production per liter is 3.079 kg CO2 (Bredson u., 2010) while burned gasoline causes 2.3 kg carbon emission per liter gasoline (Natural Resources Canada, 2014), which implies a total 5.379 kg CO2 emission per liter consumption of gasoline. In our scenario, raw material usage in production is taken as 50% for cattle manure and 50% for chicken manure. Hence, the average biogas potential for cattle manure is 42.85 Nm^3 per ton, while the average biogas potential for layer chicken manure is 116.13 Nm^3 per ton. To achieve a daily biogas potential of 77,566 Nm^3, an equal mixture of raw materials would require 905 tons of cattle manure and 334 tons of chicken manure each day. However, if only one type of manure is to be used, then 1,810 tons of cattle manure or 668 tons of chicken manure would be needed daily to reach the full biogas potential. A long truck has a capacity to carry 25 tons of raw material and consume 0.4 gasoline per km(derived based on personal communication with an expert). When only cattle manure is used as raw material, it would necessitate 145 trips in a day for transportation., Conversely, if the choice is to use only chicken manure, then a total of 53 trips to the raw material field would be required for collection. Given a distance of 40 km to the raw material field, 2320 liters of gasoline would be consumed for completely cattle manure deployment whereas 864 liters of gasoline would be used for chicken manure. In this context, daily, 12.5 tons of CO2 emissions would be emitted for collecting cattle manure, and 4.6 tons of CO2 emissions would be emitted for collecting chicken manure.

When dividing the raw materials of cattle manure and chicken manure equally, with a 50% share for each, the process involves a total of 73 trips to transport cattle manure and 27 trips for chicken manure to and from the facility. It takes 1600 liters of gasoline consumption, implying a daily 8.6 ton CO2 emission. Table 17 shows Raw Material Collection Process Carbon Emissions in numbers.

Table 17: Raw Material Collection Process Carbon Emissions

SCENARIOS/ITEMS	**100% Cattle Manure Usage**	**100% Layer Chicken Manure Usage**	**50% Cattle Manure-50% Layer Chicken Manure Usage**
Total Daily Raw Material Need(ton)	1810	668	905(cattle manure)-334(Layer Chicken Manure)
Total Km Taken	5800	2160	4000
Total Liter Gasoline Consumption	2320	864	1600
Total Daily CO2 Emission(ton)	12.5	4.6	8.6
Total Yearly CO2 Emission(ton)	4555	1696	3141

Avoided carbon emissions due to raw material collection (RMC):

Leaving manure in nature leads to environmental harm and emissions (Bakkaloglu & Hawks, 2024). Because the raw material is collected from the field, we prevent this potential carbon emission. This value for cattle manure is 34.09 kg CO2 eq. per tonne while for chicken manure is 132.91 kg CO2 eq. per tonne. Table 18 illustrates the calculation relating to avoided carbon emissions.

Table 18: Avoided carbon emissions due to raw material collection

SCENARIOS/ITEMS	**100% Cattle Manure Usage**	**100% Layer Chicken Manure Usage**	**50% Cattle Manure-50% Layer Chicken Manure Usage**
Total Daily Raw Material Need(ton)	1810	668	905(cattle manure)-334(Layer Chicken Manure)
Daily Avoidant CO2 (ton)	61.7	88.8	75.2
Yearly Avoidant CO2 (ton)	22522	32406	27464

Emission in anaerobic process (AP):

Emissions occur in the anaerobic process (Bakkaloglu & Hawks, 2024). Carbon emission leaking in the process equals 3% of the total carbon content of biogas. The daily biogas potential is measured at 77.566 Nm^3, and 40% of this biogas is CO2, resulting in a production of 31,026.4 Nm^3 of CO2. When considering 3% of the biogas potential as emissions, it amounts to 930.8 Nm^3 of daily emissions, which equals to 1.843 tons daily CO2 emission (Keen Compressed Gas Co., n.d.). Consequently, this leads to an annual CO2 emission of 672.7 tons.

Emissions in upgrading process (UP):

Carbon emission appears in the upgrading process (Bakkaloglu & Hawks, 2024), which can be varied for different upgrading methods. According to Gupta et. al (2022), Utilizing the water scrubbing method, the emission value is calculated at 1.72 kg CO2 per m^3 of biomethane.,which equals 31,654.38 tons yearly CO2 emission for our model.

Carbon emission avoidance due to natural gas substitution with biomethane (NGSB):

Because natural gas is a fossil fuel that has the same technical features as biomethane, it can be simply displaced with biomethane, which is a renewable fuel, to prevent emissions stemming from natural gas usage (Marconi & Rosa, 2023). According to Gupta et. al.(2022), the replacement of natural gas with biomethane means the avoidance of the emission of 4.89 kg CO_2/Sm^3 natural gas. In our model, the biomethane production facility's capacity of 18,396,000 Sm^3 results in an annual reduction of 89,956.44 tons of CO_2 emissions.

According to the items listed and explained above, a net carbon-saving is calculated. Raw material transportation emissions (RMT), emissions in the anaerobic process (AP), and emissions in the upgrading process (UP) are taken as carbon emission factors which is caused by biomethane production while prevented raw material emission and natural gas substitution with biomethane are accepted as carbon reduction factors, which is gained via production of biomethane.

Net Carbon Savings= CARBON EMISSION SAVINGS(CS) - CARBON EMISSION CAUSED(CE)
= (RMC+NGSB) - (RMT+AP+UP)

Annual emissions and savings are listed in Table 19. Table 19 presents that 81,952 ton net carbon savings is obtained via biomethane production.

Table 19 : Net Carbon Savings

EMISSION ITEMS(TON)/CALCULATION ITEMS(YEARLY)	**Carbon Emission Caused(CE)**	**Carbon Savings(CS)**
Raw Material Transportation Emission	3,141.3	-
Prevented Raw Material Emission	-	27,463.8
Emission in Anaerobic Process	672.7	-
Emission in Upgrading Process	31,654.4	-
Natural Gas substitution with Biomethane	-	89,956.4
	Net Carbon Savings (CS-CE)	81,952

To ascertain the net carbon savings as a percentage, we employ the formula below: subtract the sum of carbon emission items from the sum of carbon emission savings items, and then divide this by the aggregate of carbon emission items. This calculation indicates that there are net carbon savings of more than twice the amount of carbon emissions (81,952 ton CO_2/ 35,468.4 ton CO_2= 2.31).

Net Carbon Savings(Percentage)= NET CARBON SAVINGS/ CARBON EMISSION CAUSED(CE)

These results denote that biomethane production results in a significant carbon reduction. Moreover, when considering the social cost of carbon at a level of $185 per ton of CO_2 (Rennert et al., 2022), we reach annual social benefits of $15,161,094 due to the reduction of carbon emissions through the use of biomethane as can be seen in Table 20.

Table 20: Net Carbon Savings Financial Calculation

Net Carbon Savings (CS-CE)(Tons)	81,952
Carbon Social Cost Burden Per CO2($)	185
Net Carbon Savings Total Benefits($)	15,161,094

CHAPTER 6

DISCUSSION

Biomethane is an important source to substitute fossil and imported fuels to ensure energy security (Marconi & Rosa, 2023). It is well-known that reducing carbon emissions is crucial for all countries, including Turkey (Adelt et al., 2011). In our study, feasibility study for an ideal biomethane facility for Turkey is conducted by using the survey data collected from 17 biogas facilities and analyses of available inputs. OLS is used to find the main determinant of the cost of biogas production for electricity, because no firms are producing only biogas in Turkey. Moreover, threshold biogas prices are calculated via data from biogas facilities producing electricity and used for hypothetical biomethane facility cost components as raw material. Candidate locations for a biomehtane facility are identified both from the available raw materials in the region and the existing biogas facilities which provide biogas as an input to the biomethane facility. In addition, the carbon reduction potential is calculated due to an introduction of a biomethane facility.

In this regard, two linear models are produced for the OLS assumption with four independent variables. One of these models implies the most important determinant of total cost of a biogas facility producing electricity is repair maintenance expenditures, while the other one shows labor force expenditure is the most influential component to affect the total cost. In the second model, the heating cost is ranked as the second determinant, followed by the raw material as the third one, and electricity as the last one. However, in the first model, the raw material is ranked as the second determinant, followed by electricity as the third one, and the heat cost as the last one. Moreover, in the first model only the coefficient of repair maintenance (1.486) takes a value over 1, while in the second model, all coefficients take a value over 1 and labor force almost 2 (1.908). In this context, repair maintenance and labor force emerge as the most important determinants of the total cost, while raw material cost is ranked second and third in the models, followed by heat cost, which is expressed by only two firms.

For the Logarithmic Variables Regression Analysis, two different models are created, both of which indicate that the most important determinant is the natural logarithm of raw material cost (lnraw) on total cost (lncost).In the first equation labor force (lnlabor) is ranked second one, electricity (lnelectricty) as third, and with a very low coefficient value heat cost (lnheat) is last ranked. However, in the second model, repair maintenance (ln repair) and electricity are taking the same coefficient value as the second one and with very low coefficient value, heat cost as last one. The results imply that the most important determinant in the logarithmic models is raw material while heat cost is a trivial determinant.

Despite the coefficients ranking differently, the raw material cost accounts for the largest share of the total cost, followed by the electricity cost in absolute terms. The primary reason for differences lies in the scale of the variables. Some components (like raw material cost or electricity cost) may have large absolute values (high share), making them significant contributors even if their marginal effects are smaller. Coefficients in the models reflect the relative importance of each variable within the specific context of the data. Variables with smaller coefficients might still have substantial absolute effects due to their larger scale. Variables may interact with each other, meaning their combined effect on the dependent variable differs from the sum of their individual effects. Interaction effects (how variables interact with each other) can lead to differences.

For the hypothetical firms producing only biogas, the analysis indicates that the biogas raw material price ranges from \$0.08 to \$0.36 per biogas cubic meter (Sm^3). However, a biomethane facility is deemed viable when the cost goes above \$0.21 per cubic meter, considering the cost of natural gas. In this regard, it is concluded that only 3 firms out of 17 firms meet this criteria.

For a hypothetical biomethane facility, a water scrubbing method with a production capacity of 18,396,000 Sm^3 biomethane is determined as a uniquely viable method. For three different facilities meeting viable biogas raw material criteria, different IRR rates are reached. For the lowest cost biogas raw material as 0.08\$, the IRR rate is at the level of 66%, while for the most expensive one as 0.21$ is at the level of 5%, and for the middle one as 0.15$ is at the level of 35%.

Hotspots for cattle and layer chicken manure as raw material have been mapped, revealing that while the potential is widespread across the country, the majority is concentrated in centers in the western, southern, and central-southern region of Turkey. However, Çorum (Center), Kars (Center), and Aksaray (Center) districts are detected as hotspots that have strong biogas potential centers with only one facility for Çorum and no facility existing in Kars , which implies there would not be a raw material market. However, in Aksaray (Center), there are three existing biogas facilities, which can cause a raw material market and higher raw material prices. Furthermore, it has been observed that provinces spanning approximately 39-44.7 kilometers fall below the financially viable transportation distance range, which experts suggest typically ranges from 60 to 80 kilometers. For these provinces except for Aksaray, because of the lack of biomass facilities, a new biomethane facility installation would help the rural development and waste management.

Collecting raw materials in Kars, where sources may be scattered across a large area, can present logistical challenges. However, encouraging partnerships and cooperative arrangements among farmers to pool resources in specific locations can significantly enhance efficiency and alleviate the burden on individual farmers. Policymakers have the opportunity to develop incentive programs that reward farmers for collective action and collaboration. These incentives could include bonuses or preferential treatment for farmers participating in cooperative ventures, such as priority access to markets or additional financial support. Furthermore, the collection and proper management of manure play a crucial role in mitigating climate change by reducing emissions. It also helps prevent nutrient runoff, leading to improvements in water quality and reductions in odors and air pollutants associated with untreated manure. By diverting manure to biogas facilities instead of relying on traditional disposal methods like land spreading or storage, farmers can save on waste management costs. Additionally, the digestate resulting from biomethane production serves as a valuable nutrient-rich fertilizer, contributing to soil health and reducing the need for chemical fertilizers. This sustainable practice supports agricultural sustainability and promotes environmentally friendly farming practices.

For exemption from the Carbon Border Adjustment Mechanism (CBAM), which is accepted as a temporary measure with no financial responsibility until the end of 2025 (Turkish Trade Ministry, n.d.), it is stated that once biomass proves its sustainability and meets emission criteria, it would be classified as zero-emission (EUROPEAN COMMISSION, 2023). Although there are criteria for forest residuals for the production of biomass, there are not any sustainability criteria for manure-based production. therefore for this raw material, the producer only needs to prove emission savings to classify it as a zero-emission fuel. It is mentioned that the fuel must ensure emission savings compared to fossil fuels and can be certified as internal. In this emission calculation, biomass-based fuel is considered to have a zero-emission factor (EUROPEAN COMMISSION, 2023). In addition, RED II, aiming to raise renewable energy sources , where CBAM is based on, expresses to increase the share of biogas, indirectly biomethane based on animal manure and states strong emission savings of biomethane based on manure (Official Journal of the European Union, 2018).

In the section about carbon emission calculation, carbon emission owing to biogas and biomethane production, and raw material transportation are regarded as carbon emission factors while carbon avoidance because of the natural gas substitution with biomethane and raw material collection is taken as a counterbalance. Consequently, an annual carbon savings of 81,952 tons are estimated, primarily due to the substitution of natural gas with biomethane, which is the determinant factor. In this context, the fuel proves itself as a significant carbon reduction factor, aligning with the EU objectives. A limitation of the study could be the presence of response bias, where respondents may provide intentionally or unintentionally incorrect answers due to their comprehension of the questions. Additionally, the study may be constrained by a relatively small sample size.

Government support for the widespread adoption of biomethane as a fuel is justified due to its benefits in waste management, CO2 mitigation, and rural development. Following the examples of countries like the USA and India, where waste is utilized for energy production, governments can promote biomethane production. Similarly, taking inspiration from Europe, agricultural initiatives can be organized to divert waste towards biomethane production.

CHAPTER 7

POLICY IMPLICATION

It is observed that the major share of cost for a biomethane facility is raw material cost as biogas followed by electricity cost for operational cost. In this regard, only 3 out of 17 hypothetical biogas facilities' biogas selling prices cause a biomethane facility’s feasibility. In addition, biogas as raw material is composed of mostly share of its own raw material cost. Hence, there is a transmission from biogas raw material cost to cost of biogas as raw material to biomethane operational cost. Empirical study shows that in terms of the logarithmic model, the most influential variable on total cost is raw material cost for the two models while linear models show different variables such as labor force cost and repair maintenance cost. In this respect, subsidies on these cost items may lower the operational cost and cause higher biogas selling prices to be feasible and have higher NPV. The study shows that the unique effective method to upgrade biogas is water scrubbing with 18,396,000 Sm^3 capacity.

Biomethane production can back up rural development and environmental quality via waste management (Luo et al., 2020). It is suggested that it would be more advantageous to build such a facility in provinces that are not mature in terms of biogas production. In our study, Çorum (Center) with only one biogas facility, and Kars (Center) with the absence of the facilities are taken as prospective provinces for the deployment of the biomethane facility, along with their proximity feature to raw material. It is advised that these districts can be taken as prospective districts for the deployment of the biomethane facility. In addition, Aksaray (Center), with three existing biogas facilities, is selected as a prospective site for the biomethane facility. Availability of local knowledge, comprising operators, technicians, and engineers skilled in biogas production could prove invaluable for the smooth operation of a biomethane facility. Communities already acquainted with the advantages of renewable energy production through existing biogas facilities might exhibit greater receptiveness towards the establishment of a biomethane facility.

Net carbon savings stemming from biomethane production are counted as 81,952 tons yearly, in monetary terms, amounting to $15,161,094 annually. These savings can lead to biomethane production via a taxation system on fossil fuel production or selling. In this context, it can be considered as an instrument to reach Turkey’s carbon-neutral target in 2053 (United Nations Development Programme, 2023).

The CBAM mechanism categorizes this fuel within a zero-emission category and the EU views this fuel as a green fuel to back up with aims to raise its share in energy composition. Therefore, The technology’s generalization across the energy composition is necessary. Compensation subsidies to replace fossil fuels charges, which will be imposed by EU customs, can be canalized to biomethane production. In this context, the production bonus mechanism can be conducted as done in Germany explained in the Background section (Biomethane Industrial Partnership (BIP), 2023), alongside a certification program as recommended by the EU (EUROPEAN COMMISSION, 2023) and voluntary premium program for buying biomethane (Ricardo, 2021).

In the survey, 4 of the attendees expressed a lack of legislation specifically pertaining to biomethane production, while 3 of them implied they do not have a plan for upgrading the facility and the remaining 10 attendees did not give any answer for biomethane production plan. Moreover, 3 of the respondents expressed that they expect the CBAM mechanism to raise demand for biomethane production. It implies there is an insufficient information for biomethane production. Hence, we identify the need for an information program and legislation supporting biomethane production. Similar needs are found by Akinbami et. al. (2001). They recommend educational and informative programs to be carried out to raise awareness of the technology of biogas.

The current flourishing of technology suggests that it has a promising future ahead. widespread adoption is a necessity and for this purpose, policy steps are needed to spread its knowledge and consciousness across the community via campaigns and informative programs. In addition, the burden of initial investments can be alleviated through subsidy programs and voluntary premiums, wherein individuals are willing to pay extra to purchase the fuel.

CONCLUSION

Environmental concerns and waste management are raising topics across the world to reach carbon-neutral economies. In this context, Biomethane is considered a renewable fuel to fulfill carbon reduction needs and promotes environmental progress. Policies, awareness campaigns, and research on alternative fuels are thriving in various parts of the world. However, in Turkey, there is a noticeable deficiency in the development of such fuel, particularly in terms of conducting economic feasibility studies on biomethane. In this respect, the study aims to contribute to filling the gap on the topic and to imply prospective policy steps to cause galvanizing developments on this fuel. The thesis approaches the issue from various angles by identifying determinant factors of biogas as a raw material for biomethane, conducting a feasibility analysis of prospective biomethane facilities, mapping potential raw material hotspot fields, and analyzing emission savings. For this reason, analyzing the economic viability of the facility and carbon savings is a necessity for economical implications.

Our first analysis chapter assesses the main determinants of total costs of biogas firms producing electricity through OLS linear and logarithmic models via survey attendees as engineers and facility managers from 17 different biogas facilities. The main determinant is concluded as repair maintenance and labor force expenditures respectively in first and second linear models while in logarithmic models, raw material expenditures are the most important on total cost. In the first model, raw material is an important factor following repair maintenance, while in the second model, it ranks third after electricity. Furthermore, in the first logarithmic model, repair maintenance and labor force cost precede raw material cost, whereas, in the second logarithmic model, electricity cost follows raw material cost. OLS cost approach is used for the first time for biomethane and biogas in the literature.

The data collected via the survey is analyzed to produce hypothetical biogas prices because there is no firm producing only biogas. Calculated hypothetical biogas prices are used as a cost input to calculate hypothetical biomethane cost analyses. Biogas price is found as the main share of the biomethane cost composition. Only three prices are found as financially viable to produce biomethane given the natural gas price. With these three different feasible prices, the NPV approach is deployed, as many studies have been conducted in the literature, and different IRR and NPV values are reached. This situation implies that under the analyzed conditions, although not generally, the biomethane might be a profitable investment. But to generalize the fuel production to produce higher biogas prices as raw material, an incentivized mechanism is needed.

In addition, mapping analyses for cattle manure and chicken layer manure by using the Tableau program are conducted to find hotspot provinces and prospective places to deploy a prospective biomethane facility. With this respect, Çorum (Center) and Kars (Center) are appointed as prospective districts because of a lack of existing there is no biogas facilities in Kars, and only one facility in Çorum. Hence it can be easier to find more available raw material. Furthermore, Aksaray (Center), which already hosts three operational biogas facilities, has been determined as a potential location for the biomethane facility, because there might be a pool of local expertise, including operators, technicians, and engineers proficient in biogas production. In addition, communities familiar with the benefits of renewable energy generation from current biogas facilities may demonstrate increased openness to the introduction of a biomethane facility. Moreover, these places are hotspot locations, alongside their feasible proximity to borders to collect more raw material. It is expected that the facility would contribute to rural communities and development via additional revenue from animal-based waste and a cleaner environment. Moreover because of its domestic production, it can be tough to ensure energy supply security.

Because biomethane is a fuel that has the potential to replace fossil fuel usage and to reduce carbon emissions, its carbon reduction potential and its monetary value are calculated. Consequently, a strong emission reduction potential is calculated and this potential is expected to be a viable contributor to reach the 2053 carbon-neutral target.

Because biomethane is a flourishing fuel across the world as a renewable source to replace fossil fuels, it is thought that it would be a topic to be analyzed in different aspects. In addition, its potential to be taken as zero-emission fuel under the CBAM mechanism is an opportunity window for the exporting sector to pay reduced costs for customs and to contribute to the sector's competitiveness in the EU. Within this context, information champaigns and works can be conducted to raise awaraness for biomethane as a promising fuel.

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APPENDIX 1 THE QUESTIONNAIRE

Tesis Adı (Facility Name)	
Hammadde türü (Raw material type)	
Yıllık biyogaz üretim kapasitesi(m3) (Annual biogas production capacity)	
Günlük Biyogaz Üretim Kapasitesi(m3) (Daily biogas production capacity)	
Bakım Onarım için Tesisin Faaliyeti Kaç gün duruyor ? (How many days does the facility's activity stop for maintenance and repair?)	
Tesisin Kuruluş Yılı (The year the facility is built)	
Yatırım maliyeti(tesis yapımı ve makine teçhizat kurulumu)(EURO veya USD) (Investment Cost)	
hammadde maliyeti(satın alınıyorsa)(Ton başına) (Raw material cost per ton)	
Hammadde maliyeti üretici tarafından mı karşılanıyor yoksa hammadde sahibi tarafından mı? (The raw material is purchased by the producer or brought by the owner of the raw material ?)	
hammaddenin toplanması ve tesise ulaştırılmasının maliyeti(ton başına) nedir?(USD veya EURO) (Raw material transportation cost)	
Ne kadar sürede Kaç sefer Yapıyor?(haftada 3 sefer vb) (How many trips are done to procure the raw material ?)	
Tesiste Tüketilen elektrik maliyeti(m3 başına) nedir?(USD veya EURO) (Electricity cost)	
Tesiste kullanılan ısı(heat) maliyeti(m3 başına) nedir? (USD veya EURO) (Heat cost)	
Tesisin Bakım Onarım Maliyeti(m3başına) nedir?(USD veya EURO) (Repair-Maintenance cost)	
Ortalama İşçi Maliyeti ?(aylık USD veya EURO) (Labor force cost)	

Yan Ürün(Gübre) Satışından elde edilen gelir nedir ?(varsa)(USD veya EURO) (Earning by selling digestate)	
Biyogazı Biyometana yükseltme planı var mı? Yoksa Neden ? (Do you have a plan for upgrading? If not , why?	
Biyometan üretiminin m3 başına potansiyel maliyeti?(USD veya EURO)(Üretim planlanıyorsa)(Biomethane production potantiel cost, if planned?)	
Sınırda Karbon Düzenleme Mekanizması (CBAM) veya yurtiçi karbon salınımı mekanizmasından dolayı biyometan üretimine talebin artacağına yönelikbeklenti Var mı? (Do you consider demand for biomethane would rise owing to CBAM?)	
Biyogaz Tesisinin Elektrik Üretimi yerine biyomethan üretimi olarak kullanılması durumunda sermaye maliyetinde gerçekleşen iskonto(Oran) (If the facility is utilized for biomethane, what the discount rate in investment cost ?)	
Kaynak Bilgi (Attendee Informtations)	

APPENDIX 2 ANSWERS REGARDING BIOMETHANE

Questions	**Answers**		
Do you have a plan to produce biomethane ?	4 of the attendees expressed a lack of legislation pertaining to biomethane production	3 of the attendees implied they don't have a plan for upgrading the facility	10 attendees did not give any answer for biomethane production plan
Do you consider that CBAM will raise demand for biomethane ?	3 of the respondents expressed that they expect the CBAM mechanism to raise demand for biomethane production. 14 attendees did not answer.		