THE POTENTIALS AND LIMITATIONS OF UTILIZING ANIMAL MANURE FOR BIOGAS PRODUCTION IN RURAL AGRICULTURAL HOUSEHOLDS: A COMPREHENSIVE ANALYSIS OF ETHIOPIA AND TÜRKIYE

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ABSTRACT

THE POTENTIALS AND LIMITATIONS OF UTILIZING ANIMAL MANURE FOR BIOGAS PRODUCTION IN RURAL AGRICULTURAL HOUSEHOLDS: A COMPREHENSIVE ANALYSIS OF ETHIOPIA AND TÜRKIYE

With the growing threat of climate change and global warming along with the exponential exploitation of resources, the need for adaptation of renewable and cleaner energy technologies especially in emerging and developing economies has been inevitable. This thesis provides a comprehensive analysis of the potentials and limitations associated with the utilization of animal manure for biogas production in rural agricultural households, with a specific focus on Ethiopia and Türkiye. The thesis aims to identify the key factors that influence the adoption of biogas technology in these countries and provide insights into the socio-economic and environmental benefits and challenges associated with the use of animal manure for energy generation. The thesis employs a mixed-methods approach that combines a systematic literature review with primary data collected through surveys and interviews with farmers, policymakers, and other stakeholders. The results reveal that the utilization of animal manure for biogas production has significant potential for rural agricultural households in both Ethiopia and Türkiye, as it can provide an efficient, reliable, and affordable source of energy while also reducing greenhouse gas emissions. However, the thesis also highlights several limitations and challenges that need to be addressed to promote the uptake of biogas technology in these countries. These include technical, financial, and policy-related barriers, as well as social and cultural factors that influence the acceptance and use of biogas systems.

ÖZET

KIRSAL TARIM HANELERINDE BIYOGAZ ÜRETIMI IÇIN HAYVAN GÜBRESI KULLANIMININ POTANSIYELLERI VE SINIRLILIKLARI: ETIYOPYA VE TÜRKIYE'NIN KAPSAMLI BIR ANALIZI

Artan iklim değişikliği ve küresel ısınma tehdidi ile birlikte kaynakların katlanarak kullanılmasıyla birlikte, özellikle yükselen ve gelişmekte olan ekonomilerde yenilenebilir ve daha temiz enerji teknolojilerinin adaptasyon ihtiyacı kaçınılmaz olmuştur. Bu tez, özellikle Etiyopya ve Türkiye'ye odaklanarak, kırsal tarım hanelerinde biyogaz üretimi için hayvan gübresi kullanımıyla ilgili potansiyellerin ve sınırlamaların kapsamlı bir analizini sunmaktadır. Tez, bu ülkelerde biyogaz teknolojisinin benimsenmesini etkileyen temel faktörleri belirlemeyi ve enerji üretimi için hayvan gübresi kullanımıyla ilişkili sosyo-ekonomik ve çevresel faydalar ve zorluklar hakkında fikir vermeyi amaçlamaktadır. Tez, sistematik bir literatür taramasını çiftçiler, politika yapıcılar ve diğer paydaşlarla yapılan anketler ve görüşmeler yoluyla toplanan birincil verilerle birleştiren karma yöntemli bir yaklaşım kullanmaktadır. Sonuçlar, biyogaz üretimi için hayvan gübresi kullanımının, sera gazı emisyonlarını azaltırken aynı zamanda verimli, güvenilir ve uygun fiyatlı bir enerji kaynağı sağlayabileceği için hem Etiyopya'da hem de Türkiye'de kırsal tarım haneleri için önemli bir potansiyele sahip olduğunu ortaya koymaktadır. Bununla birlikte, tez aynı zamanda bu ülkelerde biyogaz teknolojisinin benimsenmesini teşvik etmek için ele alınması gereken çeşitli sınırlamaları ve zorlukları da vurgulamaktadır. Bunlar, teknik, finansal ve politika ile ilgili engellerin yanı sıra biyogaz sistemlerinin kabulünü ve kullanımını etkileyen sosyal ve kültürel faktörleri içerir.

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LIST OF SYMBOLS/ABBREVIATIONS

Symbol	Explanation	Unit
BP_T	Theoretical biogas produced	m^3
BY_M	Biogas Yield from Manue	m^3/Kg
CH_4	Methane	tonnes
DMP	Daily manure produced	Kg
EGE	Effective electricity produced	MWh
η	Engine Efficiency	
M_C	Methane Content	
MU	Usable manure for biogas production	Kg
N_2O	Nitrous Oxide	tonnes
NTLU	Number of Livestock by Tropical Livestock Unit	Heads
NL	Number of Livestock in a specific category	Heads
Wavg	Average weight of the livestock type	Kg

Abbreviation	Explanation
ABPP	African Biogas Partnership Programme
AF	Availability factor
BDS	Theoretical Biogas digester size
BEPA	Biomass Energy Potential Atlas or Biyokütle Enerjisi Potansiyel Atlası
BREF	BAT Reference Document
C/N	Carbon to Nitrogen Ratio
CHP	Combined Heat and Power
CO_{2eq}	Carbon dioxide equivalent
CSA	The Central Statistics Agency
CV	Calorific value of biogas
DF	Daily feedstock available
EBRD	European Bank for Reconstruction and Development
EREDPC	Ethiopian Rural Development and Promotion Centre
EGT	Electricity potential generation

EF	Emission Factor
ETB	Ethiopian Birr
ETL	Extraction, transformation, and loading
FAO	The Food and Agricultural Organization of the United Nation
FAOSTAT	The Food and Agricultural Organization of the United Nation Statistics
FDRE	Federal Democratic Republic of Ethiopia
GDP	Gross domestic product
GHG	Green House Gas
GWP	Global Warming Potential
H	Hydrogen
HRT	Hydraulic Retention Time
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
IPCC	Intergovernmental Pannel on Climate Change
LDCs	Least developing Countries
MEPI	Measuring Energy Poverty Index
MOWIE	Ministry of Water and Energy
N	Nitrogen
NBPE	National Biogas Programme of Ethiopia
NDCs	Nationally Determined Contributions
NEP	National Electrification Plan
NEEAP	The National Energy Efficiency Action Plan
NH_3	Ammonia
NREAP	The National Renewable Energy Action Plan
OLR	Organic Loading Rate
P	Phosphorus
PE	Polyethylene
PPP	Purchasing Power Parity
PVC	Polyvinyl chloride
S	Sulfur
SE4All	Sustainable Energy for All
SOC	Soil’s organic carbon
TEİAŞ	Türkiye Elektrik İletim A. Ş or Turkish Electricity Transmission Corporation

TFC	Total Final Consumption
TFEC	Total final energy consumption
TL	Turkish Lira
TPES	Total Primary Energy supply
TS	Total Solid Content
TurkStat	Turkish Statistics Institute
VFA	Volatile Fatty Acid
UNData	United Nation data
VS	Volatile Solid Content
WASH	Water, health, and sanitation
YEGM	Türkiye’s General Directorate of Renewable Energy

1. INTRODUCTION

The last few decades have seen unprecedented population growth in the world that in turn has facilitated economic growth, urbanization, and technological advancements. According to the World Bank data, the global population has rapidly increased by 150 % from 5.29 billion in 1990 to 7.95 billion in 2022 (The World Bank, GDP, PPP (constant 2017 international $) - World, 2022). Similarly, the gross domestic product (GDP) has almost tripled from $51.38 Trillion (constant 2017 international $) after Purchasing Power Parity (PPP) conversion factor is applied in 1990 to $139.03 Trillion (constant 2017 international $) after PPP conversion factor is applied in 2022 (The World Bank, 2023). As a result, the world has also witnessed a rapid growth in global energy consumption as well as Green House Gas (GHG) emissions. According to the IEA's World Energy Statistics, total final energy consumption (TFEC) has grown by more than 1.5 times from 7,233.3 TWh in 1990 to 11,161.1 TWh in 2019 (IEA, 2021). The rise in energy consumption has an impact on the climate and the environment as the current energy need of the world is heavily met by different types of fossil fuels such as Natural gas, oil, and coal as well as traditional biomass leading to an increase in the global GHG emission from 33,268.12 Mton CO_2 eq in 1990 to 53,786.04 Mton CO_2 eq in 2022 (Crippa, et al., 2023). The heavy reliance on fossil fuels also results in the depletion of resources such as forestry. As a result, there is a push for decoupling emissions from economic and population growth and this is realized through a shift towards the utilization of renewable energy as they are a cleaner alternative to address the rising energy demand (IEA, 2022).

Renewables include different energy sources that are non-fossil such as solar, wind, thermal (aero thermal, geothermal, hydrothermal), hydropower, ocean, and biomass with this thesis focusing on the latter and more specifically on the production of biogas from animal manure via anaerobic digestion in small-scale rural farms of Ethiopia and Türkiye. The utilization of biomass presents an interesting dichotomy. Although biomass is renewable if not properly utilized, it may not be clean and may have an adverse effect both on the environment and health. The use of traditional and woody biomass has resulted in the depletion of forests due to deforestation, which also leads to rural communities having to travel longer distances in order to collect wood for energy. On the other hand, using bioenergy in lieu of traditional and woody biomass mitigates deforestation, GHG emission, and health problems. It also addresses some of the energy concerns of countries such as energy access and energy security, which are issues that are further exacerbated in rural households, while simultaneously providing a cleaner energy source and a waste management framework, hence addressing environmental issues.

The agriculture sector especially has a high biomass potential in the form of crop or livestock waste that is underutilized and properly not managed. Livestock waste, which is the focus of this thesis, has a negative impact on the environment if not properly collected, managed, and disposed due to Methane (CH_4) and Nitrous Oxide (N_2O) emissions (EPA, 2021; Curnow, 2021).

In addition to addressing energy and environmental concerns, the uptake of bioenergy technologies also has an economic impact on the countries. Increasing bioenergy in a country's energy mix can reduce its dependency on oil. The fluctuating global prices of oil heavily affect the energy tariffs of countries reliant on oil and hence bioenergy can address energy costs and energy poverty, especially for rural community. Moreover, in cases where farmers are prosumers, bioenergy production provides farmers additional income or help them reduce energy expenditure.

One of the most common ways of treating livestock waste in order to produce bioenergy and the conversion methodology highlighted in this thesis is anaerobic digestion. Anaerobic digestion is the conversion of raw organic material into biogas which consists of 60-65% C_{H4} and 30–40% CO_2, in addition to other gases such as water vapor, Nitrogen, Oxygen, Sulfur, H_2S and NH_3 (Kamp & Bermúdez Forn, 2016).

This thesis aims to understand the role biogas plays in addressing certain energy, environment and economic challenges present in rural communities and farming households of Ethiopia and Türkiye. In order to do so, the thesis estimates the biomass and the biogas production potential in Ethiopian and Turkish rural households by using animal manure and explores how that can address environmental issues and specifically GHG emissions, as well as address energy access and energy poverty concerns. It also explores policy frameworks in place in country and regional level, as well as constraints and factors that affects the uptake of biogas technologies but also look into potential and opportunities for upgrading biogas in the latter sections.

Overall, the thesis provides valuable insights into the potential of biomass and biogas production from animal manure and its contribution to sustainable rural development and energy transition in Ethiopia and Türkiye and underscores the need for supportive policies and strategies that can facilitate the widespread adoption of this technology. Hence, the thesis is not only prominent for Ethiopia and Türkiye but for other emerging and developing countries with similar energy landscape.

2. LITERATURE SURVEY

2.1. Türkiye's Energy Profile

2.1.1. General Geography and Country Profile

Türkiye is a country that is geographically located uniquely at the crossroads of Southeastern Europe and Southwestern Asia. Based on the most recent 2023 data Türkiye has a population of 85,599,280 people (TUIK, 2023) and a land area of 783,562 km^2 making Türkiye the 38th largest country in the world (CIA, 2023a). The country is divided into seven regions; Marmara, Mediterranean, Aegean, Central Anatolia, Southeastern Anatolia, Eastern Anatolia, and Black Sea region, with the Marmar region being the most densely populated. These regions are further divided into provinces.

2.1.2. Türkiye's Energy Landscape

The geographic location of Türkiye allows the country to have a significant position in the energy trade between Central Asia, Middle East, and Europe. This also affects the energy consumption of the country with natural oil, gas, and fossil fuels being imported from neighboring countries, with Russia being the main energy provider for Türkiye and making 52% of the total imported energy. The heavy reliance on imported energy has impacted the country's energy security and energy sovereignty. Moreover, importing most of its energy needs has resulted in high electricity and gas bills and has increased household energy expenditure and in some instances poses a risk of energy poverty (Austvik & Rzayeva, 2017).

On the other hand, Türkiye has a rich natural resource including significant coal deposits, hence around half of the coal production is domestic and coal comprised 28% of the Total Primary Energy supply (TPES) of Türkiye in 2019 (IEA, 2022). In addition to coal. Türkiye also has a substantial amount of renewable energy potential. Hence, increasing the percentage of renewables and nuclear in the energy mix will contribute to addressing the climate crisis by enabling a shift to greener energy sources and a low carbon economy. This shift can also be seen in Türkiye's energy mix in which the share of renewables and in particular the share of hydro has increased in the past few years. As of 2022, the total renewable energy capacity of Türkiye has reached 55,943 MW which is more than

half of the country's total energy capacity at 53.9%. This shows an increase of 17.8% compared to 2011 numbers (IRENA, 2023).

When looking at the breakdown, hydropower and wind make up the majority of the country's renewable energy capacity contributing 31,571 MW and 11,396 MW respectively (IRENA, 2023). As of 2023, onshore wind makes up the total installed wind capacity of Türkiye (ETKB, 2020). However, 3 GW of offshore wind is licensed and currently under construction. This will increase the total capacity to 16 MW by 2027 (ETKB, 2020). When it comes to biomass, the country's generation potential is estimated at 100 TWh while the total biogas generation potential is estimated to be between 17.4 TWh to 23.3 TWh (IEA, 2021). However, only 6453 GWh of bioenergy is currently generated from the total potential which makes 19 – 25.54 % of the total generation (IRENA, 2023).

Similarly, solar is a technology that is not fully explored yet but an energy alternative with a very high potential. As of now, Türkiye has 9,426 MW of installed solar capacity (IRENA, 2023). However, its potential is twice as that of Northern Europe but there is a gap in technology and dissemination affecting optimum utilization. Hence, Türkiye aims to increase the total installed capacity of solar energy to 10 GW by 2026 (ETKB, 2020).

2.1.3. Energy access, energy poverty and energy targets

Energy security and energy sovereignty is still a concern for Türkiye due to the geopolitics of the neighboring countries and the region from which natural gas and oil is imported. Hence, reducing dependence on imported energy by utilizing the country's domestic energy supply including renewables, nuclear, and the already existing coal deposits is a priority in Türkiye's energy targets. In addition to that, expanding Türkiye's underground gas storage capacity, diversifying the energy mix, localization of energy, creating a competitive energy market, and transitioning to low-carbon economy is essential to address energy demand, ensure energy security as well as meet the country's climate targets. This is reflected in Türkiye's energy policy which is guided by market reform and energy security and is geared towards increasing the share of renewable energy to 2/3 of the total power generation by 2026 (ETKB, 2020) while accelerating investment towards renewable energy technologies (IEA, 2021). Renewable energy production and consumption has witnessed a major shift since 2009 with an increase in the utilization of hydro, solar, geothermal, and wind which also creates a much-needed shift in the country's energy mix. This can be seen in the country's total electricity generation, in which the primary source for electricity generation in Türkiye is hydropower plants followed by thermal power plants that use natural gas, coal, lignite, and fuel oil (Ozcan et al., 2015).

More importantly, the transition towards a cleaner and renewable energy in the country's energy scenario also includes a shift from the traditional use of biomass as a solid fuel to that of utilizing biomass by generating bioenergy and biogas.

As of 2023, Türkiye's electricity demand is estimated to be 416 TWh according to the Ministry of Energy and Natural resources. On the other hand, the country's annual electricity generation for 2023 is estimated at 328.3 TWh which might present energy access and energy scarcity concerns (Republic of Türkiye Ministry of Energy and Natural Resources, 2023).

Sectoral energy consumption for the country also reflects the country's energy landscape and gives a full picture of energy consumption trends. As of 2020, Industry is the largest energy-consuming sector for Türkiye and accounts for over a third of Total Final Consumption (TFC), followed by transport (27%), residential (20%) and commercial and services (13%). The industry sector consumes mainly oil and natural gas with oil also dominating energy consumption in the transport sector. Whereas natural gas dominates the residential and service sectors (IEA, 2022).

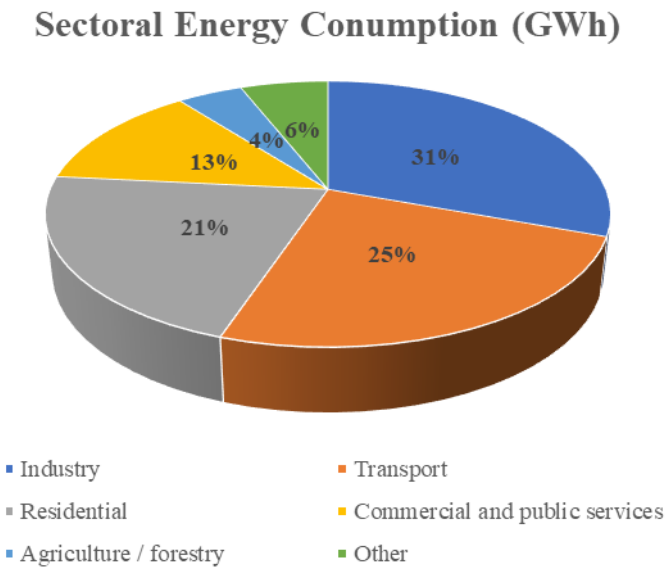

Figure 2.1. Türkiye's Sectoral energy Consumption in 2020

2.2. Ethiopia's Energy Profile

2.2.1. General Geography and Country Profile

Ethiopia, also officially known as the Federal Democratic Republic of Ethiopia (FDRE), is a landlocked county in the Horn of Africa. Ethiopia is the 10th largest country in Africa with a total land area of 1.104 million m^2 (CIA, 2023b) and is also the second highly populated country in the region with 113 million people as of 2022.The country has two administrative cities and 9 independent regional states with each one having their own administration body. Majority of the country's population is sparsely distributed over these 9 regional states with 80% of the Ethiopian inhabitants residing in rural areas spanning over the 1.1 million km^2 territory (The World Bank, 2016; OECD/PSI, 2020) Ethiopia's geographical topography coupled with the administrative structure makes it hard and expensive to connect all remote areas to the grid line and hence off-grid energy option have been increasingly preferred to address energy access challenges.

2.2.2. Ethiopia's Energy landscape

Ethiopia´s energy mix for electricity generation consists almost exclusively renewable energy (IRENA, 2020) Hydropower contributes the highest share by supplying approximately 4821 MW of the country's total installed renewable energy capacity which addresses 93.9% of the country's total electricity demand. In addition to Hydropower, wind and solar respectively contribute 404 MW and 21 MW of the total installed capacity for 2023 (IRENA, 2023). Although hydropower, wind, and solar are the main renewable energy sources that are being utilized in the country for electricity production, geothermal resources are also currently being explored. Despite the country's electricity generation solely coming from renewable energy sources, it should be noted that electricity from all sources only addresses 1.1% of the country's total energy need and the country's energy access is still low at 42%. Hence emphasize is still being given to diversifying as well as expanding the country's energy mix. One alternative that can potentially be explored is biomass energy as biomass contributes to 85.6% of the total energy consumption of the country. However, 81.2% of the biomass used is traditional biomass with dung cakes also locally known as *Kubet*, which is animal manure mixed with other agricultural waste such as straw bale, contributing to 9.1% of the energy needs whereas crop residues contribute to 8.1% of the energy needs (Kamp & Bermúdez Forn, 2016). In addition to these, other types of biomasses that are used as a source of fuel are charcoal, bagasse and bio-briquettes. However, these traditional biomasses have low conversion to heat efficiency with most only having 8% (Kamp & Bermúdez Forn, 2016) hence, a shift towards efficient bioenergy and

biofuels might be a necessity to properly utilize the country's biomass potential. The physical geography of Ethiopia is very suitable for biodigester implementation and complies with technical and operational specification that is needed for the biodigester to operate such as temperature and availability of feedstock and presents a lot of opportunity that is not fully utilized yet (Kamp & Bermúdez Forn, 2016).

2.2.3. Energy access, energy poverty and energy targets

Energy poverty is heavily interconnected with economic poverty and fully utilizing the energy potential of a country has a positive impact on the country's economy and the livelihood of the people and this is especially relevant in the case of Least developing Countries (LDCs) including Sub-Sharan Africa. According to Measuring Energy Poverty Index (MEPI) that is conducted by IEA, Ethiopia has acute energy poverty ranking as one of the highest countries in the world (Nussbaumer et al., 2012). The majority of the country's population lives in off-grid rural area and is heavily dependent on traditional biomass for energy consumption which accounts to 92% of the energy share of the country, with 89% of that being household energy, making Ethiopia one of the countries with the highest dependence on biomass with 55 million tonnes of biomass being consumed annually. This apart from being less efficient, has severe impact on the local community and environment (Gabisa & Gheewala, 2018) In communities that mainly use woody biomass, collection of biomasses can be time consuming. This is further amplified in regions where woody biomass is scarce, and women and children, who bear the burden of collecting firewood, has to spend 5+ hours walking long distance and collecting wood (Mr. Zeleke, personal communication, May 13, 2022). This can also expose them to gender based violence. It also affects them socioeconomically by taking valuable time that can instead be allocated for creating livelihoods, studying, and school. Additionally, the use of traditional biomass for cooking exposes women and girls, who mainly do the household chores, to pulmonary disease. In regard to the environmental impact, traditional biomass consumption and the ever-growing demand for energy has extensively increased the demand for firewood which has resulted in an extensive deforestation in the past 35 years. Currently, only 2.7% of the land is covered with forests. This in turn contributes to the scarcity of woody biomass and in association energy scarcity in the rural area. In addition to the depletion of resources, deforestation has also resulted in the reduction of soil quality and a decline in the preservation of aquifers which also will reduce agricultural yield due to the deficiency of nutrients and water in the soil. Environmental crisis is prevalent in the rural community of Ethiopia due to its heavy reliance on traditional biomass as energy source. Hence, the production and utilization of biogas is an alternative that can be used to reduce these impacts and address these bottlenecks. Hence, Ethiopia's energy target and electrification plan

has given priority to the utilization of renewable energy including biogas. The 2020 renewable energy target for Ethiopia aims to increase the renewable energy capacity to 16,700 MW with 5% of it being bioenergy. If these targets are implemented it will boost the total installed renewable energy capacity to 19,300 MW.

As for Ethiopia's sectoral energy consumption, the residential sector occupies the highest percentage TFC at a staggering 87% followed by the transport and industry sector (IEA, 2019). This showcases how much of an impact the residential sector has on the energy landscape of the country. The breakdown for the different sectoral consumptions can be seen in Figure 2.2.

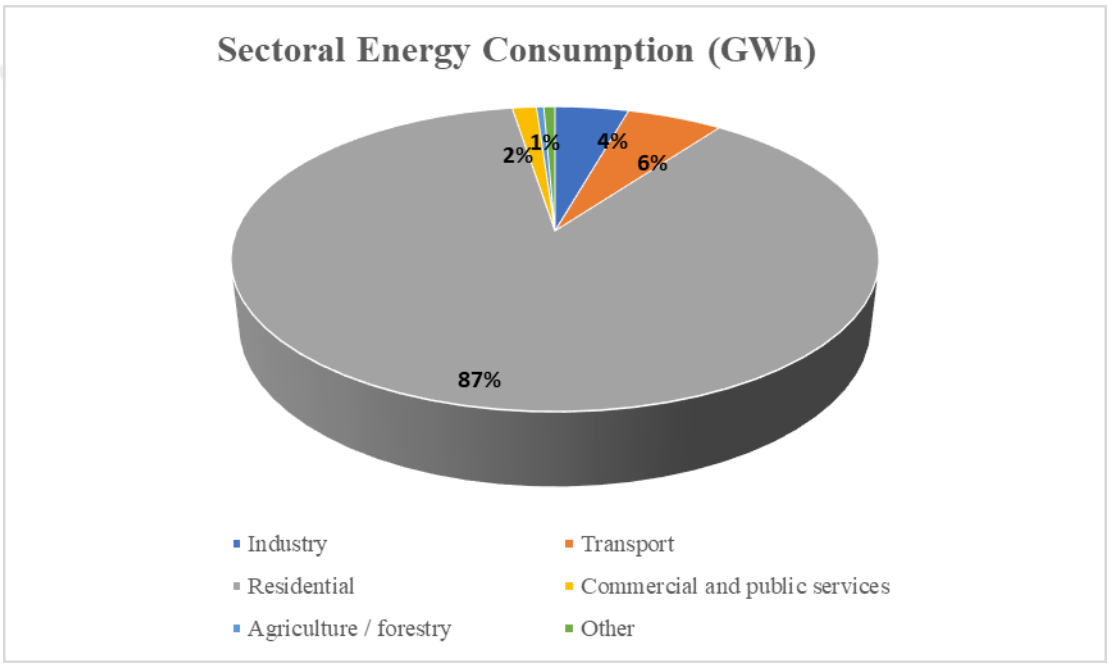

Figure 2.2. Ethiopia Sectoral energy Consumption in 2020

2.3. Similarities between the countries

Although the two countries are located in different continents and have major geographical and socioeconomical differences there are also some major similarities when it comes to their biomass potential and factors for the production of biogas. One major similarity is the farming and agriculture system. Small size farming is still dominant in both countries which makes small scale biogas production feasible. However, in the case of Türkiye there is an emergence of cooperative farming. The geography and climate of both countries for most parts also allow for efficient biogas production throughout the year. Hence this thesis focusses on the exploration, analysis and comparison of

biomass potential, the feasibility of biogas production and utilization as well as the potential of biogas in addressing different energy issues in both countries.

2.4. Exploring Bioenergy

Biomass is a great renewable energy source due to its availability, accessibility as well as flexibility in providing diverse types of fuels that can be used in solid, liquid or gaseous form which also makes it a great option for off-grid energy. Traditionally, biomass is used in its solid and raw form without being processed as an energy source especially in rural communities. However, using biomass to produce bioenergy is more beneficial in multitude of ways. The end products, biofuel and digestate, can address different needs within the off-grid and rural community such as access to clean cooking, access to electricity and light, as well as a shift to the utilization of organic fertilizer in the agricultural sector. Additionally, incorporating bioenergy in the region's energy mix has environmental benefits. In the case of Türkiye bioenergy from biomass can reduce the country's dependence on fossil fuel and coal and in the case of Ethiopia, utilizing bioenergy/biogas from biomass can reduce the dependence on traditional biomass. Hence, bioenergy can facilitate the renewable energy transition while providing cleaner energy alternatives. Moreover, using the by-product of biogas production such as digestate in lieu of industrial fertilizers can further enhance the environmental benefits of bioenergy.

2.4.1. Types of base feedstock

Biomass can be obtained from different sources such as agro-waste, forestry, agro-industrial waste, domestic waste, municipal waste, or industrial waste and the bioenergy production and bioenergy potential of the region can differ based on the type of biomass used as a feedstock. Generally, the type of feedstock used depends on the availability, the production capacity as well as the generation need. The geographical landscape and climate of the region, technical and financial capacity of the region, energy targets of the country, as well as type of stakeholders and biogas producers involved are also factors that determine the type of feedstock used.

2.4.1.1. Agro-industrial Organic waste. For manufacturers that use agricultural products, agro-industrial waste is the most preferred organic waste option which includes but is not limited to coffee husk, sugarcane bagasse, dairy product waste, cotton stocks, and waste from meat processing.

Utilizing agro-industrial waste to produce biofuels has several advantages. It can contribute to the formation of a proper waste management framework on the industrial level as well as contributes to cleaner production. Moreover, unlike some agricultural waste such as strawbale or energy crops such as maize/corn, using agro-industrial waste would not have a negative impact on the water-land-food nexus, present food security challenges in the local community or reduce feedstock availability for cattle and livestock.

2.4.1.2. Plant waste and crop residues. Another very common waste, especially in farming communities, is plant waste and crop residues. In addition to that, invading trees and weed can also be considered as an alternative in the production of bioenergy. One such example is the production of briquettes from protopis by the agro-pastoralist community of Afar region (Mr. Yisehak, personal communication, August 2021).

2.4.1.3. Livestock waste. Livestock waste or animal manure, which is the focus of this thesis, is similarly another favorable feedstock for biogas production in farming communities and in areas where there is a high animal husbandry and livestock population. Manure from cattle or other large ruminants, manure from small ruminants such as sheep or goat, as well as manure from poultry all can be used for biogas production. However, based on the manure type the variables needed for the production and production steps can differ as discussed in later sections. In addition to being an alternative, cleaner, and renewable energy source, animal manure and the utilization of animal manure for biogas production provides several benefits such as proper waste management in communities, prevention of unpleasant odor and waste related pollution, reduction of microbial pathogens and pathogen related disease on farms, as well as production of organic fertilizer. Hence, using animal manure for biogas production can be considered as a proper manure and waste management solution for the livestock sector.

2.4.2. Why Livestock waste?

Globally, the livestock sector accounts for 35-40% of the total anthropogenic methane emission and 65% of the total N_2O anthropogenic emission. Similarly, methane emission from livestock because of enteric fermentation and improper manure management contributes to 78.3% of the total agricultural methane emission (FAO, 2018). Livestock sector also represent 75–80% of the total emissions from the agriculture sector with improper manure management accounting for 6.3% of total agricultural GHG emission. Moreover, direct disposal of animal manure presents sanitation and

health problems and can create odor and hygiene problems on top of environmental pollution concerns.

As a result, animal manure and livestock waste are an attractive alternative for biogas production since the utilization of it will create an opportunity for controlled biomethane generation, tackle the sanitation and odor problem stated above, reduce unmanaged GHG emission, and address environmental pollution issues. (Melikoglu & Menekse, 2020). Animal waste also has high humidity content and high degradation potential which makes it a good feedstock for biogas generation. Moreover, these waste types do not require excessive pretreatment and can be processed in multiple ways which makes them easier to utilize especially in communities with low technical or financial capacity.

When looking at the impact of the livestock sector on a country level, Türkiye has one of the highest livestock populations in the world with more than 73.4 million livestock population as of 2022 (TUIK, 2022). Due to the high livestock population, there is an abundance of agricultural and livestock waste which presents a great opportunity for bioenergy and organic fertilizer and compost production. This is also reflected in the environmental impact data in which the agriculture and animal husbandry sector contributes to 12.8% of total GHG emissions in Türkiye. Manure based emission from improper manure management and enteric fermentation represents 60% of the total sectoral emission with 28.44 million tons of CO_2eq and 5.41 million tons of CO_2eq respectively (Ersoy & Ugurlu, 2020; Melikoglu & Menekse, 2020).

In addition to sectoral GHG emission, proper waste management is also a main concern in the agricultural and livestock sector of Türkiye. Agricultural waste such as plant and crop residues as well as animal manure are either dumped in landfills or burned. Animal manure is also sometimes partially used in the field in the raw form or left to decompose which raises a waste management concern, creates bad smell, present health and sanitation concerns in the community and impact the environment due to methane emission, water pollution, and soil degradation (Buğday Association for Supporting Ecological Living, 2017) Hence, utilizing the abundant biomass potential of the country to generate a cleaner energy such as biogas can potentially address and present solutions to these challenges.

In the case of Ethiopia, agriculture is the main economic activity of the country and contributes to 48.8% of the country’s GDP. Currently commercial and industrial farming make up a small percentage of the sector, with the majority being made up of household or small-scale level farmers.

Hence, agricultural waste is accessible on a small-scale level and creates a bigger opportunity for households to be prosumers and active stakeholders in the energy transition. Similar to Türkiye, Ethiopia also has the largest livestock population in Africa and as a result, a high biomass and bioenergy potential. However, the lack of integrated waste management framework in the rural area and as a result improper or inadequate manure management has made the high livestock population of the region a source of challenge, mainly in regard to Water, health, and sanitation (WASH), instead of an opportunity. Improper disposal of livestock waste and manure is a major source of infectious diseases in Sub-Saharan Africa and compromises the health of the local community (Avery, Anchang, Tumwesige, Strachan, & Goude, 2014). Pathogens from inadequately managed manure can contaminate water directly at the source, or by seeping into run-off water, or by contaminating piped distribution systems which is detrimental especially in regions where access to clean drinking water is already scarce. Hence, the production of biogas from agricultural waste can play a role in either developing or improving the waste collection mechanism in the region, which addresses environmental pollution and health related concerns in addition to addressing energy challenges of the community.

2.5. Overview of Biomass to Energy Conversion Methodologies

Different conversion techniques are used to convert biomass to bioenergy. The two main conversion methodologies that are used to treat organic waste are biological methods and thermal conversion methods. Biological methods include fermentation and anaerobic digestion, and Thermal conversion methods include incineration, gasification, and pyrolysis as can be seen in Figure 2.3. The type of conversion methodology is chosen based on the type of biomass used, the quality of the feedstock, the production capacity and potential, the technical and financial specifications required to treat the waste, the desired end product and the end-use sector (Ozcan et al., 2015).

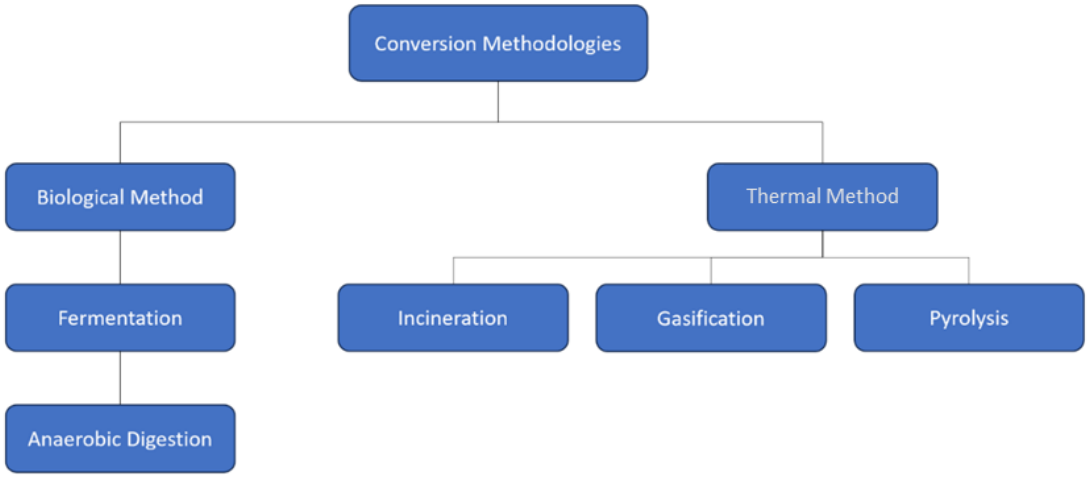

Figure 2.3. Common Biomass to energy conversion methodologies

2.5.1. Biological Methods

A wide range of techniques fall under biological conversion including common techniques such as fermentation, hydrolysis, and anaerobic digestion as well as novel techniques such as etherification or pressing. Based on the techniques chosen, different types of feedstocks are used. For etherification or pressing, oleaginous or energy crops are preferred as feedstock. Whereas ethanol and biodiesel are produced via fermentation and hydrolysis respectively cellulosic materials such as sugar and starches are the preferred feedstocks. On the other hand, wet biomass such as manure, vegetable waste, sewage sludge…etc. can be treated via anaerobic digestion in order to produce biogas, which is the focus of this thesis and is explored in detail in the coming sections.

2.5.2. Thermal Methods

Thermal conversion methodologies on the other hand includes techniques such as gasification, pyrolysis, and liquefaction. Generally thermal conversion methods are used to process dry biomass; however, the end-product and usage differ based on the process. Combustion or incineration technologies can be used to generate heat and electricity with around 80% of the end product being heat and 15% - 40% of it being electricity depending on the production efficiency (Frank et al., 2007). On the other hand, syngas is produced via gasification which can be then used in boilers to generate heat or in turbine, engine or fuel cells to generate electricity. Pyrolysis oil, which is the end-product of the pyrolysis process, is also used in a similar manner.

2.6. Overview of the Anaerobic Digestion Process

Anaerobic digestion is the biological oxidation of biodegradable organic substances via a microorganism in the absence of oxygen. This results in the production of methane as well as carbon dioxide (Ersoy & Ugurlu, 2020; Buğday Association for Supporting Ecological Living, 2017) and hence can also be perceived as a controlled biomethane generation (Melikoglu & Menekse, 2020).

Anaerobic digestion provides a variety of technical, environmental, and economic opportunities which can make it a great option for organic waste treatment. From an environmental standpoint, anaerobic digestion has the potential to reduce the release of pathogens to the environment through treatment of livestock manures and agricultural waste (Avery et al., 2014). Moreover, anaerobic digestion presents an effective GHG mitigation strategy in the agriculture and livestock sector. The presence of microorganisma in animal manure facilitates anaerobic digestion which adds to the suitability of it as an organic and livestock waste treatment option (Ozsoy & Alibas, 2015). Since anaerobic digestion is conducted in closed reactors it results in lower and more controlled emissions compared to other biological treatment options. Anaerobic digestion additionally provides energy recovery potential in the form of biogas as well as environmentally friendly and cost-effective soil treatment solution as digestate or bio slurry is another by-product.

The biogas produced via anaerobic digestion can be further be valorized or optimized to produce high quality fuel (Blanco & Gonz, 2020) Moreover, the end-products and the value-added products from anaerobic digestion which are the biogas, digestate/slurry, or compost create economic opportunities for the producers. Due to these reasons, anaerobic digestion is one of the most preferable technologies for bioenergy production and wet waste treatment (Luis & Moncayo, 2008).

2.6.1. Different stages of anaerobic digestion

The initial stages of waste-to-energy conversion methodologies is generally similar and includes feedstock collection, weighting and inputting of feedstock, feedstock bunkering, material separation and feedstock sorting, as well as pretreatment which can also be incorporated on the material separation and feedstock sorting stage. These initial stages are followed by digestion for anaerobic treatment (Ersoy & Ugurlu, 2020; Varol & Ugurlu, 2017; Pinasseau et al., 2018).

The digestion stage of anaerobic waste treatment consists of four different phases which are determined based on the type of bacteria involved. The bacterial groups that are active in anaerobic digestion work in sequence and hence, a product from one phase forms the substrate for the next phase. These phases of anaerobic digestion are hydrolysis, acidogenesis, acetogenesis and methanogenesis.

2.6.1.1. Hydrolysis. This phase is characterized by the breakdown of complex compounds in organic matter such as carbohydrates, proteins and fats into simple and soluble organic compounds. This results in the conversion of polymers to monomers including glucose, simple sugars, fatty acids and Amino Acids.

2.6.1.2. Acidogenesis. The acidogenesis phase is also commonly known as fermentation due to the presence of fermentative bacteria. During this stage, the monomers from the hydrolysis stage are converted by acidogenic (fermentative) bacteria into Acetic acid, Volatile Fatty Acid (VFA), H_2, CO_2, as well as alcohols. The production of VFA in this stage contributes to pathogen die-off, and hence the VFA concentrations should be regulated in order to ensure that acidification or process failure doesn't occur.

2.6.1.3. Acetogenesis. During this phase, the acetogenic bacteria converts VFA and other simple molecules that were produced during the acidogenesis stage into acetic acid, CO_2, acetate, formate, CO, H_2, Methanol, Methyl Amine, Propionate, and Butyrate (Avery et al., 2014).

2.6.1.4. Methanogenesis. In this phase, the hydrogen, CO_2, and acetate from the previous stages are further broken down by methanogenic bacteria in order to obtain methane (CH_4), CO_2, and water. This stage is particularly sensitive to disruption. During the methanogenesis stage, very high and very low temperatures are not preferred since methanogenic bacteria are active in average temperature (Avery et al., 2014).

2.7. Overview of operational parameters that affect anaerobic digestion and biogas production potential

The different stages of the anaerobic digestion cycle are affected by different operational parameters and factors which in relation affects the amounts, composition, and quality of biogas production (Kulkarni et al., 2021; Nie et al., 2021; Boysan et al., 2015; Ersoy & Ugurlu, 2020).

2.7.1. Digestion Temperature

The digestion temperature is one of the most essential parameters as it impacts the microbial metabolic activities which in turn affects the production and production rate of biogas. Moreover, the reactor's temperature is also related to the waiting time, which is also known as the retention time, as well as the overall digestion rate and specifically the rate of hydrolysis and methane formation. Anaerobic digestion can occur in a broad range of temperature and these temperature ranges are divided into three main groups which are psychrophilic, mesophilic, thermophilic as discussed briefly in the upcoming section.

Psychrophilic Temperature, in most literature is classified as a temperature range that is below 20 °C (Caliskan & Tumen Ozdil, 2021; Nie et al., 2021). However, compared to the other two temperature ranges, psychrophilic temperature is not mostly used in commercial anaerobic digesters for various reasons. During this stage, activities of methanogenic microbial communities are limited, which slows down the hydrolysis rate and results in a higher hydraulic retention time.

Mesophilic temperature, on the other hand, ranges between 20-45 C and is the most preferred temperature range for commercial and domestic digesters since it provides the optimum temperature for enteric bacteria. Moreover, depending on the substrate and the environment (conductive) this temperature range provides a space for pathogen multiplication. Compared to the other temperature ranges, the mesophilic temperature range is also more stable, requires less process heat, and is less at risk for ammonia nitrogen toxicity. Additionally, as the ambient temperature for Ethiopia and Türkiye ranges between 20-40 Celsius (Caliskan & Tumen Ozdil, 2021) hence is ideal for digesters with mesophilic conditions (Buğday Association for Supporting Ecological Living, 2017; Avery et al., 2014) According to SNV, the biogas plants that are disseminated in Ethiopia operate in mesophilic condition in the range of 20-45 Celsius (NBP, 2008). However, there are also cases in which the temperature might be more fitted to psychrophilic condition. In the case of Ethiopia, the mean annual temperature in some of its regions lies between 15 and 21 °C., in which case digesters that operates in the psychrophilic range is preferred (Gabisa & Gheewala, 2019).

The third temperature range, which is known as Thermophilic temperature lies between 40−65°C (Caliskan & Tumen Ozdil, 2021). Research shows that this temperature further activates extracellular enzymes which enhances the hydrolysis rate, hence allows for higher conversion efficiency, high loading rate with reduced hydraulic retention time and pathogen disinfection. However, on this

temperature range, there is low diversity in the microbial community which might affect the process instability.

Generally, most commercial anaerobic biodigesters perform under mesophilic and thermophilic conditions. Moreover, it is possible to set two stage anaerobic digesters or systems with two different temperature ranges such as mesophilic-thermophilic two-stage anaerobic system (Dalkilic & Ugurlu, 2015).

2.7.2. pH

The optimum pH value for the ideal methane production is between 6.8–7.2 (Caliskan & Tumen Ozdil, 2021). However, the needed pH Value differs based on the anaerobic digestion phase as the pH value affects the living condition of the anaerobic bacteria. For methanogenic bacteria the preferred pH is either neutral or slightly alkaline level (Caliskan & Tumen Ozdil, 2021).

2.7.3. Hydraulic Retention Time

The Hydraulic Retention Time (HRT) is the time that the substrate spends in the reactor and by relation the time period in which it stays in contact with microbes while undergoing degradation. The hydraulic retention time also reflects the period that pathogens are exposed to the conditions and temperatures of the digester and hence the time that is needed for the removal of pathogens from the substrate. Optimum hydraulic retention time facilitates efficient treatment of feedstock as well as pathogen die-off. However, to optimize the HRT the different parameters that affect the HRT should be understood.

One main parameter the affects HRT is the type of feedstock and co-substrate used. The type of feedstock used also determines the VFA produced and an increase in the VFA level can increase the pathogen die off. Apart from feedstock type, the configuration of the biodigester and the temperature in the reactor affects the hydraulic retention time along with the presence of pathogens in the substrate. Additionally, the reaction configuration or structure also can optimize the mixing in the digester as well as minimize the short-circuiting of flow, which can then reduce the biogas yield and prevents the kill-off of microbial pathogens or reduce the pathogen removal rate as that requires minimum retention time to complete (Ghangrekar & Behera, 2014). However, certain digester configuration and temperature might also lead to the growth of pathogens in certain cases.

The hydraulic retention time is determined by taking the ratio of the reactor volume to the flow rate and is monitored through the addition of the feedstock. This is a factor that is taken into consideration while designing the digester (Avery et al., 2014). The retention time for Biodigesters installed in Ethiopia is generally assumed to be 50 days (NBP, 2008).

Another factor that is closely associated with HRT is the solid retention time which is the average residence time of solids in the reactor and similar to the hydraulic retention time this factor affects the microbial biomass in the reactor. For solid retention time, a steady state means that the amount of solid entering the reactor is the same as the amount of solid leaving the reactor. However, in small scale biodigesters in which there is no solid-liquid separation tank, there will be no such factor and the solid retention time is taken to be the hydraulic retention time.

2.7.4. Organic loading rate

The Organic Loading Rate (OLR) is one other key parameter that affects the anaerobic digestion process. The OLR is defined as the amount of organic waste fed into the digester everyday per unit volume. Higher OLR defines the efficiency of anaerobic digestion and can make the process of anaerobic digestion more efficient or improves the process efficiency. Based on the operating temperature of the digester, the loading rate differs, and hence similar production efficiency can also be attained when anaerobic digestion is conducted under thermophilic conditions but with a significant energy loss (Jiang et al., 2020).

The OLR also depends on the amount of solid content in the feed and an increase in the OLR also increases inhibitory substances such as fatty acids in the digester and in some cases might hinder the anaerobic digestion process. Moreover, higher OLR can also overload the digester which in turn decreases the biogas production (Jiang et al., 2020). In addition to temperature and solid content, the OLR also depends on the concentration of active microbes in the digester and in relation, the Hydraulic retention time (Mahmudul et al., 2021).

2.7.5. Solid content

Solid Content is a parameter that determines whether the feedstock is wet or dry and moisture content and dry matter percentage are also used interchangeably in literature while discussing solid content. Solid Content or the dry matter content in the organic matter used as a feedstock can be a deciding factor in choosing the preferable and most cost-effective organic waste processing

methodology. If the waste treatment method that is selected is anaerobic digestion, the solid content also determines whether the process is dry or wet. A wet anaerobic digestion process which generally is conducted in a constant flow biodigesters has a low dry matter or low solid content that is less than 15% and certain feedstock examples are farm slurry or liquid slurry. In wet anaerobic digestion, the feedstock should be constantly stirred either mechanically via a rotating paddle or using gas which is done mostly by redirecting the biogas produced back to the substrate to ensure continuous stirring which in turn prevents suspended solids from precipitating. Whereas for dry anaerobic digestion process the solid content is in the range of 20% and 40% and a digester with a continuous mechanical stirrer which is needed to assist the flow of the feedstock through the reactor as well as prevent settling of solids and unequal pocketing is used (Mahmudul et al., 2021).

The solid content and in relation to the anaerobic digestion process type also affects the Hydraulic Retention Time, Organic Loading Rate, and Volatile Solid Content (VS). The Hydraulic retention time for both processes, is more or less the same, However, the HRT in dry anaerobic digestion has a wider range with 14-60 days recorded in most literature compared to the 25-60 days of wet anaerobic digestion systems. On the other hand, the Organic loading rate highly differs based on the type of anerobic digestion process with 12-15 Kg/day being fed into digesters for dry anaerobic digestion and less than 5 Kg/day for wet anaerobic digestion. The type of feedstock being used also determines the optimum dry matter content. In animal manure, high dry matter content is preferred as it increases the efficiency of biogas production (Ersoy & Ugurlu, 2020). The dry matter content also differs based on the manure type with solid manure having 10-30% of dry matter, while liquid slurry having dry matter content that is below 10% (Ersoy & Ugurlu, 2020). Additionally, dry matter content is used to determine whether the digestion is wet (if dry matter is below 15%) or dry and in relation the type of digester that should be used.

2.7.6. Carbon to Nitrogen Ratio

Organic feedstock includes various chemicals and nutrients with carbon (C), hydrogen (H), nitrogen (N), phosphor (P) and Sulphur (S) being the main elements. The percentage of these nutrients in the composition of the feedstock being used affects anaerobic digestion. Carbon to Nitrogen Ratio (C/N) of the feedstock is one such parameter that affects biogas production and biogas quality as it is an essential indicator of the capacity of materials to decompose. C/N differs based on the type of feedstock used. When utilizing animal manure, due to animal manure being rich with nitrogen, it can make it difficult to attain optimum C/N ratio. Hence, Carbon content should be increased before anaerobic digestion takes place.

The optimum carbon to nitrogen ratio is given within a wider range in most literature and the value depends on the substrate used. Generally, the optimum C/N ratio 20/1 to 30/1. However, in the biodigesters currently active in Ethiopia and installed by SNV, 25/1 to 30/1 C/N ratio is taken as optimum C/N ratio for the feedstocks used (NBP, 2008; SNV, 2017). Low C/N ratio in a feedstock will facilitate fermentation, whereas a higher C/N ratio can create a failure in the fermentation process due to acidification. Different feedstocks have different C/N ratio with pig and cattle manure having the most suitable C/N ratio for effective digestion with chicken and poultry dung having the lowest suitability. When it comes to vegetation and crop waste, the C/N ratio is generally high and even higher when the vegetation is old. Hence, when using vegetation and crop waste along with animal manure in co-digestion, the proportion of the vegetate waste used is essential in starting the fermentation process as well as giving optimum yield.

2.7.7. Feedstock composition

The feedstock composition is a parameter that determines the different physical and chemical characteristics of the feedstock such as chemical biodegradability, granularity, and hydraulic retention time (Avery et al., 2014). It is also the composition of organic nutrients in the feedstock such as proteins, fats, and carbohydrates and hence is a parameter that critically affects the biogas yield (Melikoglu & Menekse, 2020).

In addition to the composition of organic nutrients, the presence of trace elements can also either facilitate microbial activity in the reactor or can be toxic. On the other hand, high level of VFA, accumulation of ammonia, high concentration of heavy metals, low level of pH…etc. can create a toxic system to pathogens as well as microorganisms (bacteria) responsible for digesting feedstock (Avery et al., 2014).

The composition of feedstock can be adjusted by adding two or more feedstock as a co-substrate in the digestion process, in this case the process becomes an anaerobic co-digestion, and the biogas yield is enhanced as co-substrate provides the additional needed nutrients that lack in a single feedstock digestion.

One of the main co-substrates that can be used or mixed with cattle manure is corn silage which is a method that is used in biogas production in Europe. Crop straw is also a widespread feedstock in biogas production (Melikoglu & Menekse, 2020) Onion peel is also something that is used in some

biodigesters in Ethiopia (Mr. Zeleke, personal communication, May 13, 2022). As discussed in the previous section, C/N ratio is a factor to consider while using vegetable and crop waste as a co-substrate.

2.8. Overview of Biogas Facilities and Digesters

2.8.1. Scale of biogas facilities and digesters

Different capacities, social, economic, and technical factors determine the digester type and size being deployed and used in the countries. The biomass and bioenergy potential and feedstock and resource are one of the main capacity factors that determines the scale of biodigester facilities in the regions. The minimum feedstock required to determine the digester size is the culmination of the feedstock that is needed at the initial stage to jump start the digestion process and the daily dung or waste available in the specific plant, community, or household. Moreover, since the dung is mixed with water, water availability or scarcity should also be considered along with feedstock availability. When assessing resource capacity one thing that should also be noted is population density. Although a region might have a high biomass potential, it doesn't translate to feedstock availability especially for rural regions in which the population is sparsely spread and hence feedstock and mainly livestock and agricultural waste is not concentrated in one space. In the case of biodigesters that utilize livestock waste, this also translates to herd size either in the household, the community, or the region.

Apart from biomass potential and feedstock availability, the structure of the farming community and agriculture sector of the country, the financial capacity of the regions, the policy frameworks and support mechanisms in place determine the scale of biodigester. Access to energy and electricity, the energy potential of the countries, the energy challenge present within the countries, their energy landscape as well as energy targets are all essential factors to consider when assessing suitable digester or facility size. In developed countries large scale biogas powerplants in lieu of small-scale digesters are preferred since the latter is considered to be unstable while the former is more cost effective. Moreover, these countries have the financial and technical capacity to build, maintain, and manage the operation of large scale powerplant. Since the energy goals and targets of these countries aim at reducing fossil fuel consumption especially in the industrial sector, large scale and industrial biogas powerplants contribute to these targets on the energy transition. On the other hand, industrial and commercial level farms are few in developing countries, and small scall digesters and a less centralized approach towards the biogas industry is preferred (Avery et al., 2014). Moreover, the energy challenges within these countries are intersected with food, land, water, and resources security

making the water-food-energy-land nexus a central point in the energy discourse. Additionally, the majority of the population is not connected to the grid and energy access is still a main challenge. Hence, small-scale and decentralized energy solutions can play a big role when it comes to addressing the energy poverty and energy scarcity in these regions without negatively impacting food, land, water, and resources accessibility.

2.8.1.1. Large scale or Commercial Biogas Facilities. Large Scale biodigesters are also known as commercial biodigesters as they generally produce biogas not only for their own use but for commercial purposes. Due to the technical and financial capacity and resource needed to construct and run large scale biodigesters, they are mostly the common type of biodigesters in developed countries. Large scale biodigesters are also generally constructed to treat industrial or agro-industrial waste including waste from industrial farms and large plantations, food production facilities, paper mills…etc. as these facilities produce a significant amount of waste. (Rupf, Bahri, De Boer & McHenry, 2016).

There is an overlap in biodigester sizes when it comes to medium scale (community or institutional) biodigesters and large scale (Commercial) biodigesters depending on the country's capacity as well as the type of community or institution that is benefiting from the biodigester. However, biodigesters greater than 250 m^3 are generally considered to be large scale or in certain countries the size can go into the ten thousand range, in which case is referred as ultra large scale (Rupf et al., 2016).

Although the general design of biogas facilities and biodigesters are similar, adjustments is done on the traditional biodigester models in order to adapt to commercial scale and accommodate the size while taking the objectives and the operation specifics into account. Currently, there are four main types of large scale biodigesters which are namely batch reactors, fixed film, continuously stirred tank reactors (CSTR), and plug flow with the latter two being preferred to treat agriculture and livestock waste (Rupf et al., 2016; De Mes, Stams, Reith, & Zeeman, 2003).

2.8.1.2. Medium-scale /Community and institutional Biodigesters. are also another type of biodigesters that are present in Türkiye and to some extent Ethiopia. To have an economically feasible anerobic plant that utilizes its optimum potential, a herd size or Tropical Livestock Unit (TLU) greater than 3000 cows per community is required (Lauer et al., 2018). Medium scale biodigester can present an attractive option for communities with communal farms or feasible transportation options and a higher herd size since utilizing the biogas generated directly on the farm gives the highest net present

value. Hence, instead of small-scale and delocalized biodigester, an economically friendly and a higher manure utilization option can be achieved by creating co-operative or joint anaerobic digestion plants in communities but in the case of Ethiopia this is challenging because the technology to transport the manure as well as pipe system to distribute the gas is not yet feasible. The average sample size for village sized or community biodigester differs based on the country and type of institutes and different literature report different values. Although some literature classifies medium scale to be 40 m^3 and above (Kulkarni et al., 2021; Kristoferson & Bokalders, 2013) the consensus is that any digester above 20 m^3 is generally considered medium scale biodigester (Rupf et al., 2016). It should also be noted that, in certain cases medium scale biodigesters can go up to 200-1200 m3 for institutional (Rupf et al., 2016).

2.8.1.3. Small Scale/ Household Biodigesters. These are semi-batch reactors that takes organic compounds as feedstock, which in this case is a mix of animal manure and another co-substrate (Kamp & Bermúdez Forn, 2016) Based on the analysis made in both countries, small scale or decentralized biodigester are identified family sized or farm sized and generally have a range of 2-20 m3. Additionally, the biodigesters are either farm or household based.

These small scale biodigesters mainly consist of a large tank or some sport of sealed structure that hosts the microbial activity (Melikoglu & Menekse, 2020) Additionally, a pit or a storage unit is installed next to a biodigester in order to store the biogas produced. Apart from biogas storage space, some biodigesters will also have either a built-in bio-slurry extension or a compost pit.

2.8.2. Biodigester Types

Other than biodigester size, biodigester types is also another aspect that was explored while doing biodigester inventory of the regions since the technical and economic feasibility of the biogas process and biogas production is heavily affected by the biodigester design. Hence, determining the proper digester type that is used for biogas production is essential. Moreover, biodigester type is of particular interest as variables such as the local weather, geographical location, soil type…etc. affect the biodigester design, impertinent to size. The three main types of conventional biodigesters are Fixed Dome biodigester, Floating Drum biodigester, and Balloon biodigester (Abubakar, 2022).

2.8.2.1. Fixed Dome Biodigester. Fixed dome biodigester is also known as a hydraulic digester and is one of the most commonly built biodigester type globally. The fixed dome biodigester is a semi-flow reactor that typically consists of a fixed gasholder at the top and the digester or the fermentation

chamber at the bottom. The digester part is a filling hole where the organic waste resides and in which the anaerobic digestion takes place. Feed is added to the fermentation chamber via an inlet pipe. The biogas produced, on the other hand, leaves the fermentation chamber via an outlet pipe with a valve that is attached and will be stored in the gas reservoir. A displacement tank or a compensation tank is also built in which the slurry is stored. The fermentation chamber and the gas reservoir are built using cement, sand, granite, aggregate, bricks, stones, concrete slabs, and iron rods. As for the dome, its generally made out of plastic such as High-Density Polyethylene, Low-Density Polyethylene, and Polyvinyl Chloride. This makes the dome very flexible and optimal to hold the gas produced (Kulkarni et al., 2021).

The fixed dome biodigester has its own advantages and disadvantages compared to the other types of biodigester currently available in the market. The fixed dome biodigester is simple in its design as it also doesn't have any moving parts, occupies less area, has a long lifespan of about 20 years, and has a relatively low cost of construction. All these make the fixed dome a feasible option, especially for rural communities and households. However, there are also some disadvantages to the fixed dome biodigester. The lack of gas valve in the outlet results in having an unstable gas pressure. Moreover, the gas reservoir is prone to cracks which affects its lifespan.

2.8.2.2. Floating Drum Biodigester. The floating drum or the floating canopy biodigester is also another widely used biodigester (Kulkarni et al., 2021). The floating tube digester has two main parts; the underground digester and an inverted steel drum that serves as gas storage unit and is the floating drum part. The steel drum floats on a water jacket or fermentation slurry which provides a way to detect the volume of the gas. Additionally, depending on the gas stored, the drum moves up and down and creates the pressure that is needed for the gas to leave the tank. However, this is also one of the main downsides of the floating tube digester. Since the steel drum floats on water or the fermentation slurry, it corrodes much faster than the dome and hence needs to be maintained more frequently. This greatly reduced the digester life with most floating drum digesters lasting between 5-10 years which is comparatively lower than that of fixed dome biodigester. Additionally, it also increases its maintenance cost. Modern designs have been trying to address this issue by replacing the steel drum with fiberglass or plastic. Another disadvantage of the floating drum is its higher investment cost on top of the higher maintenance cost which makes it not the best alternative for rural or developing communities and regions. However, floating drum digester also has its own advantages. Mainly, gas leakage seldom happens in the floating drum biodigester which makes it easier to operate and maintain. The floating drum digester is a good option for regions with warm temperature (Kulkarni et al., 2021; Rupf et al., 2016; Tumwesig, Smith, & Bechtel, 2013).

2.8.2.3. Flexible Balloon Type Biodigester. The flexible balloon type biodigester is also known as the tubular flexible balloon reactor, sausage type digester, or rubber-balloon biogas digester. The flexible balloon digester is comprised of a narrow tank with a length to width ratio of 5:1. The tank is built in a trench underground, inclined at angle of 3-9 degrees which facilitates flow between the inlet and outlet pipe which are situated above the ground on the opposite sides. This also creates a gradient difference within the tank which separates the acetogenesis and methanogenesis process, creating a two-phase system (Kulkarni et al., 2021; Tumwesige et al., 2013). The flexible balloon type biodigetser is generally small scale with the common size being 2, 4, and 8 m^3.

The flexieble balloon type biodigetser has some advantages over the fixed dome and the floating drum biodigetsers. One such advantage is its water to feedstock ratio, which is lower than that of the traditional fixed dome and floating drum at 1:3. This makes the flexible balloon a great alternative in areas with water scarcity. Additionally, the flexible ballon type is a cheaper alternative with lower material cost as its constructed mainly by using polyvinyl chloride (PVC), polyethylene (PE) or plastic silo bags which also makes the materials easier to transport and cuts the installation cost in half compared to the fixed dome (Tumwesige et al., 2013). However, the materials used also contributes to the bottlenecks of using the flexible balloon biodigetsers. Due to the material used, the flexible balloon digester is prone to temperature fluctuations and needed to be insulated. Additionally, the flexible ballon has a much lower life span at an average of 5 years compared to the fixed dome with 20-30 years. Additionally, cheaper flexible balloon digesters have a narrow inlet which makes manure handling difficult resulting in sanitation issues. This can be solved by replacing the plastic inlet with concrete inlet mixer, which can be more expensive but will ensure a safe handling of feedstock.

3. MATERIALS AND METHODS

3.1. General Methodology

This thesis assesses the impact of small-scale biodigester production by making a comparative analysis between two countries with comparable biomass and bioenergy potential but a different approach to resource utilization. The thesis assesses the impact as well as bioenergy potential of these two regions through a resource-based approach. Data is collected mainly via desk research and bilateral interviews. Different literature, governmental and international databases, official reports from government and international agencies and confidential documents were analyzed in order to obtain primary and secondary data.

3.2. Dataset Collection from Databases

3.2.1. Data Sources

Several data sources were used both as primary and secondary sources in this thesis. Primary data was collected mainly via bilateral interviews with Turkish, Ethiopian, and international stakeholders including government bodies, implementing agencies, the private sectors, and end-use consumers. A total of 14 interviews were conducted and stakeholders are specifically selected on the basis of their knowledge and expertise.

For secondary data, desk research is done and open-source databases as well as confidential datasets from implementing agencies were analyzed. While conducting desk research mainly Science Direct, Web of Science, and MDPI were used. Literature from these databases was identified and filtered by using the keywords and Boolean operators (“Biodigester” AND “Country”) OR (“Small scale biodigester” AND “Country”) OR (“Anaerobic Digestion” AND “Country”) OR (“Anaerobic Digestion” AND “Animal Manure”) OR (Livestock Waste Treatment” AND “Country”) (“Livestock waste” AND “Anaerobic Digestion”). However, lack of scholarly articles published in the area for Ethiopia has made the data collection a little difficult and hence the resulting data analysis is comparatively theoretical.

Data on the population of different types of livestock including bovine animals, sheep, goats, and poultry in different regions of Türkiye and Ethiopia was mainly collected from national and international databases and statistics agencies such as The Food and Agricultural Organization of the United Nation FAOSTAT, Turkish Statistics Institute (TurkStat), the Central Statistics Agency (CSA), and Agricultural Census Database. Energy data and Energy Balance data was mainly collected from UNData, AFREC, IRENA, IEA (International Energy Agency) Energy Balance Database. Electricity generation and access scenarios are estimated by using open sources such as Türkiye's Bioenergy Potential Atlas, and IRENA's Bioenergy Simulator. Technical information and variables on biogas digesters were taken from official open access documents such as SNV's Training Manual as well as confidential documents from implementing agencies.

Policy frameworks were also analyzed by assessing official publications, reports, and documents including European Green Deal Documents; Ethiopian Federal and regional state ministries' reports such as reports from Ministry of Water and Energy (MOWIE) and Ministry of Agriculture and Forestry; as well as Turkish Provincial Ministries Organizations reports.

3.3. Resource Assessment from livestock sector in the regions

Understanding and assessing the biomass and biogas potential on a regional level is essential in informing policy decisions, setting feasible energy targets and Nationally Determined Contributions (NDCs), directing resources and capital and implementing a just energy transition. Having an estimation of a region's biomass potential helps in disseminating biogas facilities accordingly and not over invest on facilities in regions in which the feedstock capacity is low or in the reverse case, fully utilize the available biomass in regions by disseminating enough biomass processing facilities and technologies. Hence, data on the available biomass potential of each country with a specific focus on biomass potential in the livestock sector is collected from national and global statistics databases such as TurkStat, FAOStat, and the Central Statistics Agency of Ethiopia as well as through opensource tools such as IRENA's Bioenergy Simulator and Türkiye's Bioenergy Potential Atlas.

3.3.1. Biomass Potential of the regions

3.3.1.1. Türkiye. The livestock data for Türkiye is taken from TURKSTAT, which records 16.852 million cattle and 98 million poultry population resulting in 120 million tonnes of cattle waste and 2.9 million tons of laying hens' manure per annum as of 2022 (Karaca, 2019). The biomass and bioenergy potential in the livestock sector of Türkiye differs from region to region depending on

cattle and animal population, agricultural activity, weather condition and such. Based on the data collected and estimations done, Eastern Anatolia and Central Anatolian Regions have the highest biomass and biogas potential compared to the other regions with 19% of the total calculated potential. This is due to the high cattle and animal population in the region (Caliskan & Tumen Ozdil, 2021). When doing a breakdown based on provinces; Konya, Erzurum, İzmir, Balıkesir, Kars, Afyon, Diyarbakır, Aydın, Ankara and Ağrı are the provinces with the highest biomass potential (Karaca, 2019). As for biogas production potential, similarly Eastern Anatolian region has the highest potential followed by the Aegean regions of Türkiye (Ersoy & Ugurlu, 2020) Agriculture waste contributes about 2.177.553.000 m^3 of the total biomass potential of the country with the 68% coming from cattle and 27% coming from poultry (Caliskan & Tumen Ozdil, 2021). For comparison, another assessment of the biomass potential of the country is also done by exploring a study made by (Ozcan et al., 2015) in which two different scenarios were used to calculate the biogas potential of the country and 8.41 billion m3 and 4.18 billion m^3 was the estimated total biogas potential for scenario 1 and scenario 2 respectively. Additionally, the attainable energy value from the available biomass sources is estimated as 188.21 TWh/year for 2014 (Ozcan et al., 2015).

As for the future potential of the country, the literature estimates that nearly 2.14 billion m^3 of biomethane can be generated by 2026 with 1.99 billion m^3 coming from cattle and 0.15 billion m^3 coming from small ruminants such as sheep and goat. The biomethane generation is estimated to supply 2.9% - 3.3% of the country's annual natural gas demand by 2026 and has the capacity to generate 6600 GWh of electricity annually which can meet 1% of the country's electricity demand (Melikoglu & Menekse, 2020). Although this is a small amount when it comes to fully addressing the country's energy demand, the utilization of biomass addresses both energy and waste management issues and contributes to the country's green energy transition goals. Moreover, along with proper waste management, it will also facilitate cleaner production at various levels.

Table 3.1. Türkiye Livestock Population 2020 and 2021

Types of animals	Number (Head)	Share in bovine animals, sheep and goat and others (%)	Share in total animals (%)	Number (Head)	Share in bovine animals, sheep and goat and others (%)	Share in total animals (%)	Percentage Change (%)
Bovine animals	**18 036 117**	**100**	**23.8**	**17 023 791**	**100**	**23.2**	**-5.6**
Cattle	17,850,543	99	23.6	16,851,956	99	22.9	-5.6
Buffalo	185,574	1	0.2	171,835	1	0.2	-7.4
Sheep and goat	**57 519 204**	**100**	**75.9**	**56 265 750**	**100**	**76.6**	**-2.2**
Sheep	45,177,690	78.5	59.6	44,687,888	79.4	60.8	-1.1
Goat	12,341,514	21.5	16.3	11,577,862	20.6	15.8	-6.2
Other	**204 248**	**100**	**0.3**	**182 73**	**100**	**0.2**	**-10.6**
Camel	1 204	0.6	0	1 193	0.7	0	-0.9
Pig	1 353	0.7	0	1 648	0.9	0	21.8
Horse	83,718	41	0.1	74,359	40.7	0.1	-11.2
Donkey	95,809	46.9	0.1	86,455	47.3	0.1	-9.8
Mule	22,164	10.9	0	19,018	10.4	0	-14.2
Total	**75 759 569**		**100**	**73 472 214**		**100**	
TÜİK, Hayvansal Üretim İstatistikleri, 2022							
TurkStat, Animal Production Statistics, 2022							
Figures in table may not add up to total due to rounding.							

3.3.1.2. Ethiopia. Ethiopia is a country with an abundant livestock population. According to Ethiopia Statistical Service database, Ethiopia's total livestock population is estimated at 169.49 million in 2021 which makes Ethiopia the country with the highest livestock population in Africa and fifth globally. Cattle population takes the majority of that with 66.26 million while total sheep, goat and poultry population are reported to be 38.01 million, 45.72 million and 41.35 million respectively. When doing a breakdown of regional distribution, it is seen that Amhara, Oromia, and SNNP are the regions with the highest numbers of animal population from the 9 regional states in the country (Central Statistics Agency, 2021). Due to this high animal population, livestock waste makes up 18.8% of the total biogas potential of the country as of 2018. However, this potential is not fully utilized, and more work is being done on the national level to increase the share of biogas in the energy mix and increase (Gabisa & Gheewala, 2018).

Table 3.2. Ethiopia Livestock Population 2020 and 2021.

	2021			2020			
Types of animals	Number (Head)	Share in bovine animals, sheep and goat and others (%)	Share in total animals (%)	Number (Head)	Share in bovine animals, sheep and goat and others (%)	Share in total animals (%)	Percentage Change (%)
Bovine animals	**66 260 987**	**100.0**	**39.1**	**70 291 776**	**100.0**	**37.6**	**-5.7**
Cattle	66,260,987	**100.0**	39.1	70,291,776	**100.0**	37.6	-5.7
Sheep and goat	**83 729 363**	**100.0**	**49.4**	**95 378 200**	**100.0**	**51.0**	**-12.2**
Sheep	38,013,272	45.4	22.4	42,914,865	45.0	22.9	-11.4
Goat	45,716,091	54.6	27.0	52,463,335	55.0	28.0	-12.9
Other	**19 495 242**	**100.0**	**11.5**	**21 468 960**	**100.0**	**11.5**	-9.2
Mule	357,743	1.8	0.2	382,782	1.8	0.2	**-6.5**
Horse	2,138,928	11.0	1.3	2,148,492	10.0	1.1	-0.4
Donkey	10,020,518	51.4	5.9	10,791,896	50.3	5.8	-7.1
Camel	6,978,053	35.8	4.1	8,145,790	37.9	4.4	-14.3
Poultry	**41,350,684**	**100.0**	**24.4**	**56,992,987**	**100.0**	**30.5**	**-27.4**
Total	**169 485 592**		**100.0**	**187 138 936**		**100.0**	

ESS, Crop and Livestock Product Utilization, 2022
Figures in table may not add up to total due to rounding.

3.3.2. Theoretical Biogas Potential

The biogas potential is calculated directly based on the livestock population of the countries via two approaches. The first one is using a set of direct calculations based on formulas and estimations derived from literature reviews and official reports by also taking variables obtained from bilateral interviews into account. These results are compared with the results from the second approach which makes use of open-source platforms and tools, mainly IRENA's Bioenergy Simulator and the Biomass Energy Potential Atlas or Biyokütle Enerjisi Potansiyel Atlası (BEPA) specifically used for Türkiye.

3.3.2.1. Scenario 1: Formula for Theoretical Biogas Potential. Based on reviewing literature focusing on both Ethiopia and Türkiye and after identifying variables that affect biogas production from the bilateral interview's formula is developed to estimate the theoretical biogas produced based on the total biomass potential as well as the biomass potential in household and farm level.

To calculate the theoretical biogas potential, the amount of usable manure should be first calculated. The usable manure is calculated separately for each livestock type such as cattle, sheep and goat, and poultry.

$$M_U = N_{TLU} \times DM_P \times VS \times AF \quad (3.1)$$

In which: M_U is the Usable manure for biogas production (Kg/head)

N_{TLU} is the Number of Livestock by Tropical Livestock Unit (head)

DM_P is the daily manure produced (Kg/head)

VS is the total volatile solid content in manure (% per Kg manure)

AF is a unitless availability factor.

The average age animal number in household is converted to tropical livestock units by taking the average animal weight into account in order to standardize the animal size. DM_P value differs based on the livestock type and data is directly taken from The Biomass Energy Potential Atlas for Türkiye. Whereas, for Ethiopia, the value is obtained via desk research with a focus on research papers that are conducted within Ethiopia or with a focus on Ethiopia. Similar to the daily manure produced per animal type, the volatile solid content also differs based on the manure type as discussed in section 2. The VS is a percentage of the solid content in manure and a value range is determined based on literature. Similarly, the availability factor is estimated by taking the factors that affect it such as manure collection practices, the barn staying time of the animal, and grazing habits of the animal into account. The number of livestock is standardized to livestock unit in order to cover differences in livestock due to age and weight. The number of livestock in TLU is calculated as:

$$N_{TLU} = N_L \times W_{avg}/1000 \quad (3.2)$$

In which: N_L is the Number of Livestock in a specific category such as cattle, sheep, goat, or poultry (heads)

W_{avg} is the average weight of the livestock type (Kg)

The theoretical biogas potential from usable manure is then calculated.

$$BP_T = M_U \times BY_M \quad (3.3)$$

In which: BP_T is the theoretical biogas produced (m^3)

BY_M is the Biogas Yield from Manure (m^3/Kg)

Additionally, the effective biogas production on a farm level is also estimated based on the methodology presented by (IRENA, 2016) in order to get a more accurate representation of biogas yield. (IRENA, 2016) have derived a biogas yield factor for different temperature and hydraulic retention time. Hence, a temperature range value is first taken from the World Bank climate change knowledge portal for both Türkiye and Ethiopia and hydraulic retention time is also calculated for small scale biodigester size in the range of 2-12 m^3 using the formula below:

$$HRT=\frac{BDS}{DF} \tag{3.4}$$

In which: BDS is the Biogas digester size (m^3)

DF is the daily feedstock available or collected (m^3/day)

The daily feedstock amount depends on the water feedstock ratio which is estimated based on bilateral interviews, project documents, and literature review and is the total value of substrate added to the biodigester daily.

The gas production is then assumed by taking the yield factor for the calculated HRT and estimated temperature of the regions as stated by (IRENA, 2016) and to calculate that by the total biodigester size and total Volatile solid obtained from total daily substrate.

The theoretical and effective biogas produced is then used to estimate the electricity production. This is done by multiplying the methane content in the biogas (M_C) which is 60-65% as well as the calorific value of biogas (CV) given in MJ/m^3 to the theoretical biogas produced which gives us the theoretical electricity potential generation (EG_T) which is calculated in MJ and then is converted to KWh. This can then be used to calculate the effective electricity produced (EG_E) by also taking the engine efficiency (η) into account. A default value range as set by IEA is used for the calorific value of biogas which is 16-28 MJ/m^3. η or efficiency of a biogas engine is also calculated based on values obtained from literature and is taken at 0.25.

$$EG_T=(BP_T\times M_C\times CV)/3.6 \tag{3.5}$$

$$EG_E=EG_T\times \eta \tag{3.6}$$

3.3.2.2. Scenario 2: Open-Source Bioenergy potential Tools. Two open-source bioenergy potential tools were referenced in order to also analyze the biomass and biogas potential of the regions as well.

These two tools are IRENA's Bioenergy Simulator and The Biomass Energy Potential Atlas or Biyokütle Enerjisi Potansiyel Atlası (BEPA).

The IRENA Bioenergy Simulator is an open-source geospatial tool that provides preliminary bioenergy production values by taking different variables including biomass potential from different resources, technology used, energy efficiency conversion factor, and end-use into account. Hence, based on the livestock population data acquired for both Ethiopia and Türkiye, the bioenergy potential was calculated by using the Bioenergy Simulator tool. That value is then compared to the bioenergy potential estimated by direct calculation using formulas developed from research and literature review.

In order to calculate the bioenergy potential using the IRENA bioenergy simulator first the area or region under study is selected.

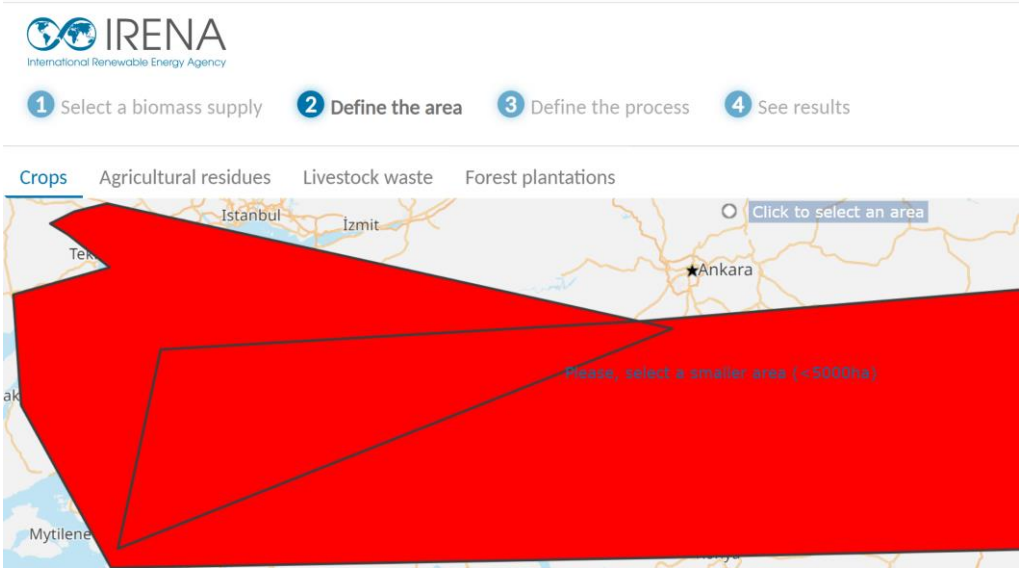

Figure 3.1. IRENA Bioenergy Simulator 1

The type of waste is then selected from the four options: Crops, Agricultural residues, livestock waste, Forest Plantations. For this thesis, livestock waste is the option selected. The tool then asks for variable inputs and specifically for livestock waste number of heads and daily biomass production per head. If value is not assigned for the latter, the simulator equates it to the total volatile solid and has set a default value of 3.65 kg/head for dairy cow or cattle. Buffalo has the highest total volatile solid or daily biomass production rate, whereas poultry has the lowest.

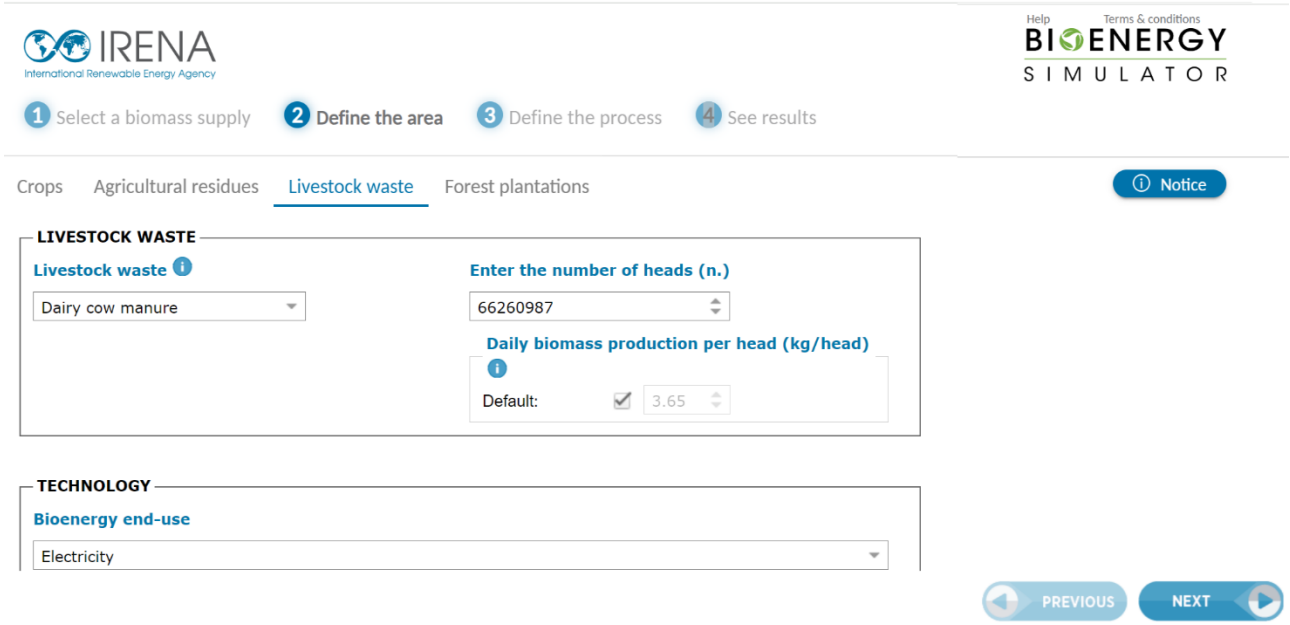

Figure 3.2. IRENA Bioenergy Simulator 2

Technology is then selected for the bioenergy end-use from the options Electricity. Heat, and Combined Heat and Power (CHP). For each option there is a bioenergy conversion technology. For Electricity the technologies considered in the tool are engines, gas turbine, and steam turbine. For heat a biomethane water heater is the conversion technology used and for heat and power a biomethane CHP- Engine is simulated. The simulator will also provide an option to input overall electrical and thermal efficiency value or assigned a default one.

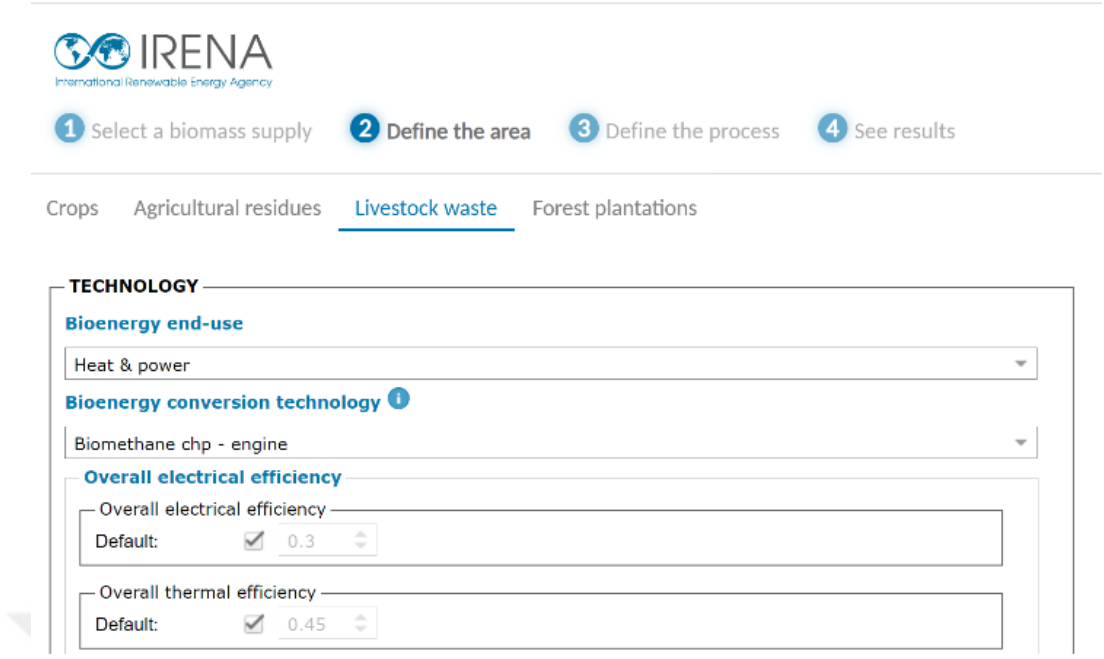

Figure 3.3. IRENA Bioenergy Simulator 3

The tool will then process all the variables and provide final value for biomethane, bioenergy, and gross electricity production.

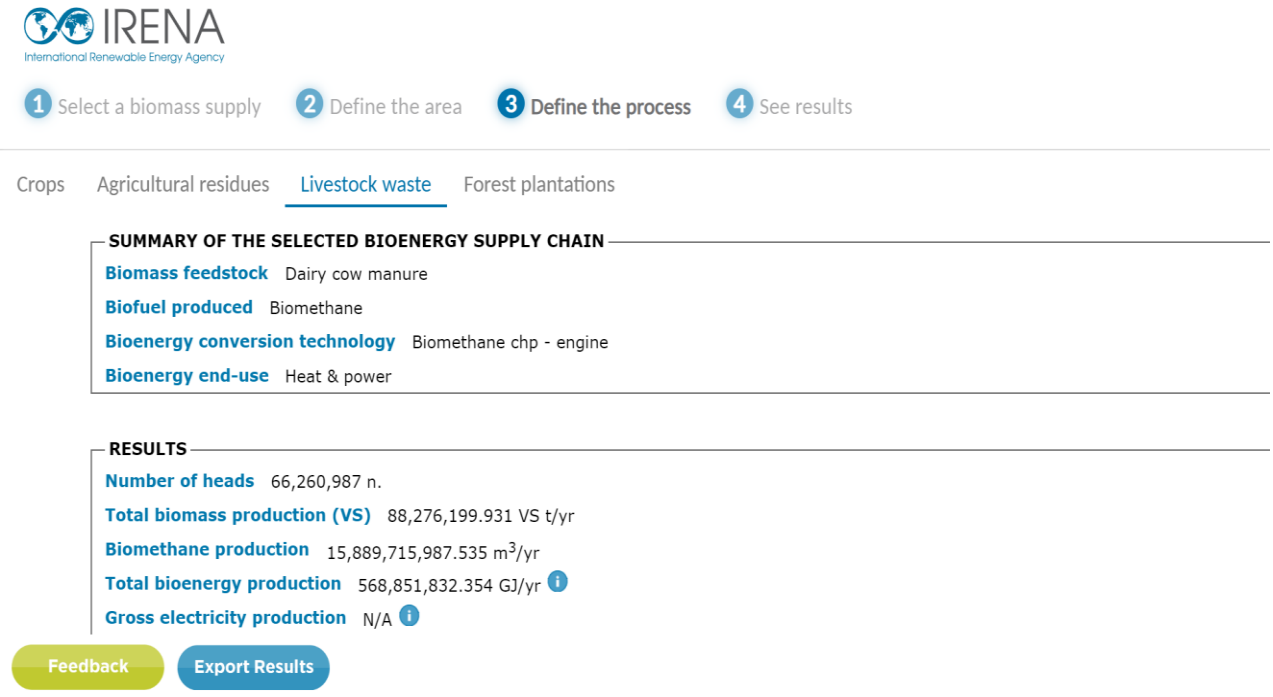

Figure 3.4. IRENA Bioenergy Simulator 4

The Biomass Energy potential Atlas (BEPA) is an open-source bioenergy potential assessment tool under Türkiye's General Directorate of Renewable Energy (YEGM). The tool also serves as a database and presents data on the number of animals, specifically for cattle, poultry, sheep and goat as well as animal waste per year (ton/year). In addition to data on livestock, the atlas also provides data on crop waste, vegetable waste, forestry waste, and municipal waste. Moreover, the default waste to energy conversion technique on BEPA is anaerobic digestion. Hence, in addition to IRENA's Bioenergy Simulator, BEPA is also used as a tool to assess the bioenergy potential from the livestock sector in Türkiye which is then used to compare the theoretical value calculated in section 4 based on formulas derived from literature and research.

BEPA calculates the bioenergy potential by taking three variables into account. These variables are:

- The livestock population
- Amount of waste per animal
- Amount of energy or methane content per waste

However, it should be noted that estimations are made in order to determine these values and not all parameters such as geography and weather condition of the regions, feeding and grazing habits of animals…etc. are considered since getting value for these metrics on a country level is difficult.

3.4. Assessment of different biogas facilities and digesters

After collecting data on biomass potential of the countries, different scaled biogas production facilities, such as big scale powerplants, medium and small-scale biodigesters were studied in order to get a full understanding on the feasibility and impact of adopting different types of biogas facilities in the regions and have a grasp of the reality on the ground. Moreover, by using data from statistics offices, national biogas program and energy frameworks, official reports, bilateral interviews, confidential source, and desk research an inventory was made on the total biogas facilities present in both countries on aggregated and disaggregated level to further support the analysis. This section will present the data on the different types of biodigesters present in both countries as well as the variables that affect the type of biodigester present.

The biodigester size and type present in both Türkiye and Ethiopia are further explored in the following section by taking all the different factors into account while analyzing the issues they address as well as the bottlenecks and gaps still present.

3.4.1. Biodigesters in Ethiopia

The types of biogas digesters that have been disseminated in the past two decades in Ethiopia range from fixed dome to Indian floating Drum, to bag digester (Kamp & Bermúdez Forn, 2016) However, the fixed dome biodigester is the main type of biodigester used in Ethiopia and the model was introduced by SNV-Ethiopia in 2008 through a Nepalese consultant and hence the Nepalese GGC 2047 biodigester with a concrete dome and was the model that is used for mason training in the initial stages of the National Biogas Programme of Ethiopia (NBPE) program. However, since the GGC 2047 digester was a 1990 model, some adjustments were made when adapted such as hanging the storage capacity. Further adjustments were made to the design by SNV Ethiopia to reduce construction costs which was mainly done by replacing the concrete dome with a brick dome. Additionally, the dimension of the digester was changed in order to fit the design specification needed to be adapted to the average Ethiopian household with change being made on the effective gas storage capacity. The buffer volume on the top of the digester was also reduced on this model. This new adjusted design can be seen in Figure 3.5 and is called the "Ethiopia 2015 Digester". Another adjusted fixed dome design for Ethiopia also includes the SINIDU biodigester and the Solid-State Digester (SSD) (SNV, 2018; Mr. Zeleke, personal communication, May 13, 2022; Mr. Abiy, personal communication, March 6, 2023).

One aspect of the biomass potential of the region is the amount of dung collected daily per animal which differs throughout the year depending on different factors such as grazing habits of the animals as well as the availability of fodder. Hence, the annual maximum average of dung collected is taken as a default value when determining the daily feeding rate of the digester or the organic loading rate of the digester. Daily gas production also determines the gas storage capacity within the digester. For the current digester models, the most effective design is developed in a way that it can store 50% of the daily gas production from maximum feeding. In addition to that, HRT, which depends on the feedstock availability as well as temperature is also a variable that is taken into account in the design with a range of 35-60 days of retention time. The design specification of the biodigester hence were adjusted according to these assumptions.

The initial small-scale fixed dome biogas digesters that were constructed in Ethiopia has sizes ranging between $4m^3$ to $12m^3$ (Gabisa & Gheewala, 2019; SNV, 2021). However, under the NBPE+ the biodigester size has also scaled up to 16 m^3 (Mr. Carlos, personal communication, September 22, 2023). Biodigester inventory for the installed biogas digesters in Ethiopia is done and is found in Appendix A. Table A.2.

According to design models obtained from NBPE general model for the Ethiopia Modified Biodigester consists of:

1. Inlet or mixing tank.
2. Stirring facilities: generally, for household plants a normal stick is used to pock and stir. However, this is not efficient. Hence a more automatic process can be explored.
3. Inlet Pipe(s) separate for cattle dung/pig manure and latrine.
    a. Pipe diameter should be 10-15 cm for liquid substrate, for fibrous substrate it is 20-30 cm, plastic or concrete pipe.
4. Digester: Digestion tanks that are thermally insulated, heating systems, mixer systems, discharge systems for sediments and substrates
5. Gas Holder (dome)
6. Manhole
7. Outlet (Displacement Chamber) and overflow opening.
8. Main Gas Pipe and Turret
9. Main Gas Valve
10. Pipeline
11. Water Outlet (Water Trap or Drain)
12. Gas Analysis Equipment
13. Gas Tap
14. Gas Lamp with rubber hose
15. Gas Stove with rubber hose pipe
16. Compost pit(s)

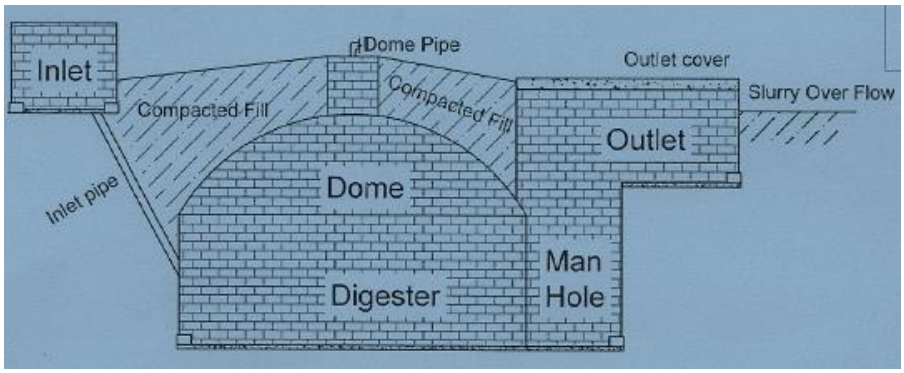

Figure 3.5. Schematic diagram of the Fixed Dome Biodigester installed in Ethiopia.

3.4.2. Biodigesters in Türkiye

Biogas production in Türkiye was first explored in 1957 by the Institute of Soil and Water Research. Following that, facilities were constructed for initial testing by the government in the 1960s with Eskişehir Soil Water Research Institute of the Ministry of Agriculture being the leading institute for biogas facilities at that time and installing 8 pilot small farm biogas projects within Eskişehir. However, lack of technical and knowledge capacity has resulted in these projects failing (Gömec, 2013).

The 1970s, however, saw an increase in government led biogas projects and following the 1980s oil crisis, more push was given to increasing biogas facilities in the country. Some of these projects were also funded and supported by international organizations such as UNICEF. One notable example was the 35 m^3 facility in Muş which facilitates the development of more facilities by the government (Kumaş et al., 2019; Gömec, 2013).

Some notable biogas facilities that have been constructed in the country that mainly uses livestock waste includes İZAYDAS in Kocaeli, which uses both animal and crop sources as substrates, Beypazarı-Ankara which uses chicken manure as well as Sütaş, which uses animal manure to provide 15% of its factory's energy needs (Gömec, 2013).

Around 42 biogas powerplants as well as landfill or wastewater to energy converting facilities were identified in Türkiye that are either operational or under construction. Confidential data sources were used along with assessing registered projected under the Impact registry of gold standard. The list of the biogas facilities can be found in Appendix A. Table 1.A. The inventory shows that Türkiye mainly has larger scale intuitional and industrial biogas facilities. One such example is the ultra-large-scale Tire biyogaz (Tire biogas powerplant) which consists of 3 plants each with 10,000 m3 capacity.

3.5. Environmental Impact Assessment of a shift to biogas

The environmental impact assessment mainly focuses on analyzing the impact a shift to biogas has in GHG emission abatement. The assessment is done by developing formulas for two scenarios which are Emission reduction due to proper manure management and Emission reduction due to using an alternative cleaner energy source. Some of the values for the variables needed in the calculation such as emission factor values and values for indirect N_2O emission due to volatilization are taken

from 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (Gavrilova et al., 2019)

3.5.1. Emission reduction due to proper manure management

The emission reduction due to proper manure management is calculated by taking CH_4 and N_2O emissions into account.

Methane emission during manure management is calculated by taking the guidelines from the IPCC GHG emission inventory, in which, either the number of livestock or total animal manure required to the biodigester in the region is identified and that is multiplied by the emission factor as specified by IPCC is used (Gabisa & Gheewala, 2019; Karaca, 2019; Gavrilova et al., 2019).

$$CH_{4\ EMM}=N_{TLU} \times EF \quad (3.7)$$

$$CH_{4\ EMM}=DM_P \times EF \quad (3.8)$$

Table 3.3. Total N_2O emission from the livestock sector

N_2O Emission (million Tonnes of CO_{2eq})	ETHIOPIA 2020	ETHIOPIA 2021	TÜRKIYE 2020	TÜRKIYE 2021
Cattle	32,657,492	30,857,035	10,661,337	10,625,845
Sheep	3,499,443	3,148,399	3,361,410	3,604,846
Goat	5,322,876	4,799,975	1,199,867	1,235,448
Poultry	245,552	255,147	1,693,295	1,739,217

On the other hand, N_2O emission from manure management data is directly taken for the national level. Data ETL (extraction, transformation, and loading) is done from FAO database as well as IPCC GHG Inventory to obtain the N_2O emission values as well as the CH_4 emission factors which are given as Kg/TJ. The GHG emissions are converted to carbon dioxide equivalent ($CO_{2\text{-}eq}$) over100 years of global warming potential (GWP).

The total N_2O emission from livestock waste takes into account enteric fermentation on top of emission from manure management, emission from manure left on pasture and emission from manure directly applied to the soil. The breakdown for this can be found in Appendix C, Table C.1 - Table C.3.

Methane emission during the biogas production process is also considered while doing emission abetment comparison, and for that, only leakage is taken into account since methane emission is considered as if it is zero in anaerobic digestion. Leakage depends on the biogas production and the methane collection efficiency which differs based on the type of digester selected as well as region (Gabisa & Gheewala, 2019).

$$CH_{4\ EL} = CH_{4\ Produced} \times (1\text{-}CE) \times EF \quad (3.9)$$

In which: CE is a unitless collection efficiency given in percentage and differs based on the type of biodigester used. The estimated methane emission is then converted to $CO2_{eq}$ unit in order to have the full picture of GHG emission abetted.

3.5.2. Emission reduction by energy substitution

GHG emission reduction from the substitution of fossil fuels is calculated after analyzing the overall fuel use of both regions and two scenarios are considered. The first is GHG emission due to direct use of biomass and fossil fuel and hence emission due to fuel consumed in the household that isn't biogas is estimated. This is calculated according to the guidelines provided under stationary combustion by IPCC's GHG emission inventory report and multiplying the amount of fuel combusted by a household or a farm by the default emission factor of a given GHG for that specific fuel.

The second scenario is emission due to electricity production from fossil fuel which is applicable only to Türkiye. In order to do so data on electricity production by fuel type as well as electricity consumption data by sector is first estimated based on data from Turkstat, official statistics reports, and report from Türkiye Elektrik İletim A. Ş (TEİAŞ) or Turkish Electricity Transmission Corporation. The electricity generation data by fuel type is used to estimate the amount of fossil fuel used and based on that the GHG emission is estimated in the similar manner to that of scenario 1 in accordance with IPCC's GHG Emission Inventory guidelines.

3.6. Economic Impact Assessment of a shift to biogas

In order to make an assessment on the economic impact of biogas technologies and the use of biogas, first data is taken on the energy and electricity costs of the regions. The energy and electricity costs of the regions is estimated by taking electricity and energy expenditure data on household level including expenditure on natural gas, coal, wood, and traditional biomass from country statistics

agencies and annual census data. Additionally electric tariff on household level is also calculated. The total value is then compared to the capital and maintenance cost of small-scale and farm level biodigesters from reports by implementing bodies and bilateral interviews conducted. Table 3.4. – Table 3.6. shows the electricity and gas tariffs of the countries.

Table 3.4. Household electricity prices by consumption bands for Türkiye

End-user average price (1) (Cents(2)/kWh)				
Consumption bands	2020	2021		2022
(kWh)	**Period II**	**Period I**	**Period II**	**Period I**
T < 1 000	73.7	80.2	91.1	128.1
1000 ≤ T < 2500	73.6	79.7	90.4	130.7
2500 ≤ T < 5000	73.4	79.4	90.3	140.9
5000 ≤ T < 15,000	73.0	79.1	90.0	162.0
T ≥ 15,000	73.2	78.7	89.5	183.3

TÜİK, Elektrik ve Doğal Gaz Fiyatları, I. Dönem: Ocak-Haziran, 2022

TurkStat, Electricity and Natural Gas Prices, Period I: January-June, 2022

(1) End-user average price refers to price paid for 1 kWh electricity by household end-user which includes all taxes

(2) Local currency unit (Turkish Lira is used as the value in USD will be very low.

Table 3.5. Natural gas prices by consumption bands for Türkiye

End-user average price (1) (Cents(2)/m^3)				
Consumption bands (m^3)	2020	2021		2022
	Period II	**Period I**	**Period II**	**Period I**
T < 522	190.4	197.8	230.4	310.2
522 ≤ T < 5220	184.7	191.7	221.5	294.4
T ≥ 5220	185.1	189.8	225.6	293.2

TÜİK, Elektrik ve Doğal Gaz Fiyatları, I. Dönem: Ocak-Haziran, 2022

TurkStat, Electricity and Natural Gas Prices, Period I: January-June, 2022

(1) End-user average price refers to price paid for 1 kWh electricity by household end-user which includes all taxes

(2) Local currency unit (Turkish Lira is used as the value in USD will be very low.

Table 3.6. Electricity Tariff for Residential sector by consumption block for Ethiopia

Tariff amendment	**As of Dec. 2019 onward**	**As of Dec. 2020 onward**	**As of Dec. 2021 onward**
Tariff Category kwh/month	Currency/kwh	Currency/kwh	Currency/kwh
1st block Up to 50kwh	0.273	0.273	0.273
2nd block Up to 100kwh	0.5617	0.6644	0.767
3rd block Up to 200kwh	1.0622	1.3436	1.6250
4th block Up to 300kwh	1.2750	1.6375	2.0000

The electricity tariff value is taken from Ethiopia Electricity utility for Ethiopia and the electricity and natural gas prices for Türkiye are taken from Turkstat data.

In addition to tariff data, household energy expenditure data is also collected by taking household energy consumption from other fuel types such as firewood, coal, cow dung, and LPG into account since household energy demand for both countries don't only depend on Natural gas and electricity as seen in Table 3.7. World Bank data is used to convert consumption and expenditure values by taking CPI (Consumer Pirce Index) inflation into account in order to standardize the finding.

Table 3.7. Average Household Energy Price for Türkiye and Ethiopia

FUEL	Ethiopia Rural HH Price	Türkiye Rural HH Price
Natural Gas (Currency/m3)	0.02448	0.206
LPG (Currency/m3)		0.00622
Firewood (Currency/Kg)	1.65	2.75
Charcoal (Currency/Kg)	5.1	1.06
Cow Dung (Currency/Kg)	1.656	-
Electricity (Currency/KWh)	0.4591	0.8485
*Local currency unit (Turkish Lira for Türkiye and Ethiopian Birr for Ethiopia) are used here as their value in USD will be very low		

The total electricity and energy expenditure of a household or farm is then compared to the cost of the biogas plant which includes both the initial capital cost and maintenance cost in order to assess the economic feasibility of using small-scale biodigester. Subsidies and levies can also be addressed if relevant.

In this analysis another dimension is also explored which is the intersectionality between electricity access and electricity affordability. To do so, Energy Sector Management Assistance Program (ESMAP) and Sustainable Energy for All (SE4All)'s Multi-Tier Framework is used as a benchmark in which the cost of a tier-3 energy access (365 kWh annually) is less than 5% of household income (Bhatia & Angelou, 2016).

3.7. Assessing Government and regulatory frameworks, incentives, and policies

The environmental and energy objectives in national policies and frameworks of the country determine the extent to which renewable energy is integrated in the energy mix and how waste is utilized within the energy framework. Hence policy frameworks and targets are analyzed from both Türkiye and Ethiopia and assessment is done by checking these main points:

- Frameworks and policies specifically target or mention biogas.
- Biogas for rural community and agricultural sector is considered.
- Annual/Periodic goals and targets regarding biogas are set.
- Annual/Periodic goals and targets regarding biogas are met.
- Biogas in the energy mix is a point of discussion.

- Biogas is explored as an energy source to address energy challenges.
- Incentives are in place to increase biogas utilization.

The policy and frameworks that are explored for the countries are the National Electrification Plan (NEP), the flagship national biogas program of Ethiopia NBPE and NBPE+, the African Biogas Partnership Programme (ABPP), as well as the Africa Bioenergy Policy Framework for Ethiopia. For Türkiye, BAT Reference Document (BREFs), the National Renewable Energy Action Plan, the National Energy Efficiency Action Plan (NEEAP), the Renewable Energy Support Mechanism (YEKDEM), VISION 2023, EU's Renewable Energy Directive, and the European Green Deal were all assessed.

4. RESULTS

4.1. Biogas and Electricity generation Potential

The formulas derived in 3.3.2 are used to calculate the theoretical biogas potential of livestock waste in one fixed year for Ethiopia and Türkiye both on a national level as well as rural household level to better understand the overall impact of small-scale biodigesters. Moreover, methodology presented by (IRENA, 2016) is used as a guide to calculate the effective biogas production potential on a household level specifically since it takes the solid retention time, temperature of the regions as well as biogas digester capacity into account. These values are observed in parallel to what is obtained by using IRENA's Bioenergy Simulator and BEPA.

4.1.1. Calculated Theoretical Biogas Potential

The formulas derived in section 3.3.4. are used in order to calculate the total theoretical biogas potential (BP_T) for Türkiye and Ethiopia both in National and Household level as can be seen in Table 4.2 and Table 4.3 as well as Figure 4.1. According to formula 3.3., in order to calculate the Theoretical biogas potential, the usable manure (U_M) and the biogas yield from manure (BY_M) value should first be determined. The usable manure value in the tables is calculated using formula 3.1 and hence first the independent variables such as the number of livestock on national and household level as tropical livestock unit (N_{TLU}), the daily manure production rate from livestock (DM_P), and Volatile Solid Content (VS) in manure are estimated.

The livestock population value from Table 3.1. and Table 3.2. is converted to tropical livestock units based on Formula 3.2 and by using average weight of livestock in the regions in order to get the Number of livestock as TLU under Table 4.1. As the average weight of livestock differs from region to region literature relevant to the countries being discussed is mainly used to estimate the weight as can be seen in Appendix B under Table B.1 and Table B.2.

Table 4.1. Türkiye and Ethiopia Number of Livestock in TLU

Livestock Type	**Number of Livestock** (Türkiye – Head)	**Number of Livestock** (Ethiopia - Head)	**Average Weight of Livestock** (Türkiye - Kg)	**Average Weight of Livestock** (Ethiopia - Kg)	**Number of Livestock as TLU** (Türkiye - Head)	**Number of Livestock as TLU** (Ethiopia - Head)
Cattle	17,220,903	66,260,987	310	242	5,338,480	16,035,159
Sheep	35,194,972	38,013,272	58	28	2,036,029	1,052,208
Goat	10,922,427	45,716,091	56	30	609,144	1,371,483
Poultry	353,561,499	41,350,684	3	1	883,904	43,211

As can be seen both in Table 4.1. Ethiopia has a very high livestock population and in particular a very high cattle population which contributes to its high theoretical biogas capacity. On the other hand, Türkiye also has a very high poultry population in comparison to Ethiopia and hence biogas production potential from poultry litter is much higher in Türkiye than that of Ethiopia.

Similar to how the average weight of livestock was estimated, the daily manure production, total volatile solid values, and biogas yield value are also determined by referencing literature relevant to the countries as seen in Appendix B, under able B. 3 – Table B.8 in the Appendix B showcases the values for these variables found in literature along for Türkiye and Ethiopia respectively. For variables in which more than one value is recorded from literature, the mean, the standard deviation, and the standard error is calculated and the calculated mean value for the variables is the one used to calculate the total theoretical biogas potential (BP_T). Multiplicative propagation of error based on the error factor determined for the Total Volatile Solid and Biogas Yield from Manure is also used to calculate the margin of error used for the theoretical biogas production under Table 4.2 and Table 4.3. which shows the annual calculated theoretical biogas potential for Türkiye and Ethiopia respectively. Availability factor is not taken into account while calculating the theoretical biogas potential on a national level as obtaining a full picture on feeding, grazing, and collection habits on a country level is not feasible and accurate estimation couldn't be done. Hence, the biogas potential results under Table 4.2 and Table 4.3 the maximum obtainable theoretical biogas capacity of the countries.

Table 4.2. Türkiye's Theoretical Biogas Potential

Livestock Type	**Number of Livestock as TLU** (Head)	**Daily Manure Produced** (Kg)	**Total Volatile Solid** (%)	**Usable Manure** (Kg)	**Biogas Yield from Manure** (m3/KgVs)	**Theoretical Biogas Potential** (m3/Year)
Cattle	5,338,478	19.20	0.12	12,444,000	0.36	1,623,786,535 ± 216,783,464
Sheep	2,036,029	2.72	0.28	1,548,138	0.28	156,807,052 ± 56,589,703
Goat	609,144	1.81	0.20	221,595	0.21	16,580,849 ± 8,857,470
Poultry	883,904	0.09	0.26	21,1556	0.50	3,870,930 ± 637,154

Table 4.3. Ethiopia's Theoretical Biogas Potential

Livestock Type	**Number of Livestock as TLU** (Head)	**Daily Manure Produced** (Kg)	**Total Volatile Solid** (%)	**Usable Manure** (Kg)	**Biogas Yield from Manure** (m3/KgVs)	**Theoretical Biogas Potential** (m3/Year)
Cattle	16,035,159	13.73	0.153	33,787,640	0.365	4,501,358,400 ± 1,839,090,202
Sheep	1,052,207	0.36	0.32	120,779	0.29	12,784,467 ± 2,532,458
Goat	1,371,483	0.45	0.25	151,576	0.29	16,044,348 ± 6,289,858
Poultry	43,211	0.079	0.021	74	0.105	2,841

The VS and biogas yield amount for poultry differs for Türkiye and Ethiopia with poultry litter having more dry content in Türkiye compared to Ethiopia which might be due to feeding habits. The total theoretical biogas potential of the countries is then calculated to be 1.8 billion m^3 and 4.53 billion m^3 for Türkiye and Ethiopia respectively. However, despite the high calculated theoretical potential, the utilized biogas capacity in the countries is much lower which can be due to capacity, finance, resources, knowledge, and policy limitation which are further discussed in section 4.5.

Based on the theoretical biogas potential estimated for a national level, the higher and lower electricity potential from biogas is estimated by taking the calorific value provided by IEA for biogas which is 16-28 MJ/m^3. The CH_4 content in the biogas in literature differs with most being in the range of 50-75%. However, for the calculations, a smaller range of 60-65% is used. (Kamp & Bermúdez Forn, 2016 ; Karaca, 2019; Ozsoy & Alibas, 2015) A biogas engine efficiency of 25% is also used.

Table 4.4. Total electricity generation potential for Türkiye and Ethiopia on a National level

Country	Theoretical Biogas Production (M^3/Year)	Lower Theoretical Electricity Potential (GWh/Year)	Higher Theoretical Electricity Potential (GWh/Year)	Electricity generated (GWh/Year)
Türkiye	1,801,045,367.03	4802.79	9,105.28	1200- 2276
Ethiopia	4,530,190,056.85	12,080.51	22,902.63	3020- 5726

The average electricity generation potential from biogas is calculated to be 1738 GWh and 4373 GWh for Türkiye and Ethiopia respectively. Despite the calculated high generation value, no data was recorded for electricity generation form biogas for Ethiopia despite the presence of small-scale biodigesters within the country as can be seen in the biogas digester inventory in Appendix A in Table A.2. This shows that despite the country's biogas potential, the biomass is still being utilized on small, off-grid levels and electricity generation for the grid from biomass is yet not realized. Moreover, the electricity that can be generated from the total biogas production from Table A.2 is only 3-7 GWh compared to the calculated theoretical electricity generation of 4373 GWh. Hence, more should be done in order to utilize the country's biomass potential to the fullest while integrating biogas into the energy mix. On the other hand, Türkiye's electricity generation from biogas has been on an upward trend with electricity generation from biogas being recorded as 4082 GWh for Türkiye as of 2021 (IRENA, 2023). Hence, the livestock sector alone can contribute to 42.6% of the current total generation using animal manure alone.

Since the thesis is mainly centered around small-scale biogas potential, theoretical biogas potential and effective biogas potential are also calculated on a household level specifically for rural communities. The main parameters that were considered here are the average herd size per rural household for the countries as well as the manure availability factor which is also the manure collection coefficient, and these were estimated based on literature. Table B.4.1 - Table B.4.2 in Appendix B showcases the values obtained for these two variables along with the source. Although the herd size is taken on an average across the countries, it is noted that the average herd size across the country differs especially in Ethiopia due to the high presence of pastoralist communities in the Oromia, Afar, Gambella, and Somalia regions, in which the number of ruminants animals and especially goat is very high. Hence, the theoretical biogas potential is much higher for pastoralist communities compared to farming communities. Similarly for Türkiye regions such as Konya, Ankara, Balıkesir, Manisa, and Denizli have a very high animal population compared to other regions as can be seen from the livestock maps obtained from BEPA under Appendix C. In the case of

Ethiopia, small-scale biogas dissemination is not as widespread in the pastoralist regions under NBPE program in Ethiopia with only dissemination to these regional states starting under the NBPE+ in 2017 (Mr. Carlos, personal communication, September 22, 2023; SNV, 2017). As for Türkiye, as can be seen under the list of biogas plants in Türkiye in Table A.3 in Appendix A, large scale biogas plants are present in these regions but small scale biodigester presence can still not be deduced. Hence, the total theoretical household biogas potential is estimated on average for all regions without separating the outliers.

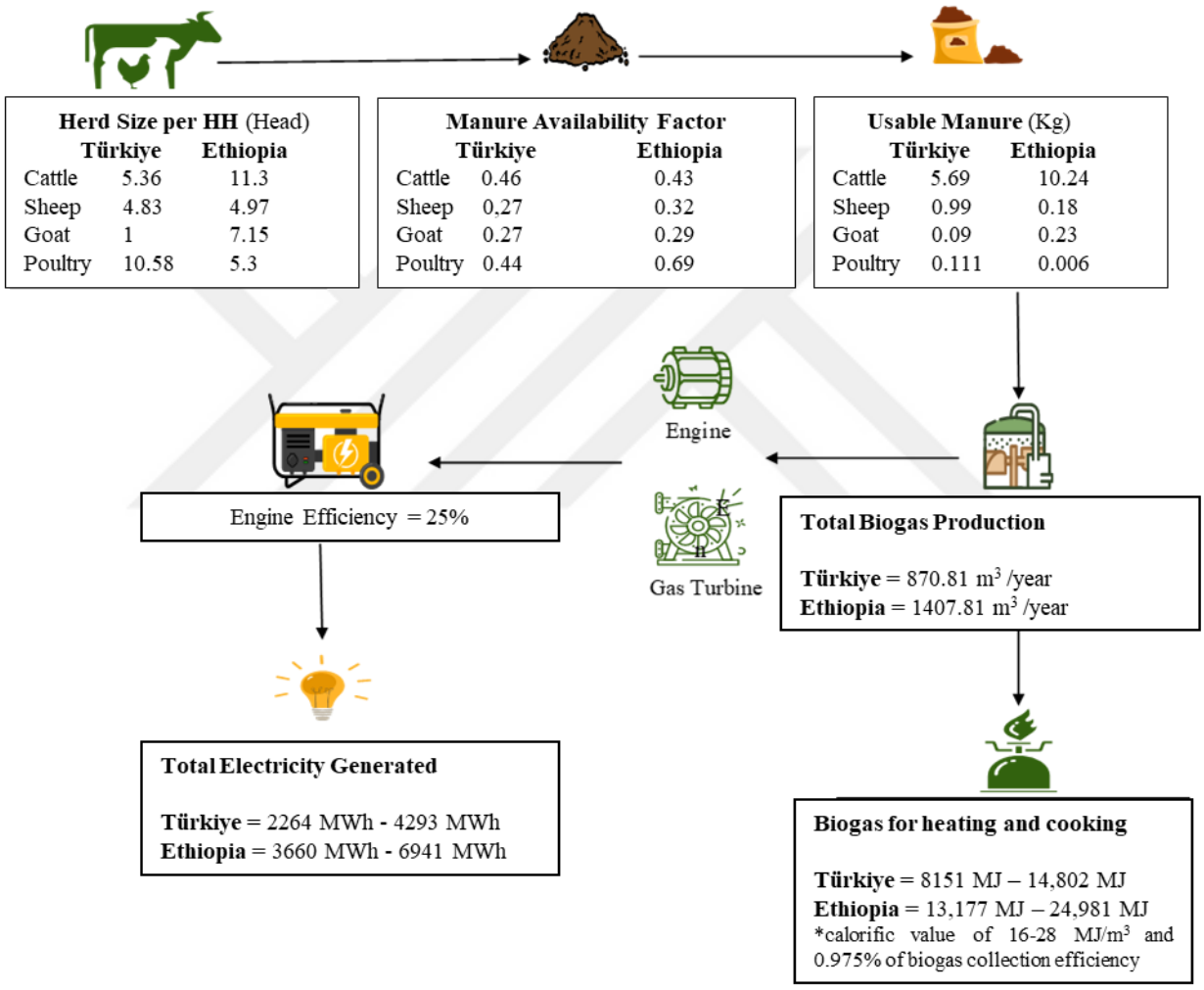

Figure 4.1. Annual Theoretical biogas potential and electricity generation of Turkish and Ethiopian rural Households

The diagram in Figure 4.1 shows the calculated annual theoretical biogas potential for rural Turkish and Ethiopian households that can be obtained from usable animal manure by taking the availability factor which is the manure collection efficiency from Appendix B Table B.10. Manure Collection Efficiency Table B.10 into account as well the theoretical electricity generation potential

by taking the calorific value range of 16-28 MJ/m^3, a methane content of 60-65%, and a biogas engine efficiency of 25% similar to that of national level calculations. Certain variables such as the daily manure production per animal, Total Volatile Solid percentage and the average biogas yield values are the same as the values used in Table 4.2 and Table 4.3.

In addition to the total theoretical biogas potential, the effective household biogas potential is also estimated on a household level to account for retention time, temperature and biodigester size. The hydraulic retention time is calculated for different biodigester sizes based on daily feedstock available which takes the total amount of manure produced from every livestock type as well as the water added to the mix. The feedstock to water dilution ratio is taken as 1:1 and 1:2 ratio for Ethiopia and Türkiye respectively. The traditional fixed dome biodigester generally have water to feedstock ratio of 1:1. However, water availability and access is a concern for small scale rural households and in the case of Ethiopia water scarcity is one of the challenges faced when it comes to biogas digester dissemination (Mr. Zeleke, personal communication, May 13, 2022). Hence, work has been done in improving the biodigester design in order to accommodate for this problem as discussed in later sections and a lower feedstock to water dilution ratio was also used to do this calculation due to that. The average daily feedstock for Türkiye and Ethiopia is then calculated to be 0.154 m^3 and 0.136 m^3 respectively and HRT is estimated based on that.

Table 4.5. Hydraulic retention time for small scale biodigester

Biodigester Volume (m^3)	**Feedstock Retention Time ETHIOPIA (Days)**	**Feedstock Retention Time TÜRKIYE (Days)**
2	15	13
4	29	26
6	44	39
8	59	52
10	73	65
12	88	78

The annual mean temperature value is taken from the World Bank's Climate Change Knowledge Portal. As can be seen in Figure 4.2, the countries' temperature map shows variation across regions. Hence, two temperature ranges are used to calculate the yield factor for Türkiye and 4 temperature ranges are used for Ethiopia.

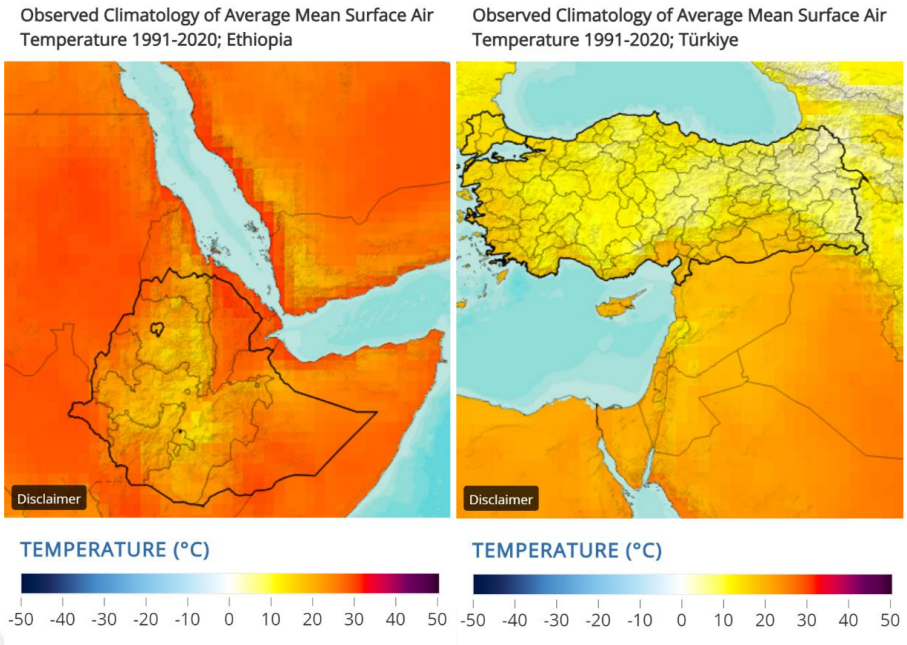

Figure 4.2. Heat Map showing Average Mean Surface Air Temperature for the countries.

Based on this temperature range, the daily effective biogas potential for household that use small-scale biodigester with 2-12 m^3 capacity is calculated.

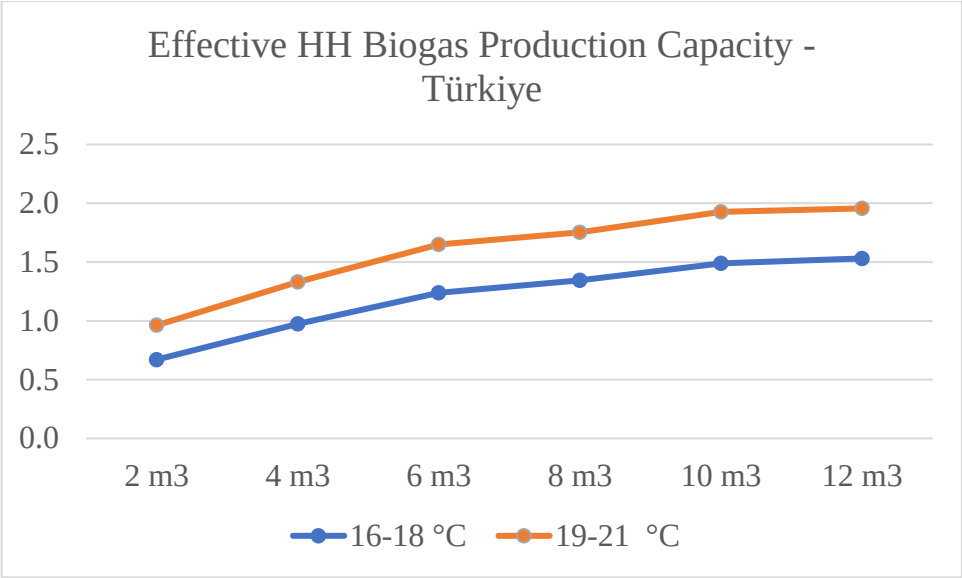

Figure 4.3. Effective Household Biogas Production Capacity - Türkiye

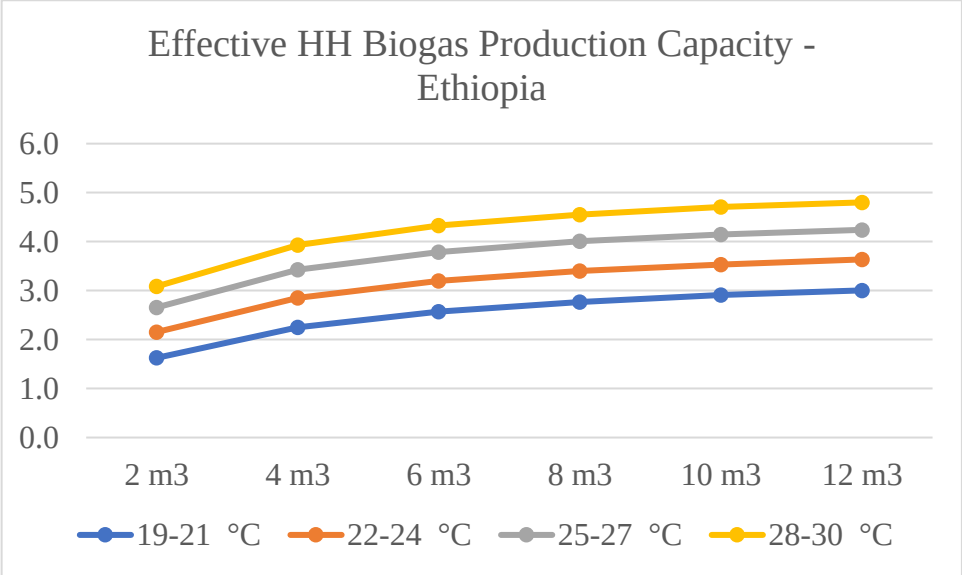

Figure 4.4. Effective Household Biogas Production Capacity - Ethiopia

The effect of temperature in total biogas production is seen in Figure 4.3 and Figure 4.4. The biogas production rate increases with an increase in temperature with regions with higher annual air surface temperature having a higher biogas yield. For Türkiye's highest temperature range, which is between 19-21 °C, the effective biogas production is calculated to be 1.957 m^3. On the other hand, for Ethiopia, the highest temperature range is 28-30 °C and the effective biogas production is calculated to be 4.801 m^3. Controlling the temperature and ensuring a stable temperature condition in digesters is essential, this is especially important in Türkiye, in which the average air temperature

fluctuates seasonally, as radical drop or increase in digester temperature as well as frequently fluctuating temperature negatively impacts both the gas production and the digester's functioning. For domestic level and small-scale digesters, the temperature can be regulated by implementing different construction techniques and tips such as:

1. Constructing the digester in a very sunny place/in a space with a direct access to sunlight
2. Maintaining 40 cm top filling on dome
3. Composting can be carried out on top of the digester dome with the thickness of the composting facility being 2 to 4 feet. Covering the composting facility with mud plaster will also prevent the heat produced during composting from leaving and hence can provide optimum temperature for the digester especially during colder seasons. With or without composting, covering the dome is a good practice for maintaining temperature.
4. Preparing the feedstock mix in the morning and leave it to heat up till the afternoon before being added into the digester.

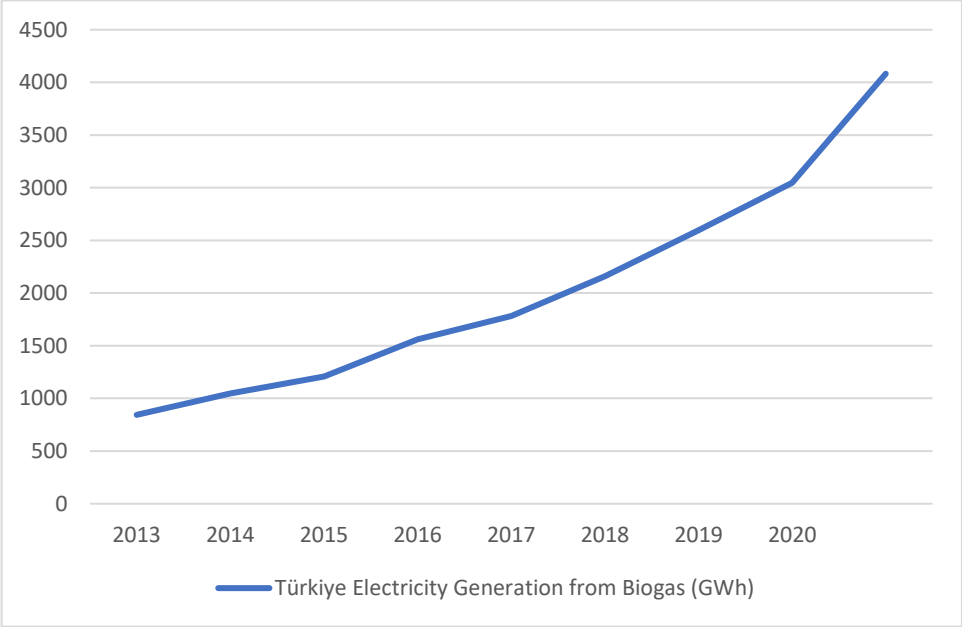

Figure 4.5. Türkiye Electricity Generation from Biogas (GWh)

On a household level, apart from the electricity generation values in Figure 4.1, average daily electricity generation for households that use small scale biodigester is also calculated based on the effective biogas potential as seen in Figure 4.3 and Figure 4.4. Depending on the biodigester scale and temperature, the daily biogas production for the households can range between 0.677 m^3 - 1.957 m^3 for Türkiye and 1.673 m^3 - 4.801 m^3 for Ethiopia which can generate 0.7332 KWh - 3.71 KWh and 1.81 KWh - 9.1 KWh electricity per day depending on biodigester size and temperature and also

after factoring a 0.975 biogas collection efficiency from fixed dome biodigester as set by (Gabisa & Ghewalla, 2019).

The average annual energy consumption for Ethiopian and Turkish rural households is 46,917 MJ and 38,656 MJ respectively as can be seen in Figure 4.6. As mentioned previously, the energy discourse in a lot of developing and emerging economies addresses the food-water-energy nexus and highlights energy access for cooking. This is also reflected in Ethiopia's energy consumption in which Ethiopia's daily energy usage is mainly due to cooking with the baking of injera taking the majority of the household energy consumption (Mr. Getu, personal communication, April 12, 2022). The lack of efficient cookstoves as well as efficient *mitad* contributes to the high energy consumption and mainly firewood. Additionally, rural Ethiopian households have also a very low access to electricity.

Within the clean cooking sector globally, there is still more work to be done in adapting commercial propane and butane stoves into efficient cookstoves that utilize biogas. Generally, biogas stoves require to meet a certain biogas and air ratio and a ratio of 1:10 is specified in literature (Rajendran, Aslanzadeh, & Taherzadeh, 2012). Additionally, the adjustment on traditional cooking stoves and the design and development of stoves is made by taking other non-technical aspects into consideration as well. These include the cooking habits of the community, the food culture, as well as the needed local requirement such as ease of handling of the biogas stove, ease of cleaning, temperature adjustability…etc. This is also one of the main challenges that is faced in cultures with complicated cuisines such as Ethiopia in which a biogas stove couldn't meet the needed high temperature requirement in order to prepare the local staple *Injera* and to a lesser extent local stews that require longer cooking time. It should also be noted that, constant utilization of biogas stove on high temperature can result in malfunctioning of the stove which is one of the main bottlenecks in the development and production of biogas stove in cultures that require high temperature to prepare their cuisine (Rajendran et al., 2012; Roubík & Mazancová, 2019). However, in general, biogas cookstoves are similar to conventional appliances that run on commercial gas fuels.

The biogas requirement for cooking is also taken as 0.3 m^3 - 0.9 m^3 per person per day based on reviewed literature (Raja & Wazir, 2017). In the case of Türkiye, the lowest range is taken as cooking is less time intensive process. For Ethiopia, an average value is taken at 0.6 m^3 when looking into the biogas amount that is needed for cooking per household. Again, it should be noted that the biogas amount needed varies depending on the country and the cuisine. Based on the assumed biogas consumption value and by taking world bank estimates for number of people per rural household, it is calculated that 0.96 m^3 and 3 m^3 biogas is utilized for cooking per day in Türkiye and Ethiopia

respectively and this makes up 49 % and 62.5 % of the maximum effective biogas that can be produced in rural Türkiye and Ethiopia households respectively. Biogas cookstove are also considered to be efficient cookstoves due to having a higher efficiency than that of traditional stoves. Hence, a shift towards biogas for cooking can address issues related to energy efficiency as well.

In addition to providing an efficient clean cooking solution, the utilization of biogas stoves also eliminates indoor pollution and hence addresses pulmonary health risks and issues that mainly affect women and children as well and is a technology that should be explored more.

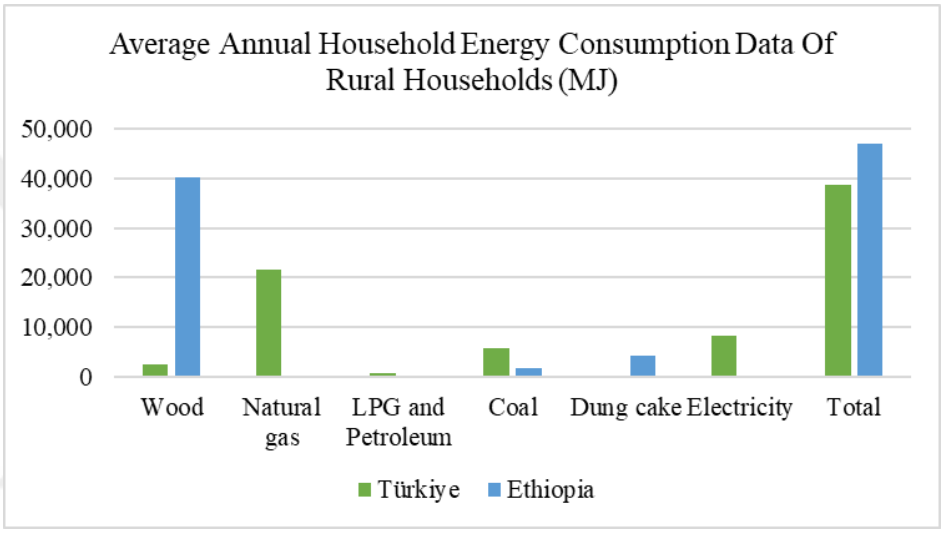

Figure 4.6. Average Annual Energy Consumption in Rural Households

On the other hand, due to heating, the demand for Natural gas is really high in the average rural Turkish household. This will be further discussed in Section 4.5 but the spike in the natural gas price over the past few years can severely affect the energy affordability of Turkish households that mainly relies on Natural gas. However, the replacement of natural gas by biogas is still not feasible in Türkiye as that required upgrading and biomethanation which is further discussed in section 4.6. Nonetheless, substituting biogas in lieu of other energy sources or adopting biogas to the daily energy consumption of households can still address few of the energy access challenges in rural households. The maximum calculated effective biogas potential from Figure 4.3. and Figure 4.4. can be equated to 49,066.22 MJ and 20,000.53 MJ for Ethiopia and Türkiye respectively. This can fully replace the total household energy need in rural Ethiopia as well as improve the energy security and accessibility of the households and can replace up to 52% of Türkiye's rural households energy needs or adds onto the total household energy consumption and increase households' total energy access.

This section analyzed the potential of heat and electricity that can be generated from biogas on a small household level by looking into electricity generation from biogas and biogas potential for clean cooking. It should also be noted that Combined Heat and Power (CHP) generation is also possible via biogas. A CHP enables both the production of heat and electricity since it has both a turbine or engine for electricity generation and a heat recovery system. The most accessible small-scale CHP uses internal combustion engine and have an efficiency that ranges between 80-95% and can generate between 5 KW to 1 MW of power (UNEP, 2017). However, this may not be very feasible for household level especially due to the cost of CHP and due to not being able to produce biogas on a household level that is sufficient enough to run the CHP. Additionally, literature also shows that the available heat for utilization generated in a CHP is lower when manure is used as a substrate (Siddiqui, Zerhusen, Zehetmeier & Effenberger, 2020). However, CHP has a comparatively higher efficiency than that of separated conversion (Clarke Energy, 2021). Moreover, the heat generated in the CHP plant can also be utilized to heat the digester itself which is beneficial in the case of biodigesters in Türkiye where the average temperature might go down below the preferred range. Hence the potential of using CHP in the scope of small-scale rural biogas production should be explored more. Novel and emerging technologies such as micro gas engines with a generation capacity less than 5 KW are being developed and might be more fitting for small scale biodigesters if fully developed and commercialized (UNEP, 2017).

4.2. Environmental Impact Assessment of a shift to biogas

4.2.1. Emission reduction due to proper manure management

As can be seen from the data in section 3.6.1. Türkiye and Ethiopia have a high level of N_2O emission from the livestock sector. Moreover, while looking at the data, it can be seen that Ethiopia has a much higher emission due to manure left on pastures, which makes up 90% of the total livestock N_2O emission of the country. The value is also high comparatively to Türkiye. The calculated livestock manure production from Ethiopia and Türkiye for 2021 was 80.72 million tonnes and 39.87 million tonnes respectively with Ethiopia having 2 times more manure production. However, the N_2O emission due to manure management is 3 times higher in Ethiopia than that of Türkiye. This can be due to the weather condition of the regions, the grazing habits of livestock, or the manure management and manure collection practices in place. Based on the bilateral interviews conducted (Mr. Zeleke, personal communication, May 13, 2022), the latter is a challenge prominent in the country and the data obtained highlights how the lack of waste management framework on a country as well as sectoral level can contribute to an increase in GHG emissions. In addition to an increase in GHG

emission, manure being left on pasture or being directly applied to the soil also affects the soil's organic carbon (SOC) cycle.

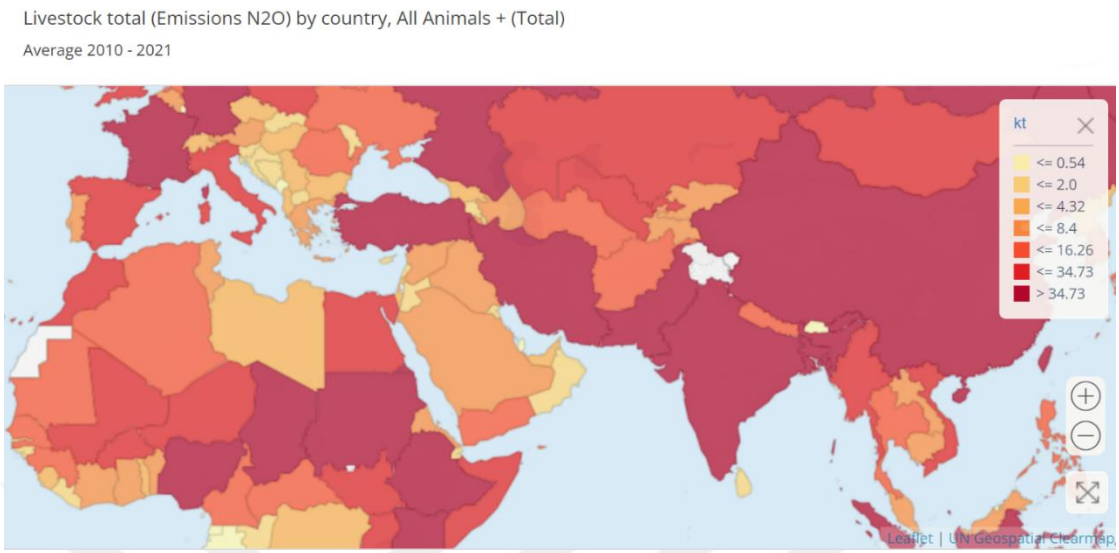

Figure 4.7. N_2O total emission map for all livestock types

Methane emission for manure management on the other hand is calculated by extracting methane emission factors for different types of livestock based on the guidelines provided under IPCC's GHG emission inventory. The parameter "Annual Average temperature is between 15 °C and 25 °C" is applied when taking the methane emission factor for both countries. The methane emission factor for goat, sheep, and poultry is the same for Ethiopia and Türkiye. However, for cattle, the value differs as FAO stat offers differing emission based on regions and a higher emission value was assigned for Türkiye which can be seen on the calculated methane emission value for cattle in Table 4.6. This shows how geography and weather can further exacerbate the GHG emission in livestock or agricultural sector and hence, this factor should be taken into account while developing environmental policies.

Table 4.6. CH_4 Emission from manure management

	Methane Emission Türkiye (Tonnes of CO_{2eq})	**Methane Emission Ethiopia** (Tonnes of CO_{2eq})
Cattle	2,535,777.97	400,878.97
Sheep	8,144.12	4,208.83
Goat	2,588.86	5,828.80
Poultry	397.76	19.45

On a household level, the methane emission due to manure management is estimated at 335 Kg of CO_{2eq} for Ethiopia and 4466 Kg of CO_{2eq} for Türkiye with the majority of the emission for Türkiye coming from cattle and due to the higher emission factor used.

Based on these calculations the emission reduction on National level due to proper manure management can go up to 39.5 million Tonnes of CO_{2eq} for Ethiopia and 19.75 million Tonnes of CO_{2e} for Türkiye. Similarly on a household level, based on the herd size in a household, the total GHG emission reduction in the livestock sector due to proper manure management and utilization is calculated to be 6527 Kg of CO_{2eq} and 4761 Kg of CO_{2eq} for Ethiopia and Türkiye respectively annually. These values can change or can be reduced depending on the manure management practice and waste framework set in place as well as with change in grazing habits and space.

4.2.2. Emission reduction by energy substitution

Based on IPCC's GHG Inventory, the GHG emission from the energy sources used on a household level in Türkiye and Ethiopia are given in Figure 4.8 and Figure 4.9. For each GHG, the emission factor used differs between the countries.

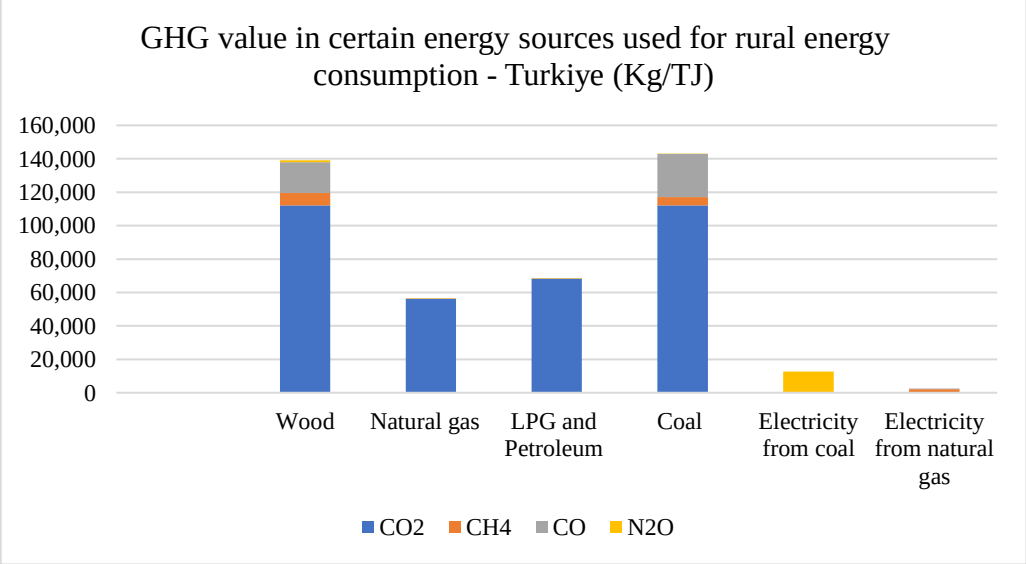

Figure 4.8. GHG value in certain energy sources used for rural energy consumption - Türkiye (Kg/TJ)

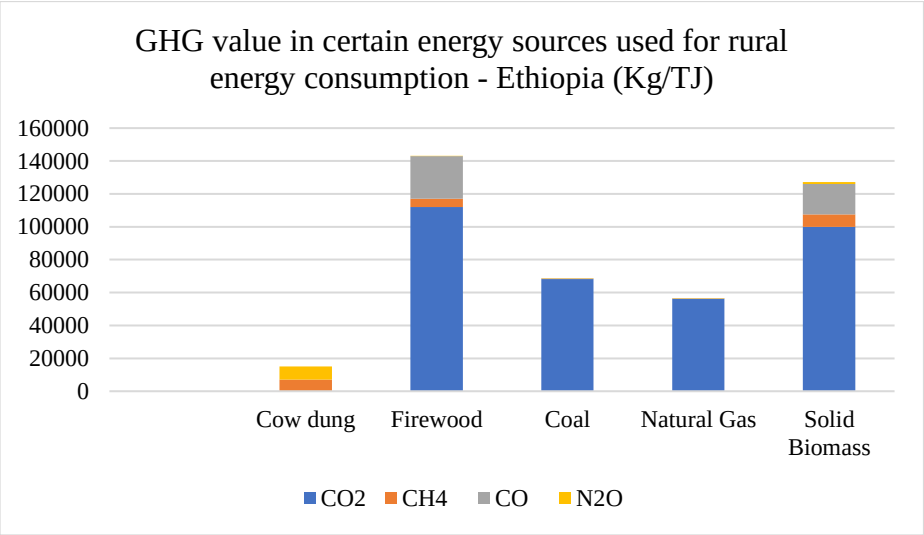

Figure 4.9. GHG value in certain energy sources used for rural energy consumption - Ethiopia (Kg/TJ)

The rural household energy consumption data is also calculated in Table 4.7 which is then used along with the values in Figure 4.8 and Figure 4.9 to calculate the total emission data for rural household and emission per household as presented in Figure 4.10 and Figure 4.11 respectively.

Table 4.7. Energy consumption data for Turkish and Ethiopian Households

Fuel	**Rural Consumption-Türkiye** (TJ)	**Rural Consumption-Ethiopia** (TJ)	**Consumption Per HH Türkiye** (MJ)	**Consumption Per HH Ethiopia** (MJ)
Firewood	14,717	625,689	2,389	40,324
Natural gas	132,505	3,182	21,506	205
LPG and Petroleum	4,206		683	
Cow Dung		67,391		4,343
Solid Biomass		27,749		1,788
Coal	35,846	27,890	5,818	1,797
Electricity	50,894		8,260	
Electricity from coal	3,954		642	
Electricity from natural gas	2,031		330	

Based on the data presented in Figure 4.10 and 4.11, it can be seen that almost 50% of total GHG emission from energy consumption on national level and household level comes from Natural gas for Türkiye. Coal and wood also contribute a high percentage to the overall figure since they are also primary energy source for households. The total emission in rural communities and the emission per household is 14,960,997.687 Metric Tonnes CO_{2eq} and 2385.19 Kg CO_{2eq} respectively.

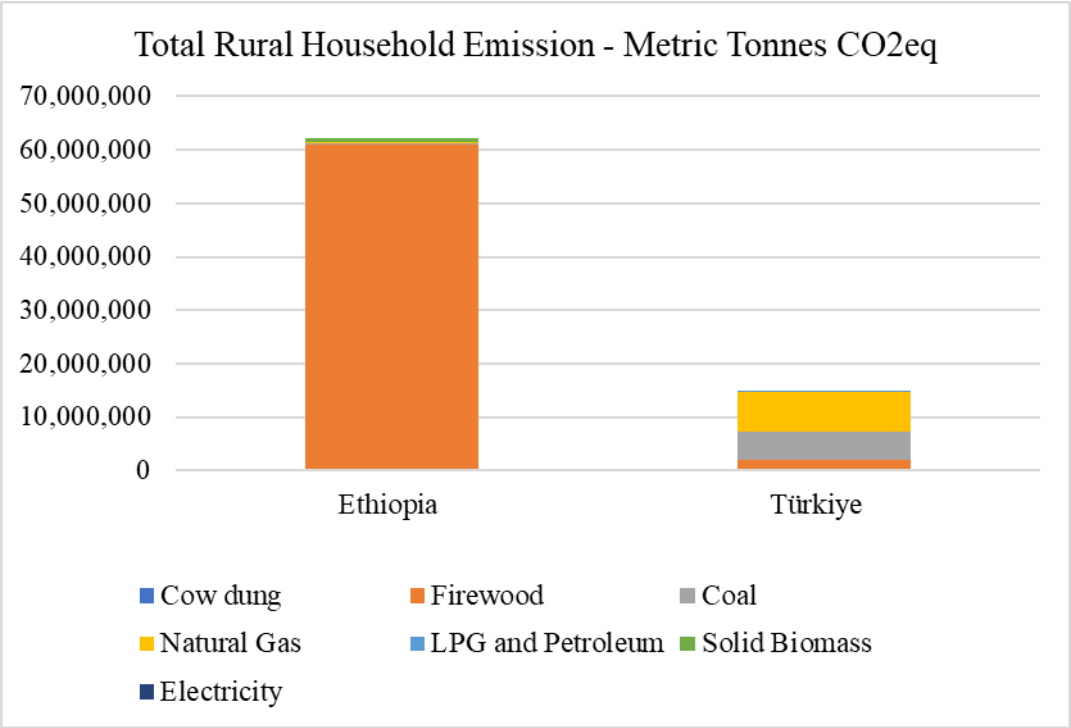

Figure 4.10. Total rural household emission for Ethiopia and Türkiye

Similarly, based on the calculation, more than 97% of all emissions in Ethiopia derives from the use of firewood as principal source of energy and the total emission in rural communities and the emission per household is 62,172,209 Metric Tonnes CO_{2eq} and 4006 Kg CO_{2eq} respectively. It can be seen that due to the usage of firewood, Ethiopia's household emission is significantly higher than that of Türkiye. Moreover, as discussed in the previous section, due to lack of efficient cooking practices and technologies, households end up consuming more energy. Hence, the inclusion of biogas in the energy mix can reduce the dependency on firewood as an energy source on a household level, can facilitate the energy transition and increase the share of renewable energy in the country's energy mix by replacing traditional biomass or by reducing the dependence on it on a household level and in relation, facilitates the adaptation of clean cooking and efficient cooking technologies.

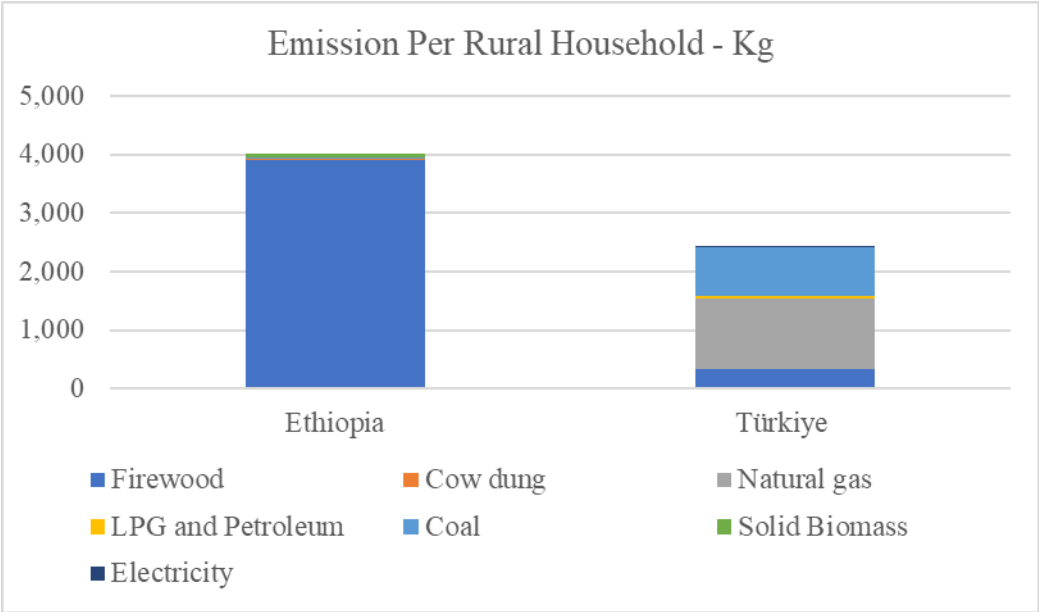

Figure 4.11. Emission per rural household for Ethiopia and Türkiye.

Methane emission during the biogas production process is also considered while doing emission abetment comparison, and for that, only leakage is taken into account since methane emission is considered as if it is zero in anaerobic digestion. Leakage depends on the biogas production and the methane collection efficiency which differs based on the type of digester selected as well as region. For Fixed dome the collection efficiency is taken as 0.975 (Gabisa & Gheewala, 2019). By taking a methane content of 60-65%, the methane emission from biogas production is calculated to be 1626 Kg CO_{2eq} and 1821 Kg CO_{2eq} for Ethiopia and Türkiye respectively which is higher than the methane emission from improper manure management. Hence, construction of a solid biodigester, with little to no leakage, as well as proper handling of biogas after production is essential if emission is to be reduced via proper utilization of manure and production of biogas.

Although CO_2 emission from biogas is generally considered to be biogenic in literature and hence has a neutral or zero impact on the environment, emission form combustion of biogas is still calculated in order to get a full picture. Most of the literature available on calculating GHG emission from combustion of biogas focuses on biogas generators with a much higher installed capacity than that of the electricity generators in small rural household explored in this thesis. As a result, focus is mainly given to biogas cookstoves only when considering emission from the combustion of biogas. In some cases, the biogas stove used may not be efficient and is not burning well which results in the emission of CO_2, CH_4, CO and other organic compounds. Similar to other household GHG emission, IPCC's GHG Inventory is used as a reference. Based on the average people per rural household and the biogas consumption for cooking value discussed in section 4.1 from literature, it is calculated that

a Turkish rural household can produce between 306.12 Kg CO_{2eq} and 535.82 Kg CO_{2eq} from using biogas for cooking. Whereas an Ethiopian household produces 956.59 Kg CO_{2eq} and 1673.93 Kg CO_{2eq} from using biogas for cooking. The comparatively higher emission amount is mainly related to the cooking habit and the cuisine of the localities as discussed earlier but also highlights the need for improved and efficient biogas technologies including efficient cookstoves.

4.2.3. Emission Reduction from the utilization of digestate and compost as a Fertilizer

Although, this thesis doesn't quantify the environmental impact of synthetic fertilizer, as the focus is on biogas as an end product, utilization of organic fertilizer such as bio slurry or compost, can also have a positive impact on the environment. Apart from emission from the use of synthetic fertilizer, another factor that is considered is the whole life cycle of synthetic fertilizer. The production stage of synthetic fertilizer is especially a topic of interest as utilizing phosphorus that is accessible in an organic digestate or compost decreases the need to import or produce synthetic fertilizers. It also reduces the dependence and consumption of both fossil fuel based and mineral fertilizers and in relation agricultural greenhouse gas emission is reduced. Estimation for the GHG emission reduction is usually done by calculating the total amount of ammonia, nitric acid, and phosphoric acid reduced due to a decrease in synthetic fertilizer production as well as the fossil fuel reduced due to the reduction in the production and use of fossil-fuel base fertilizer in a regional and annual basis by looking into the annual production in that region. In regions in which fertilizer is imported and not produced, GHG emission due to the importing of fertilizers can also be taken int account.

Another main stage in which GHG is emitted is during the application of synthetic fertilizer due to nitrification and denitrification happening in the soil. The GHG emission on this stage can be assessed by taking the amount of crop land that synthetic fertilizer is applied to and calculating the rate of nitrate, nitric acid, and Ammonia released during the nitrification and denitrification process in the soil due to the utilization of synthetic fertilizer. In the case of both countries, the farming community heavily uses synthetic fertilizers. Particularly in Ethiopia, there is still little to no practice of using natural fertilizer with it being applied to only 10.2% of the land (Kamp & Bermúdez Forn, 2016) However, currently due to the economic crisis in the country, it has been challenging to buy synthetic fertilizer which has incentivized farmers as well as the Ministry of Agriculture to adopt natural fertilizers into the agricultural system (Mr. Zeleke, personal communication, May 13, 2022). In addition to reducing GHG emission and negative environmental impacts of synthetic fertilizer, using compost and digestate as a fertilizer provides several other benefits including improving the soil structure as well as water infiltration and retaining capacity. Compost and Digestate also supply

essential nutrients such as N, P_2O_5 and K_2O to the soil. Moreover, in the case of temperate regions such as Ethiopia, the utilization of organic fertilizer either prevents or reduces the steady loss of soil organic matter (Luis & Moncayo, 2008).

However, since bioslurry has pathogenic microorganisms, specific measures should be taken to ensure that the pathogens won't affect human health if either bioslurry or compost are applied directly to the agricultural land. Additionally, bioslurry should not be applied to foods that are grown close to the ground, foods that are consumed raw within 3 months of harvest, and foods that are unlikely to be peeled (Avery et al., 2014). Bioslurry can also be composted which makes it safer for application since the composting process reduces the pathogenic microorganisms in the slurry. Moreover, composting is also a way to make a drier material from the liquid slurry which makes the application and transportation easier and more feasible compared to the liquid bioslurry (Avery et al., 2014).

Bioslurry can be composted on different scales depending on the total manure collection such as on-site treatment which includes home composting, vermicomposting systems via small scale composting plant, as well as the more traditional pit composting and can be coupled with small-scale biodigesters; off-site treatment in which group of farmers can come in as a collective to build medium scale operational facility for livestock waste management, and finally via large scale facilities that have both biogas and compost processing facilities.

The compost produced then should be treated in adherence to time and temperature requirements in order to reduce pathogens. For a closed compost treatment system, three days at 60 Celsius are the general time and temperature quality assurance scheme. For open window system however, either ten days at 55 °C or three days at 65 °C is the scheme followed. These values can vary depending on regions (Stehouwer et al., 2022). Some national standards set in place include Turkey's Composting Communique (No. 29286, 05.03.2015) which is set by the Turkish Ministry of Environment and is aimed at regulating the collection and recycling of waste with every municipality being responsible for collecting and treating their own bio-degradable waste. Moreover, the regulation also outlines the technical criteria of composting facilities and the final compost quality and standards (Buğday Association for Supporting Ecological Living, 2017). On regional level the Waste Framework Directive 2008/98/EC, and Animal By-Product Regulation 1069/2009/EC both set composting standards for EU. Ethiopia, however, is yet to develop a proper composting quality standard and requirement.

4.3. Economic Impact Assessment of a shift to biogas

The socio-economic impact and the socio-economic performance of producing and using biogas on small-scale, household, or community level in rural communities is an impact factor that is also explored and estimated. Utilizing biogas can make the local community prosumers and can cut their energy and electricity costs or address energy affordability and poverty issues. Similarly, agricultural or farming costs can be reduced by shifting into organic fertilizer and compos. Moreover, biogas and fertilizer can be a source of revenue for the farmers themselves if there is a market for biogas and locally produced compost.

The annual and monthly energy cost for a household is calculated based on the energy price data from Table 3.4.-Table 3.7. in section 3.7

Table 4.8. Household Energy expenditure for Türkiye and Ethiopia

Expenditure by energy source	**Ethiopia (USD) -2019 Value**	**Türkiye (USD)-2021 Value**
Natural Gas	0.049	62.47
LPG		1.12^{-5}
Firewood	224.84	453.06
Charcoal	10.89	54.37
Cow Dung	19.88	
Electricity	6.78	238.82
Total Annual Energy Expenditure	198.16	381.18
Total Monthly Energy Expenditure	39.317	31.76
Total Household Expenditure	514.08	5751.0
Energy as percentage of household expenditure (%)	7.65	4.60

The calculated expenditure and consumption data shows that a rural Ethiopian household specifically falls under energy poverty, if ESMAP's benchmark is taken as a guideline, with an average household having a Tier 2 or lower electricity and energy access while allocating more than 5% of the total household expenditure for electricity and energy.

When assessing how and if small scale biogas production can address this issue, what should be noted is the initial capital cost and if available maintenance cost. According to SNV, the average

biogas digester costs around 525 USD. However, NBPE program covers half of that cost and hence household are expected to provide on average 245 USD for biodigester construction. As the estimated household biogas production can cover 100% of household's energy needs, the annual reduction on energy expenditure from using biogas alone can compensate for the initial construction cost. Similarly for Türkiye 0.92 USD/KWh is capital cost based on average numbers given by IEA and 0.13 USD/KWh is maintenance and operation cost (IEA, 2018). Although not quantified, reducing the use of synthetic fertilizer can also create a positive economic impact on household level.

Another socio-economic impact that might be harder to quantify is job creation and employment opportunities. The dissemination of small-scale and community level biodigesters provides new employment opportunities for the local masons, technicians, as well as energy experts in the presence of a viable market.

4.4. Assessing Government and regulatory frameworks, incentives, and policies

Analyzing both local and global environmental regulations, directives, and energy policies, assessing their impact, and exploring their intersection with country level policy frameworks can help in providing a better perspective regarding the feasibility of bioenergy adaptation and the effectiveness of the policies that are already in place. Table 4.9 provides an overview of these policies, frameworks, and regulations which are further assessed in this section based on bilateral interviews with government officials, private stakeholders, and multilateral organizations as well as by analyzing official directives and reference documents.

Major Energy frameworks including directives, strategies, initiatives, best techniques and policies both on a country and regional level are identified as can be seen in Table 4.9 and Table 4.10 also presents a breakdown of these frameworks from the perspective of biogas by using 7 indicators.

Table 4.9. Main Frameworks in the countries and region

Country	Framework	Brief overview of the Policy/Framework
Türkiye	YEKDEM (Renewable Energy Support Mechanism)	- YEKDEM is a Feed in Tariff mechanism that is established in 2005 and revised in 2011. New amendment was introduced in 2016 - Extended in 2020 for 6 months till 2021 - Price adjustment made in anew decree on April 30, 2023
	The National Renewable Energy Action Plan	- The National Renewable Energy Action Plan is based on EU's Renewable Energy Directive (2009/28/EC).
	BAT Reference Document	- The Best Available Techniques (BAT) Reference documents include horizontal briefs addressing cross-cutting and intersectional issues such as energy efficiency.
	EU's Renewable Energy Directive	- EU's Renewable Energy Directive (2009/28/EC) is a legal framework out into place in 2018 that requires renewables to have 32% of the total energy consumption by 2030. - A revision was done for the renewable energy directive in 2023 increasing the percentage to 42.5%
	EU RES Directive	- The initial Directive 2001/77/EC was the directive on the promotion of renewable electricity. -The initial directive was replaced by Directive 2003/30/EC which is the directive on the promotion of bioenergy and biofuels.
	EU Green Deal	The European Green Deal is a set of policy initiatives that aim to accelerate a just and inclusive green transition in the EU in order to achieve climate neutrality by 2050. The EU Green Deal was approved in 2020 after the adaption of EU's Climate Law on March 4th 2020.
Ethiopia	NEP	- The National Electrification Plan (NEP) is an action plan that was launched in 2017 in different phases with the aim of achieving universal electricity access by 2025 with 65 percent of that being through grid connection and 35 percent through off-grid technologies
	NBPE	The National Biogas Programme of Ethiopia is implemented in three phases. The first phase run between 2009-2013. The follow up phase has concluded in 2017 and has broaden the goal of the programme and has worked on increasing the engagement of the private sector. Currently, the National Biogas Programme of Ethiopia is on its third phase which is also known as the NBPE+
	The Africa Bioenergy Policy Framework	The Africa Bioenergy Policy framework is a Joint collaboration effort that was initiated in 2010 between the African Union Commission and the United Nations Economic Commission for Africa (UNECA)

Table 4.10. Indicators centering biogas to assess Framework

Framework	Specific Mention of Biogas or Biogas part of overall framework	Biogas for rural community and agricultural sector	Biogas in Energy Mix
YEKDEM (Renewable Energy Support Mechanism)	YES - Feed In Tariff Mechanism is applied to all renewable energy producers including biogas producers - Support entities that generate renewable electricity both with and without a production license including biogas producers	NO - There is no particular specification.	YES - The renewable energy technologies covered under YEKDEM are Solar. Hydro, Geothermal, Bioenergy, Biogas, Wind, and Tidal Energy
EU's Renewable Energy Directive	YES - Appendix V specifically focuses on Biogas and Bio-CNG (compressed natural gas) with the utilization of wet and dry manure being two of the three proposed routes for the production of biogas and bio-CNG.	YES - The main focus is advanced biofuels in transportation sector. However, there is a push to ensure that biogas will not be produced from energy crops in order to address food security issues.	YES - Appendix V specifically focuses on Biogas and Bio-CNG (compressed natural gas) with the utilization of wet and dry manure being two of the three proposed routes for the production of biogas and bio-CNG
EU RES Directive	YES - The directive proposes the utilization of all sorts of biomass as well as biowaste to generate energy and requires member states to set a National Action Plan tailored in accordance with their national policies with the aim of mobilizing biomass resources for different uses.	YES - The directive discusses complementary European legislations and frameworks such as Waste Framework Directive 2008/98/EC, Renewable Energy Directive 2009/28/EC, and Animal By-Product Regulation 1069/2009/EC in respect to the utilization of energy from biowaste including biogas in agriculture sector.	YES - The directive proposes the utilization of all sorts of biomass as well as biowaste to generate energy and requires member states to set a National Action Plan tailored in accordance with their national policies with the aim of mobilizing biomass resources for different uses including energy.
EU Green Deal	YES - Both the EU Methane strategy and the Biomethane Industrial Partnership (BIP) are strategies supporting the EU Green deal and that are directly linked to biogas and biofuel production.	YES - EU “Farm to Fork” and “Biodiversity” Strategies also highlight the role that agricultural community plays including the reduction of fertilizer use by at least 20% as well as address biodiversity losses including natural resources and pollution.	YES - Both the EU Methane strategy and the Biomethane Industrial Partnership (BIP) are strategies supporting the EU Green deal and that are directly linked to biogas and biofuel production.

Table 4.10. Indicators centering biogas to assess Framework (continued)

The National Renewable Energy Action Plan	YES - The integration of biogas into the natural gas network is underlined based on (Article 16(7) and Article 16(9) and (10) of Directive 2009/28/EC).	YES - Measures to increase biomass availability, taking into account other biomass users including agricultural communities is discussed.	YES - Estimated primary energy biogas production from biomass in agriculture is defined under its targets
BAT Reference Document	YES - BREFs present best practices and techniques on anaerobic digestion as well as biogas pretreatment methodologies for different end use. - However, BREFS is not a set of frameworks	YES - BREFs section on anaerobic digestion also includes biogas production from agricultural by-products like manure and other animal by-products as well as the use of digestate in farms.	NO - BREFs present best practices and techniques in order to reduce sectoral energy consumption and increase energy efficiency including in biogas facilities but do not particularly discuss biogas in the energy mix.
NEP	YES - The NEP incorporates both the National biogas Programme (NBPE) and the National Improved Cookstove Programme (NICP) with both centering around biogas production and access to clean cooking including biogas usage.	YES - The NEP itself doesn't specifically mention this but the NBPE is part of its Off-grid energy access plans.	YES - There still exist a gap but waste to energy conversion and its role in the countries overall energy mix is discussed.
NBPE	YES - The NBPE is the main Biogas programme in the country and fully centers around biogas production and biogas technology dissemination. - Each phase NBPE sets targets and goals on the amount of biodigester disseminated and biogas produced.	YES - The NBPE+ operate under the objectives of improving the living standards of farmers as well as reducing the GHG emission and exploitation of biomass and forestry in the farming community by increasing the dissemination and usage of biogas digesters.	YES - The NBPE aims at incorporating biogas in the country's energy mix and increase the share of biogas within the energy mix. It particularly pushed biogas technologies to off-grid communities in order to address energy access.
The Africa Bioenergy Policy Framework	YES - Policy incentives and recommendations are put into place in order to facilitate and assist countries in establishing targets on bioenergy including biogas as well as support small farmers	YES - Aim to set policies in order to establish a sustainable bioenergy sector while addressing challenges in the agriculture sector and rural communities, including waste management and land use.	YES

Table 4.10. Indicators centering biogas to assess Framework (continued)

	Annual/Periodic goals and targets regarding biogas	**Biogas to address energy or environmental challenges**	**Financial Incentives**
YEKDEM (Renewable Energy Support Mechanism)	NO -There is no set target or goal aimed in particular to biogas production	YES - The mechanism particularly does not explore the impact of RET on environment or in addressing energy issues	YES - As of 2023, the base and ceiling price to sell biogas is 8.1 USD/KWh and 9.9 USD/KWh
The National Renewable Energy Action Plan	NO - There is a target set to utilize 3,537 Ktoe of biomass but is not specifically biogas.	NO - Nothing specifically discussed in the action plan.	NO - The action plan itself doesn't present financial incentives but acknowledge how the Feed-in-Tariff Mechanism present has resulted in an increase in small scale biogas production by farmers.
BAT Reference Document	NO - BREFs present best practices and techniques in but do not set targets	YES - BREFs discuss emission and other related environmental impact from both agricultural waste and anaerobic treatment and presents best practices and techniques. .	NO
EU's Renewable Energy Directive	YES - An increased utilization of biogas as well as advanced biofuels especially in the transportation sector is set as a target in the revised version.	YES - Advanced biofuels and biogas are expected to be in ethe energy mix in order to reduce emission especially in transportation and aviation sector.	YES - It suggests introducing targets that combine advanced biofuels and biogas and setting a minimum expected percentage for biofuel and biogas in the energy mix.
EU Green Deal	YES - Under the Biomethane Industrial Partnership (BIP), a target is set to produce and utilize 35 BM3 of biomethane annually to support EU's 2030 targets	YES - It aims to reduce greenhouse gas emissions to at least 55% via several objectives and targets that incentivize the adoption of biogas technologies in different scales. - The EU Methane strategy under the European Green Deal prioritizes the reduction of methane emission.	YES - Depending on the region and country green subsidies are put into place and tax exemptions are provided for biomethane use.

Table 4.10. Indicators centering biogas to assess Framework (continued)

NEP	YES - Similar targets that are set under the NBPE are reflected here.	YES - Biogas technologies are set to address off-grid and low-income household energy challenges.	YES - Similar incentives that are presented under the NBPE are reflected here.
NBPE	YES - Each phase sets a goal for total biogas digester to be disseminated. The initial phase set the target of installing and disseminating 8161 biodigesters. Phase two also targets 360,000 households in rural areas.	YES - Biogas technologies are set to address off-grid and low-income household energy challenges.	YES - The initial capital cost for biodigester construction is subsidized by 50%, tax exemption for the first five years of production of digester, and on digester parts imported machineries. -Free land for farmers to implement biodigesters on.
The Africa Bioenergy Policy Framework	NO - Policy incentives and recommendations are put into place in order to facilitate and assist countries in establishing their own targets on bioenergy, including biogas, as well as support small farmers. But no specific target or goal is set.	YES - The policy framework discusses the water-food-energy-land nexus and the role that biogas plays and sets sustainability criteria with respect to that.	YES - A set of frameworks are put into place to assist financial institutions with their investment as well as create a bioenergy market in the countries.

As can be seen in Table 4.10, some of the main energy related policies and strategies for Türkiye includes the National Renewable Energy Action Plan, the National Energy Efficiency Action Plan (NEEAP), and the Renewable Energy Support Mechanism (YEKDEM). The National Renewable Energy Action Plan, which is funded by European Bank for Reconstruction and Development (EBRD), is based on EU's Renewable Energy Directive (2009/28/EC). Under this action plan the integration of biogas into the natural gas network is underlined based on (Article 16(7) and Article 16(9) and (10) of Directive 2009/28/EC). Apart from the NREAP, EBRD also funds The Türkiye Sustainable Energy Finance Facility.

YEKDEM on the other hand, is a premium Feed-in Mechanism which is based on a "Feed-in" Tariff system (Ozcan et al., 2015). The RESM provides incentives for power plants that has renewable energy certificate under the "Law of renewable energy sources for the generation of electrical energy" and individuals with unlicensed electricity generation but with an REC certificate.

Energy targets are also essential and needed in order to track the development of the plans and programs. For Türkiye, VISION 2023, is one of the major energy targets and it aims at supplying 30% of Türkiye's energy demand from renewable energy sources as well as increase renewable energy source in the energy mix by the year 2023. However, there is no specific target for manure-based biogas production in Vision 2023.

On a regional level one of the most prominent environmental frameworks is the European Green Deal. The European Green Deal is a set of policy initiatives that aim to accelerate a just and inclusive green transition in the EU in order to achieve climate neutrality by 2050. The European Green Deal also aims to address environmental and climate challenges concerning the EU by setting out targets under different thematic focal points. The production, dissemination, and utilization of biogas technologies as well as compos mainly intersects with three thematic focal points that are explored under the EU Green deal; Environment and the Ocean, Energy and Agriculture (European Commission, 2023).

The Energy thematic focal point and its key principle "ensuring a secure and affordable EU energy supply" especially includes several objectives and targets that incentivize the adoption of biogas technologies in different scales. These targets are:

- decarbonizing the energy system in order to reach climate objectives in 2030 and 2050.
- Prioritizing energy efficiency
- Facilitating the rapid phasing out of coal and decarbonizing gas
- Affordable energy supply for consumers and businesses in EU which can be realized by also making consumers prosumers.
- A consumer focused just energy transition.
- energy efficiency and more sustainable solutions across sectors in order to achieve decarbonization at the lowest possible cost and biogas facilities can play a role especially within the agriculture sector.
- Facilitating the decarbonization of the gas sector and a shift towards biofuel and biogas can help in achieving this target.

Under the agriculture thematic focal point, the key principle of reducing the environmental and climate footprint of the EU food system aligns with the utilization of biodigesters and transition towards organic fertilizer such as compost in lieu of synthetic fertilizer. Similarly, under the Environment thematic focal point key targets such as a zero-pollution ambition for a toxic-free

environment including the reduction of GHG emissions and mainly CO_2, CH_4 as well as the preservation and restoration of ecosystems and biodiversity including forestry and soil quality can be addressed by reducing the usage of traditional biomass, increasing the share of biogas and biofuels in the energy mix and utilizing compost in agriculture (European Commission, 2023a).

One interesting aspect to note in regard to the EU Green Deal and anaerobic digestion is also the EU's involvement in Ethiopia's NBPE Programme by being one of the funding agencies along with SNV and the government of Ethiopia. The EU also helps in setting up public private partnerships as well as encourage the involvement of microfinance institutes and develop a system in which these finance institutes are connected to the end-user, in order to address financial challenges such as access to credit. Additionally, the EU also sets up platform with the aim of expanding the local private sector within the renewable energy, biogas, and agri-food sector as well as make the local community prosumers which is in line with the EU Green deal strategy to achieve a carbon neutral economy by 2050. One such platform is the Digital Global Biogas Corporation that is funded by EU's Horizon 2020 program. The platform is working on developing the market and the space for biogas and biomethane technologies in developing and emerging economies as part of expanding Europe's biomethane or bioenergy industry with Ethiopia being one of the target countries (DiBiCoo, 2022).

Apart from the EU green deal, another policy frameworks and directive on the regional level that is applicable in Türkiye is EU's Renewable Energy Directive (2009/28/EC). Although the directive explores different aspects of renewable energy, it also touches upon biogas and biofuel utilization. Within the directive, Appendix V specifically focuses on Biogas and Bio-CNG (compressed natural gas) with the utilization of wet and dry manure being two of the three proposed routes for the production of biogas and bio-CNG Additionally, the proposed revision for the renewable energy directive in July 2021 discusses an increased utilization of biogas as well as advanced biofuels especially in the transportation sector. It also explores how to enhance the sustainability criteria of bioenergy and find synergies between the EU's Biodiversity strategy and address loopholes that negatively impact the targets such as the prohibition of biomass from primary and biodiverse forests. The EU Directive also has the Biomass cascading scheme which takes the environmental and economic added value of woody-biomass into consideration before utilization.

Another directive that is essential in biomass, biogas and bioenergy dialogue is the RES Directive. The initial Directive 2001/77/EC, which was the directive on the promotion of renewable electricity was replaced by Directive 2003/30/EC which is the directive on the promotion of bioenergy and biofuels. The directive proposes the utilization of all sorts of biomass as well as

biowaste to generate energy and requires member states to set a National Action Plan tailored in accordance with their national policies with the aim of mobilizing biomass resources for different uses. It also explores measure and standards on how bio-wastes are counted towards renewable energy targets of the countries (European Commission, 2019).

Additionally, another important regional document with respect to Türkiye and its agriculture sector is the BAT Reference Documents (BREFs). The BREFs covers specific agro-industrial activities. However, there are also horizontal briefs addressing cross-cutting and intersectional issues such as energy efficiency. Under EU, the BREFs covers anaerobic digestion as well as waste treatment including mechanical biological treatment.

When it comes to Ethiopia, the country's energy policy and framework is centered around electrification with The National Electrification Plan (NEP) being one of the main foci. The NEP is an action plan that was launched in 2017 in different phases with the aim of achieving universal electricity access by 2025 with 65 percent of that being through grid connection and 35 percent through off-grid technologies including biogas and bioenergy. The NEP also explores how the private sector can be an active stakeholder in the development of energy infrastructures in off-grid areas within the context of green jobs (The World Bank, 2019).

The biogas scene in Ethiopia is recent and growing with the biogas sector on organizational level starting with the launch of the National Domestic Biogas (NBPE) programme in 2008 which now serves as the main biogas and bioenergy programme in the country (SNV, 2023; Mr. Zeleke, personal communication, May 13, 2022). The NBPE is one part of the multi-national African Biogas Partnership Programme (ABPP) spearheaded by SNV. The National Biogas Programme of Ethiopia is implemented in three phases. The first phase run between 2009-2013 and was aimed at installing and disseminating 8161 biodigesters. The follow up phase has concluded in 2017 and has broaden the goal of the programme and has worked on increasing the engagement of the private sector in the biodigester construction and dissemination including developing entrepreneurship skills and building knowledge and capacity. Additionally, the second phase also pushes on the utilization of bio slurry as an organic fertilizer. Currently, the National Biogas Programme of Ethiopia is on its third phase which is also known as the NBPE+. The NBPE+ is a scale up programme and operate under the objectives of improving the living standards of farmers as well as reducing the GHG emission and exploitation of biomass and forestry in the farming community by increasing the dissemination and usage of biogas digesters. Moreover, the NBPE+ cover all the 9 regions unlike the first two phases which were only focusing on 4 regions (Mr. Carlos, personal communication, September 22, 2023,

2023; SNV, 2017). On a regional level, the energy security and energy access challenge of the continent is heavily tied to food security. Hence, the AU has set The Africa Bioenergy Policy Framework which addresses the water-food-energy-land nexus and sets sustainability criteria.

Promoting biogas and bioenergy might be a challenge to policy makers and active stakeholders. However, the sector has emerging advantages and provides environmental and economic benefits as discussed in section 4.2 and 4.3 such as cost reduction due to decreased dependence in fossil fuel, diversification and localization of energy which decreases energy poverty and insecurity, and environmental benefits. Moreover, these benefits can further be amplified as the sector has rapidly developing and evolving technology. Hence, policy and market incentives have been put into place in both regions to motivate different actors to utilize and adopt digesters.

Some of the incentives that are put in place for Ethiopia includes Tax exemption for the first five years of production of digester and digester parts as well as tax exemption for business that import machineries. Moreover, free land was provided for farmers to implement biodigesters along with subsidy being given to biogas users to compensate initial cost for domestic biodigesters (Kamp & Bermúdez Forn, 2016; Mr. Carlos, personal communication, September 22, 2023; Mr. Zeleke, personal communication, May 13, 2022).

For Türkiye, the RE Support Mechanism (YEKDEM) has put different incentives in place including substantial feed-in tariffs as well as exemption from the annual licensing fee for 8 years for RES plants including biogas plants, and reduction of the licensing fee to only 1% after the initial 8 years. Additionally, licensing priority and grid connection priority is given to renewable energy sources and producers/providers (Ozcan et al., 2015).

4.5. Bottlenecks and challenges that impact biodigester dissemination and biogas utilization

Based on conversations with stakeholders, bottlenecks and challenges to the adaptation and dissemination of biodigester as well as the production of biogas are identified and classified as financial and resource challenges, knowledge and capacity challenges, systemic and structural challenges and cultural challenges. There is an intersection between these factors, and they also reflect how multifaceted this topic is.

4.5.1. Resource and financial challenges

One of the most essential factors that affects the adaptation and dissemination of biogas technologies is availability of resources including natural resources such as raw feedstock and water, as well as construction materials such as bricks, cement, piping tube…etc. The availability and accessibility of natural resources in a region can affect the adaptation of biogas technologies in that region in both a positive and a negative manner. Having an easy access to traditional biomass or energy source in the region might discourage the local communities from transitioning to renewable energy technologies, especially when all or a percentage of the capital cost comes from the local communities themselves, which is the case under Ethiopia's NBPE. On the other hand, having an abundance of traditional biomass also translates to the region having a high biomass potential hence high ability to generate biogas and with the right policy incentives and awareness raising programs, it could motivate the local communities to transition to a cleaner energy.

In the case of manure based biodigesters, one of the main resource challenges is the efficient collection of feedstock as most farmers don't have specific grazing land for their livestock but rather share common grazing land which makes it difficult to collect manure. Additionally, lack of proper waste management framework can also affect efficient collection of feedstocks. This is reflected on the lower manure collection efficiency value estimated in the previous sections which also impacts the amount of biogas that can be produced.

Additionally, climate induced complications further affect the feedstock supply and biogas production. In the case of Türkiye, the seasonal variation in temperature as well as the variation in average air surface temperature of the country means that biogas production capacity differs from region to region making it difficult to establish one set system across as well as produce biogas year-round without utilizing temperature control systems. Moreover, the time series data obtained from the Climate Change Knowledge Portal in section 4.1, the average surface air temperature of the country has dropped throughout the years which further complicates the production of biogas.

Ethiopia, on the other hand, has been prone to drought in the past few years including an El Nino induced drought in 2015 which has significantly reduced the number of livestock in the country. Additionally, seasonal drought and dry seasons in different regions can present a challenge especially coupled with water scarcity since the traditional fixed-dome model requires at least an equal amount of manure and water daily (1:1). As a solution, 80% of the biodigesters that were disseminated in the country in recent years were connected to the toilet or septic tank. This addresses the water scarcity

as well as sanitation issues (Kamp & Bermúdez Forn, 2016; Mr. Carlos, personal communication, September 22, 2023). On the downside, the integration of latrines has discouraged the local community from properly utilizing the biodigesters as they find it difficult and off putting to handle and treat the byproducts. Another solution that was presented for the water scarcity was introducing a different or alternative biodigester type with a lower water-feedstock ratio in lieu of the traditional fixed dome biodigester which is the Solid-State Digester (SSD) with 1:4 ratio water to feedstock dilution ratio in the case of SNV (Mr. Carlos, personal communication, September 22, 2023).

Apart from feedstock availability, limitation in the supply of raw materials that are needed to build digesters is also another challenge. In the case of Ethiopia, this is the recurring cement crisis. Moreover, with a limited supply the cost of construction material is bound to rise which has more adverse impact on the rural community. Additionally, most of the digester parts such as pressure gauge, biogas lamps, biogas valves are produced outside of the country and the local currency value derives the prices up, making it harder for the local community to purchase and construct digesters. Attempts have been made to create a local market for biogas technologies but lack of investment as well as a firm support towards entrepreneurship are still challenges that should be overcome (Mr. Zeleke, personal communication, May 13, 2022). Additionally, the current political instability in the country has contributed to economic instability and an overall low level of competitiveness in the country. For Türkiye, the rising inflation in the past few years have also make the purchase of raw materials difficult.

Resource related challenges also includes inefficient resource utilization of the countries. As Türkiye and Ethiopia has a lot of small-scale farms and as animal husbandries and livestock is distributed throughout different regions, there is a need for a widespread of farm-based biomethane systems and incorporate bioprocessing on individual farm levels to fully utilize the biomass potentials of the regions. This means following a decentralized approach for biogas generation and utilization. However, most work that has been done so far especially in Türkiye is on large scale and centralized level with most production facilities being aggregated in limited regions and hence creating competition over resources. On the other hand, Ethiopian rural community also has high biomass potential, but most is not utilized due to lack of technology. This is especially prominent in the agro-pastoralist community as discussed in the section 4.2 in which there is a very high numbers of livestock per household or community but due to the nature of the community and its constant movement, it makes it harder and difficult to install fixed biodigesters. One alternative that can be explored in this case for both Türkiye and Ethiopia are the use of portable biodigester. Portable biodigester is currently mainly used in Kenya. Unlike fixed dome biodigesters, these plants do not

require ownership of land, as well as expertise in installing, maintaining and operating the system and hence can be a better alternative for pastoralist communities or projects that may not necessarily require license.

Access to resources is also tied to another factor which is purchasing power or the financial capacity of the consumers and producers. As stated above, the availability of traditional biomass or other energy sources coupled with the difference in the price of alternative energy sources, most importantly oil and fossil fuel, to that of the total cost needed to implement and disseminate renewable energy technologies is a deciding factor in adopting these renewable energy technologies. In the case of biogas, the total cost includes the starting capital for biogas plants, biodigester installation prices, as well maintenance and operational costs throughout the digesters' life cycle. Although it is identified that a shift towards biogas would reduce the energy expenditure of a household and can recompensate the initial cost for biodigester, which is 245 USD after subsidies in Ethiopia and 281 USD for Türkiye, households still may not be able to afford the initial cost. This is especially prominent in the case of Ethiopia in which the biogas programmes and projects as well as capacity development are mainly spearheaded by the NBPE under SNV. Prior to SNV, the then GTZ and now GIZ was the implementing partner of the programme and used to provide institutional and large-scale prefabricated biodigesters to the community. This in turn has created negligence within the community since there is no sense of ownership and the community doesn't consider itself a stakeholder. However, SNV carries a different approach that is aimed at making the community a stakeholder. Under SNV's programme funding for residential level biodigesters is brought from three sources; SNV, the farmers or beneficiaries, and HIVOS for the first 2 phases of the programme (Dr. Tesfaye, personal communication, November 11, 2022; Mr Carlos, personal communication, September 22, 2023). SNV also supports with technical aspect including free installation and has also set the ABPP which channels additional fundings into the NBPE However the framers still need to provide a percentage of the construction cost as well as materials in order to foster a sense of ownership and also reduced negligence as they consider the biodigesters their personal properties (Mr. Zeleke, personal communication, May 13, 2022; Dr. Tesfaye, personal communication, November 11, 2022). Hence, in order to ensure that farmers and benficiaries will have a sense of ownership but also simultaneously provide opportunities for farmers from different economic strata, the Development Bank of Ethiopia has slowly been establishing micro-Finance institutions that have been providing initial investment funds for the farmers/beneficiaries to further assist biogas development in Ethiopia. For both countries, the increasing value of foreign exchange which simultaneously causes the local currency to have a weak purchasing power also impacts the development of small-scale biogas sector.

The market availability for the end-product and value-added product which are energy (biogas), and fertilizer (digestate and compost) is also another critical economic factor. The existence of such a market can benefit the producers such as the local farming community by presenting new economic opportunity (Luis & Moncayo, 2008). Moreover, the availability of a market for end-products can also result in the facilitation of innovation and entrepreneurship and create opportunities for investors (Mr. Zeleke, personal communication, May 13, 2022; Mr. Getu, personal communication, April 12, 2022). The market availability is closely linked to the public perception of the products which is also influenced by the public needs. This is especially the case of compost. When it comes to biogas, although the market can be small when it comes to rural areas and developing countries, opportunities are more diverse in countries like Türkiye in which biogas is produced in powerplants and in larger scales, hence the biogas produced can be burnt on site and can be used by the powerplant to generate heat and electricity. It can also be upgraded to biodiesel which can be then use in the transportation sector or be pumped into the grid in lieu of natural gas.

4.5.2. Capacity and Knowledge Challenge

The economic factor on the other hand has an impact on the capacity factor and the ability of the regions to disseminate biogas technologies as well as implement biogas programs, as one of the main bottlenecks when it comes to capacity is the availability of funding. Additional capacity factors include the presence of biogas programs and projects on local and national level in order to nurture community and citizen awareness and know-how as well as technical knowledge regarding biogas and renewable energy technologies. Active and diverse stakeholder involvement is crucial for capacity building and awareness rising of biogas initiatives. Since the rural area has a low population density, it can be feasible to gain social acceptance of the initiatives presented but the social and cultural landscape of the community should also be understood. Moreover, emphasize should be given on how these rural areas have a high availability of the needed feedstock and raw material such as agricultural and livestock residuals that can be used to meet the potential demand and hence these should be framed in an attractive manner for the user. This also ties to the social structure and norms of the local community and highlights how the lack of social attention and awareness also presents a challenge. The limited presence of social networks and cooperatives in the regions also further exacerbates the challenge as it contributes to the lack of social activities such as awareness raising campaigns.

When it comes to knowledge related challenges, one of the main issues is technical know-how. Small-scale biodigester installation is generally done by masons from the local community. And albeit the continuous training program that is being given to new masons there is still a lack of technical knowledge and experience regarding digester technologies which translates into lack of skilled and educated labor and put limitations on the human capacity. Moreover, these masons are not hired full time to work on biodigester projects, hence work on other projects on the side. This creates a gap in the availability of masons and increases the time that it takes to disseminate biogas digesters as well as create a lack of continuous work opportunity for masons themselves. Lack of knowledge doesn't only put restriction on the masons but also the farmers and beneficiaries. Lack of know-how regarding the full potential of the biodigesters has resulted in underutilization of these biodigester facilities (Mr. Getu, personal communication, April 12, 2022; Mr. Zeleke, personal communication, May 13, 2022; Kamp & Bermúdez Forn, 2016). This results in the biogas facilities retiring earlier than expected. Bad reputation of non-operational facilities from previous biogas projects have also reduced the reception of digesters within the community and has skewed the knowledge and perspective of beneficiaries regrading biogas technologies.

In addition to proper utilization of biodigester, having proper knowledge and know-how in the management and handling of feedstock (manure) as well as the end-product, biogas and digestate, is also essential. Improper handling of feedstock and by-products exposes the operators and users to pathogens so creating awareness on microbiological safety is important. Increasing promotions as well as expanding on capacity building and awareness raising programs by implementing body can address these issues. However, the lower literacy rate of the country makes it challenging to disseminate such programs and make them wide-reaching.

Newer approaches should be taken to further smooth out the acceptance of digesters in these regions. This includes knowledge and citizen awareness raising programs that explores the impact of biogas on the environment, economy, and livelihood of the beneficiaries in these regions can go a long way in addressing the aforementioned challenges.

4.5.3. Cultural and socio-economic challenges

The utilization of biogas technologies is also affected by the culture of the region. Especially in countries in sub-Saharan Africa, including Ethiopia, the energy discourse is heavily integrated with the water-food-land nexus and food security and access to clean energy entails access to clean cooking and efficient cookstoves. Hence the energy discourse also takes the food and the culture of the regions

into account and cultural and anthropological factors play a role when it comes to adapting energy technologies. In regard to the utilization of biogas, the biggest challenge is the lack of cookstoves, locally known as *mitad*, that utilizes biogas to make the local staple sour dough bread, *Injera*, that needs high energy. And as seen in Section 4.2 and 4.3, the highest energy consumption for rural household in Ethiopia is due to cooking. Hence, biogas programmes on a country level should also prioritize the development of new technologies suitable for biogas utilization.

The status differences and economic disparity in both countries as well as the presence of different classes and tribes within the same region, in the case of Ethiopia, can also affect the dissemination of biogas technologies on a regional level.

4.5.4. Structural and systemic challenges

The SNV spearheaded NBPE has been the main biogas and biodigester program in Ethiopia supported by the government. Although, having one main implementing body has made digester dissemination in the country more structured, creates a systematic and centralized approach, and make the monitoring and evaluation process easier to track it can also affect the involvement of diverse stakeholders. According to stakeholders, strong presence of government and government involvement in projects affects the engagement of the private sector and private entrepreneurs (Mr. Getu, personal communication, 2022). Although, the NBPE has incorporated diverse actors, including private sectors, local communities such as masons and farmers, regional level government bodies such as woredas, ministerial bodies, there still is not an equal engagement between these different stakeholders. Similarly for Türkiye, due to the bigger presence of private companies within the biogas production scene, small-level farmers and households face difficulty in fully being prosumers within the sector. Moreover, for both countries, there is still a very weak or non-existent presence of local small scale Biogas Construction Enterprises (BCEs) due to lack of market as discussed in the previous section.

Another structural challenge that is further exacerbated by the lack of diverse implementing bodies is that SNV gives more focus for the deployment of biogas technologies which leaves a blind spot when it comes to maintenance and follow-up of digesters and in relation the longevity of these projects. Hence, a body that works on maintenance and follow-up can make the dissemination and proper utilization of biogas technologies successful. However, it should be noted that there have been isolated efforts separated from NBPE that is trying to address the gap and burdens within the sector

(Kamp & Bermúdez Forn, 2016) including works that are being done by local entrepreneurs and researchers (Mr Getu, personal communication, April 12, 2022).

Additionally, the different transitions and the frequent structural changes between organizations including ministerial bodies, especially in Ethiopia, also is a challenge that should be addressed as it results in confusion in delegation of responsibilities and authorities. At the start of The National Biogas Program, the program was spearheaded by the Ethiopian Rural Development and Promotion Centre (EREDPC). However, the organization ceased to exist. Following that the NBPE was under the former Ministry of Mines and Energy which was then transitioned to the Ministry of Water, Irrigation and Energy (MOWIE). This kind of restructuring can lead into the inter-ministerial and organizational tensions and misalignments over delegation of responsibilities (Kamp & Bermúdez Forn, 2016).

In Türkiye's context although biogas production is done on a larger scale with biogas powerplants, small-scale livestock farms are more prevalent and hence there is a lot of unused potential due to the lack of a robust management system (Ersoy & Ugurlu, 2020). Additionally, country level energy frameworks as seen in Section 4.4 mainly focus on large scale production of biogas and hence there is a policy and framework gap when it comes to addressing small scale or medium scale biogas production.

Apart from energy policy and frameworks focusing on biogas production, the countries should also have a waste management framework in place in order to ensure proper waste utilization. However, in the case of Ethiopia, an integrated waste management policy is not yet developed. Additionally, there is not a separate entity on a ministry level on waste management and waste related topics are rather addressed under the Ministry of health, infection, and proper sanitation making it hard to streamline. Türkiye however has the Composting Communique (No. 29286, 05.03.2015) which is set by the Turkish Ministry of Environment and is aimed at regulating the collection and recycling of waste with every municipality being responsible for collecting and treating their own bio-degradable waste. Moreover, the regulation also outlines the technical criteria of composting facilities and the final compost quality and standards (Buğday Association for Supporting Ecological Living, 2017).

Other limitations and challenges in the structural and policy side are the minimum incentives set within the countries' energy framework specifically targeting the biogas sector development which

in turn affects private sector engagement and leads to weak private sector development, lack of credit facilities in the regions, as well as poor commitment of stakeholders at regional level.

4.6. Addressing challenges and optimizing the end-product

Addressing the challenges discussed in the previous section while optimizing the biogas production process, improving biogas production efficiency, and fully utilizing the end products in biogas production plays an important role in the accelerated integration of biogas technologies in local communities. Integration of biogas technology on a country level especially requires the optimization of the end product production and usage which are the biogas and bioslurry.

Different techniques can be implemented on different stages of biogas production, from feedstock collection to pre-treatment in order to optimize biogas production efficiency and upgrade biogas quality as well as improve the utilization of bioslurry. For a substrate-focused optimization the techniques that could be explored can vary from choosing suitable substrate and co-substrates to applying pretreatment techniques to make the substrate more adaptable to the digestor (Muhammad nasir & Mohd ghazi, 2015). Additionally, feedstock collection, management and separation can also affect manure recovery rate as well as the quality of biogas produced. The manure recovery rate also differs based on the different animal types. Dairy cattle have the highest potential for manure recovery with manure recovery rate for small ruminants being much lower than other livestock types. Hence, smart manure management systems and feedstock composition that takes this into account can help in improving.

4.6.1. Proper feedstock collection and feedstock quality assurance

A solid, pre-existing, integrated waste collection framework is essential when it comes to ensuring that animal, agricultural, and agro-industrial waste is properly collected and utilized. Proper waste collection creates a supply of “clean’ biowaste which contributes to reduced cost on pre-treatment as well post-production upgrading. It can also build consumer confidence on biogas and compost quality and in turn create a market which can encourage and increase investment in biogas and composting facilities. National, regional, and local policies and targets can be set to measure progress and proper biowaste collection and separation can also be done on national, regional, and local level (Luis & Moncayo, 2008).

Another way of improving feedstock quality is pre-treatment which is done at an initial stage in order to sort out the raw material and prepare it for anaerobic digestion. This is especially essential when using raw materials with high lignocellulosic fiber such as animal manure. Lignocellulosic fiber in the animal manure is not fully digested hence, pretreatment of feedstock can enhance the anaerobic digestion/enzymatic digestibility of the biomass by altering the lignocellulosic structure, by increasing its porosity, reducing or removing the lignin and hemicellulose content in the feedstock and making the biomass easier to breakdown. Additionally, pretreatment can affect the formation of intermediates which, in turn, affects pathogen reduction in the substrate. Pretreatment of feedstock is an essential step for efficient biogas production as it optimizes the biogas yield and can be used to upgrade the quality as well by increasing the methane yield in which biogas produced under same condition but with a lesser methane content will have a lesser methane yield (Muhammad nasir & Mohd ghazi, 2015).

The methodologies that can be used for pretreatment of feedstock are diverse and can be classified by the type of technology used or by the change the pretreatment causes on the feedstock. The main pretreatment techniques that are mostly explored in literature are physical, biological, thermal, chemical, and thermochemical techniques which are discussed in detail below. However, based on the scale of the waste treatment technology, other novel pretreatment techniques including cavitation, high-pressure homogenization, thermal hydrolysis, chemical pretreatment/post-treatment can also be taken into consideration.

Physical pretreatment alters the physical property of the lignocellulosic biomass through mechanical process such as milling. grinding, extrusion by using centrifuge, sieve, pressing…etc. These can be done either in an automated way or manually with it being the latter for small-scale biodigester in developing countries. For animal manure, maceration, which is the grinding, chopping, and blending of the biomass, is the simplest as well as the most doable pretreatment alternative as it can be done manually by small-scale biodigester owners. In addition to increasing the surface area for the microbes to penetrate the substrate by grinding, chopping…etc. the feedstock, physical pretreatment is also used to separate the solid in the substrate from liquid or impurities such as sand, slit and other suspended solids via sedimentation or screening.

As the name suggests, thermal pretreatment is the utilization of heat such as slow heating (70-90 Celsius) to alter the structural, physical and chemical properties of the biomass. Similarly, chemical pretreatment is the addition of acids or alkalis (bases) in order to solubilize or precipitate lignin. However, the use of chemicals requires a cost and may also not be safe for handling hence

presents a capacity as well as accessibility challenge when it comes to adapting it into small-scale biodigester production. In certain cases, both heat and chemicals are use simultaneously for pre-treatment which is also known as thermo-chemical pretreatment methodology.

Pretreatment of the feedstock mainly impacts the hydrolysis process as hydrolysis is the first stage in the series of reactions where polymers are broken down into monomeric and oligomeric compounds. The presence of lignocellulosic fiber or lignin in organic feedstock put a restriction on this breakdown process and prevents or limits the substrates from being hydrolyzed making the hydrolysis stage a relatively slow process. This also makes hydrolysis the rate limiting stage in anaerobic digestion and controls the lag time on start-up or the initial stage.

In addition to the initial stages, pretreatment techniques are also used to further treat the by-products of anaerobic digestion during the final stages. This includes proper slurry storage and biogas handling.

4.6.2. Utilization of Co-substrate to optimize biogas production and biogas quality

In addition to the main feedstock, some other substrate can be added to the feedstock mixture to improve the anaerobic digestion efficiency as well as improve the quality of final products. In this case, the process is known as co-digestion and recent studies show that co-digestion provides more benefits than the use of one substrate. Based on the parameter that needs to be improved such as the biodegradability of the waste, the methane content in the final product, the C/N ratio, pH, feed composition, percentage of dry material…etc. different co-substrates can be introduced to the digestion process. Additionally, different co-substrate composition adds different macro and micronutrient to the feedstock. Within the agricultural sector, agricultural waste such as strawbale, wheat and rice straws, bagasse can be used as alternative co-substrate for biogas production and provides a cost effective and accessible option to balance nutrients during biogas production than that of utilizing nitrogen containing chemicals. In the case of small scale biodigesters in Ethiopia, the digesters are usually connected to septic tank or toilets and human waste has also been used as a co-substrate while animal manure is utilized as the main feedstock. This in turn facilitates a faster biodegradation as human waste has high biodegradability compared to that of animal manure. Onion peels are also used for (Mr. Zeleke, personal communication, May 13, 2022).

The digester used during co-digestion can also be configured to further improve the production efficiency as well as enhance the added effect of the co-substrate or address particular issues with biogas production. Such examples included the SINIDU biodigester and the Solid State biodigester.

4.6.3. Cleaning of biogas and Biomethanation

Biogas quality can further be improved by removing impurities from the biogas after production such as water, H_2S, CO_2, as well as particles as which apart from reducing impurities will also reduce the risk of corrosion in engines and generators if used as a fuel while increasing the methane content in the biogas. Biogas is upgraded not only to increase its efficiency but to also make it versatile in application and use. In order for biogas to be used for transportation or injected to a grid, it needs to be upgraded to biomethane via biomethanation which is the process of upgrading the methane content in biogas in order to have similar methane value to that of natural gas ranging between 80% - 97% and by injecting H_2 into an anaerobic digester in which the indigenous hydrogenotrophic methanogens convert the H_2 along with the CO_2 in order to generate CH_4 (Bassani et al., 2015). The removal of CO_2 results in a high-quality gas with an increased heating value and increased methane content than that of the average 60-65% used in the assessments made in the thesis (Zhao et al., 2010). As of now, sorption and separation technology are mainly used for CO_2 removal in Biogas production. Another method of increasing methane content in biogas is purification which is the removal of water, H_2S and other trace contaminants or trace elements apart from CO_2 (Akyürek, 2019).

Biogas purification and upgrading technologies as well as methodologies to compress, store and dispense biogas and biomethane are mainly accessible and feasible for large-scale biodigesters. However, for small-scale and farm-level biodigesters, a cost-effective method for purification and upgrading is less accessible and developing and adapting such a technology could provide farmers with their energy needs by providing them with a fuel that can be used in generators to produce electricity or transportation as well as a source of revenue by replacing or complementing electricity costs and making the farmers prosumers (Zhao et al., 2010)

Currently, Ethiopia doesn't have the technology to upgrade biogas and Türkiye is developing the technology under TEMSAN, a company affiliated with the Ministry of Energy and Natural Resources with the aim of producing biomethane rom animal waste. (Castim, 2022) However, lessons could be learned from different countries in Europe such as France, Germany, Denmark, and the Netherlands as well countries like the United States and Canda that have been making use of biogas upgrading technologies and have been incorporating biomethane in their energy mix. Within the EU context,

France and Germany specially are leading examples. France has one of the fastest growing biomethane markets and has been investing the highest among the EU27 into the Biometahne sector (European Commission, 2023b). Similarly, Germany has contributed 1/3 of the total biomethane production in EU27 with the majority of it being produced in biomethane plants that utilize agricultural substrate as a feedstock. It is also interesting to note that the use of biomethane differs from country to country. In the Case of Germany, biomethane is mainly used in electricity generation either in CHP plants or to the grid. On the other hand, in countries like The Netherlands, there is more work being done in using biomethane in the transportation sector with 20% of the total production of biomethane going to the sector. However, similar to other markets, there is still space and opportunities for growth within the biomethane sector and in EU as upgrading biogas has only started in 2011 in the EU (European Commission, 2023b).

The production of biomethane is particularly essential in the context of EU as biomethane is integrated in EU's renewable energy plans as discussed in section 4.4. In addition to that, the recent REPowerEU Plan also highlights biomethanation with hydrothermal gasification being the biomethanation technology presented for wet and organic feedstocks (EBA, 2022). Additionally, The EU also has the EU Biomethane Country Fiches that are in place in order to encourage collaborations between industry stakeholders and countries in the production and utilization of biomethane. Overall, there has been an increase in the production of biomethane over the years in Europe with the majority of biomethanation plants being farm-based. This is particularly of interest within the scope of the thesis as it showcases opportunities and possibilities of growth for farm-scale biogas producers. Hence, there is a space to share experiences and best practices form the already existing biomethane market in EU especially in relation to agricultural biogas production mainly in Türkiye but also Ethiopia.

4.6.4. Improving Biogas and biodigester technologies

The quality of biodigester as well as the efficiency of the conversion technologies also affects the biogas production capacity. The average biogas engine electrical efficiency that was taken in the assessment done in this thesis is 25% and an improvement in the biogas generators that is being used can increase the efficiency and alter the final effective electric generation. Additionally, using high quality material for the construction of biodigester, albeit pricey, can help in keeping the biodigester temperature constant in regions with fluctuating surface air temperature. It can also make the handling of feedstock and biogas easy and can reduce biogas leakage.

5. CONCLUSION

At both global and national levels, it is necessary to diversify the energy mix of total energy supply and consumption. in order to attain clean, affordable, and accessible energy as well as decarbonize different sectors including household and the agricultural sector. In emerging and developing countries, biogas is one of the energy sources with a high potential but seldom utilized. Similarly, within rural and farming communities of Ethiopia and Türkiye, livestock waste is a potential energy source that is not properly utilized. An average Ethiopian and Turkish rural household have a maximum annual biomass potential of 73,598.79 MJ and 29,995.14 MJ respectively just from animal manure. This can address 100 % of a rural household's energy need for Ethiopia and 78% of a rural household's energy need for Türkiye. Moreover, the electricity that can be generated from this biogas potential is Tier 5 for Türkiye and Ethiopia. Hence, a shift from traditional biomass to biogas can address energy access issues that off-grid and rural households face. Moreover, with rising energy prices, households being prosumers rather than just consumers might reduce the economic burden on communities and address energy poverty and affordability concerns. It is calculated that, a rural household with a biodigester can save 100 USD in Türkiye and 200 USD in Ethiopia annually. Additionally, biogas is one of the few renewable energy technologies that can also be used for clean cooking, which is essential when it comes to developing countries such as Ethiopia, in which food security is an important part of the energy discourse. The daily biogas generation potential in Ethiopia and Türkiye can fully address the energy needs of rural households for cooking. However, biogas cookstoves are not as commercially available within the countries, but there is still development within the sector. Biogas usage also reduces the GHG emission of rural communities and livestock sector. The full utilization of the animal manure potential per household can abate an average of 7732 Kg of CO_{2eq} in Ethiopia and 4745 Kg of CO_{2eq} in Türkiye of the total GHG emission that is caused due to the improper manure management as well as GHG emission from other energy sources due to household energy consumption. If biodigester leakage is prevented and biogas is combusted properly in efficient cookstoves, this value can increase to 10,533 Kg of CO_{2eq} for Ethiopia and 7146 Kg of CO_{2eq} for Türkiye.

Despite, all the opportunities, there still exist factors and bottlenecks that hamper the uptake and dissemination of biogas technologies including social factors such as consumer awareness or non-involvement of all stakeholders; financial factors including resource, and capacity constraints; as well as institutional factors relating to policies and frameworks. In order to address the financial constraint, private sector involvement is essential within the biogas sector as well as in biogas production and

promotion. Additionally, the biogas sector and market must be established, developed, and maintained. This can be achieved by centering the energy dialogue around biogas; by setting biogas specific energy plans, mechanism, and targets; by creating an efficient infrastructure and system for sustainable exploitation of biomass for bioenergy production which includes a modern livestock rising methods as well as by developing national, regional and local integrated waste management framework to fully utilize and properly manage the biomass resource present. Database for bioenergy and biomass assessment can also be developed in order to understand the potential present on country and household level and better channel dissemination effort. Türkiye has developed BEPA in that aspect and this can be a lesson learned and best practice that can be adapted for Ethiopia.

On a policy level, developing a framework for the assessment of energy access and emission reduction from biomass and utilization of biomass can also help in further improving the energy targets in place. Additionally, the importance of multi-sector and multi actor engagement and the inclusion of private sectors as well as the diversification of the main organization or program responsible for the implementation and dissemination of the technology.

Additionally, cash incentives and subsidies in place can be beneficial in the short run but is not a sustainable way of supporting the sector for a long term. Hence new methods of supporting beneficiaries throughout the lifecycle of the digester such employing energy and electricity mechanisms as well as feed in tariff that specifically target biogas producers could be explored.

Finally, scaling up the small-scale household biogas sector to the community level so that there will be a centralized biogas production for certain small villages can help in addressing resource utilization challenges currently present. Moreover, community level biodigesters are beneficial and can address some of the financial constraints present as they help share the initial capital cost as well as the maintenance cost among the household in the village or community.

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APPENDIX A: ADDITIONAL SOURCES

Table A.1. List of Interviewees

	NAME	ORGANIZATION	DATE OF INITIAL INTERVIEW/COMMUNICATION
1	Dr. Yisehak Seboqa	Ethiopia's Alternative Energy Technology Dev't and Promotion Directorate	04-08-2021
2	Mr. Mehmet Gultekin	Invest Trading & Consulting AG, Environmental and Quality Manager	19-10-2021
3	Mr. Serkan Anacak	Sütaş Karacabey	22-03-2022
4	Ass. Prof Binyam Zemene	Bahirdar University	25-03-2022
5	Mr. Getu Alemayehu	GM Clean Energy and Fuel Efficient Technology Developer and Disseminator Plc. President of Amhara Improved Cook Stove Association	12-04-2022
6	Mr. Zeleke Ademe	NBPE- Amhara	13-05-2022
7	Mr. Erdem Sahin	Turkish German Biogas Project	07-06-2022
8	Beneficiary 1 (Woman)	Biodigester owner in Sululta Town	12-09-2022
9	Beneficiary 2 (Man)	Biodigester owner in Sululta Town	12-09-2022
10	Dr. Tesfaye Bedane	University College Berlin	03-11-2022
11	Mr. Abiy Girma	Ministry of Water and Energy – National Biogas Programme Coordination Unit	06-03-2023
12	Mr. Carlos Bueso Varela	SNV Ethiopia	22-09-2023
13	Ms. Hiwote Teshome	SNV Ethiopia	22-09-2023
14	Mr. Yetnayet Girmaw	SNV Ethiopia	22-09-2023

Table A.2. Biogas Digesters Inventory - Ethiopia

Year of Installation	Total Capacity	Annual production	Number of digesters	Unit Size	Beneficiaries (People)	Beneficiaries (HH)
2008	490	59,780	98	5	461	98
2009	150	18,300	30	5	141	30
2010	3,655	445,910	731	5	3,436	731
2011	8,205	1,001,010	1,641	5	7,713	1,641
2012	12,555	1,531,710	2,511	5	11,802	2,511
2013	15,750	1,921,500	3,150	5	14,805	3,150
2014	12,315	1,502,430	2,463	5	11,576	2,463
2015	11,300	1,378,600	2,260	5	10,622	2,260
2016	12,765	1,557,330	2,553	5	11,999	2,553
2017	12,955	1,580,510	2,591	5	12,178	2,591
2017	14,945	1,823,290	2,989	5	14,048	2,989
2018	24,888	3,036,336	4,148	6	19,496	4,148
2020	28,116	3,430,152	4,686	6	22,024	4,686
2021	19,446	2,372,412	3,241	6	15,233	3,241
2022	29,370	3,583,140	4,895	6	23,007	4,895

Table A.3. Türkiye Biogas Powerplants Inventory

Plant	Capacity	Year	City	Province
AFYON BIOGAS/Afyon Landfill Gas to Energy Project	4.01	2013	Afyonkarahisar	Afyon
ALTACA MERAM BIOGAS PLANT				
ANKARA KATI	1.5	1997	Ankara	Ankara
BANDIRMA MAURI	3.2	2007	Bandirma	Balekesir
BASMAKCI BIOGAS POWER PLANT PROJECT				
Bolu Landfill Gas to Energy Project, Türkiye				
BOR BIOGAS-SOLAR HYBRID PROJECT				
CANAKKALE LANDFILL GAS POWER PLANT				
Cankiri Landfill Gas to Energy Project				
CICEKDAGI BIOGAS	0.27	2012	Cicekdagi	Kirsehir
DE SOLAR 7 BIOGAS ENERGY PLANT				
FRITO-LAY IZMIT	0.635	2012	Izmit	Kocaeli
FRITO-LAY TARSUS	0.33	2008	Tarsus	Mersin
GAZIANTEP MELIKE	2	2009	Baspinar	Gaziantep
GAZIANTEP NAKSAN	8	2009	Baspinar	Gaziantep
Gazisehir LFG Utilization Project				
GONEN ENERJI	1.067	2012	GOSB Teknopark	Balikesir
GURES SARUHANLI	2.3	2018	Saruhanli	Manisa
Halilbeyli Biogas Plant				
IBB Biomethanation Plant Project				
IBB Seymen Landfill Gas to Energy Project				

Table A.4. Türkiye Biogas Powerplants Inventory (continued)

Plant	Capacity	Year	City	Province
IBB Waste Incineration and Power Generation Plant Project				
Izmir Odemis Biogas Power Plant				
IZMIT IZAYDAS	0.33	2010	41310 Izmit	Kocaeli
KIRSEHIR BIOGAS	1.5		Kirsehir City	Kirsehir
Kuzey Biogas Energy Project				
MAV BOLU BIOMASS	36	2022	Hacikoyu - Goynuk Dist	Bolu
PAMUKOVA AK GIDA	1.487	2011	Pamukova	Sakarya
PANAB CORLU BIOGAS PLANT				
PANAB TEKIRDAG BIOGAS PLANT				
POLAT HOTEL	2	2007	4149 Yesilyurt	Istanbul
POLATLI BIOGAS	0.793	2014	Polatli Dist	Ankara
SAKARYA BIOGAS POWER PLANT				
SAKARYA LANDFILL GAS POWER PLANT				
Samsun Landfill Gas to Energy Project, Türkiye				
SUTAS AKSARAY	2.134	2012	Aksaray City	Aksaray
SÜTAŞ BINGOL BIOGAS PLANT				
SUTAS KARACABEY	1.067	2012	Karacabey Dist	Bursa
Tire Biogas Power Plant				
Tokat Landfill Gas to Electricty Project				
Usak Landfill Gas to Electricty Project, Türkiye				

APPENDIX B: VARIABLES USED WITH SOURCES

Table B.1. Livestock Average Weight – Ethiopia

Livestock Type (L_T)	**Average Live Weight (Kg)**	**Source**
Cattle/Dairy Cow	242	(Li et al., 2023)
	250	(Mekuriaw & Harris-Coble, 2021)
Sheep	27.68	(FAO, n.d.)
	29.1	(Vila & Amane, 2022)
Goat	30	(Gatew et al., 2015)
Poultry	1.045	(Tadesse, 2015)

Table B.2. Livestock Average Weight - Türkiye

Livestock Type (L_T)	**Average Live Weight (Kg)**	**Source**
Cattle/Dairy Cow	310	(Soysal, Gürcan, & Özkan, n.d.)
Sheep	57.85	(Aytekin & Öztürk, 2012)
Goat	57.9	(Koyuncu & Altıncekic, 2013)
	51.83	(Yilmaz, Kor, Ertugrul, & Wilson, 2012)
	57.6	(Daskiran & Koluman, 2014)
Poultry	2.5	(CPTürkiye, 2023)
	2.1	(İnci & Karakaya, 2019)

Table B.3. Average Daily Manure Production Per Animal – Ethiopia

Livestock Type (L_T)	**Average Manure (Kg)**	**Source**
Cattle/Dairy Cow	- 16.94 (7%) - 9.5 - 14.75	(Tadele, 2015) (Tegegne et al., 2007)
Sheep	- 0.5536 - 0.582 (2% of weight) - 0.2768 - 0.291 (1% of weight)	(James Charles Cook et al., 2022)
Goat	- 0.6 (2% of weight) - 0.3 (1% of weight)	(James Charles Cook et al., 2022)
Poultry	-0.021 - 0.136	(Zhang et al., 2023)

Table B.4. Average Daily Manure Production Per Animal - Türkiye

Livestock Type (LT)	**Average Manure (Kg)**	**Source**
Cattle/Dairy Cow	19.2	(BEPA, 2023)
Sheep	2.72	(BEPA, 2023)
Goat	1.81	(BEPA, 2023)
Poultry	- 0.091 - 0.165 - 0.125	(BEPA, 2023) (Big DutchMan, 2023) (Dalkilic & Ugurlu, 2015)

Table B.5. Total Solid and Volatile Solid Content in Manure – Ethiopia

Livestock Type (L_T)	**TS/VS**	**Source**
Cattle/Dairy Cow	- (16.3-18.9 % of TS) / (83.3-87.5 % of VS) - 2.67 VS Kg/d - 1.86 TS Kg/d/h and VS is 93%	(Tegegne et al., 2007) (Gabisa & Gheewala, 2019) (Tolessa, 2023)
Sheep	-0.3 Vs Kg/d) - 0.37 TS. Kg/d/h and VS is 91%	(Gabisa & Gheewala, 2019) (Tolessa, 2023)
Goat	-0.33 Vs Kg/d) - 20% for TS and 77.4% for VS - 0.42 TS. Kg/d/h and VS is 60%	(Gabisa & Gheewala, 2019) (Hailu & Chimdessa, 2020) (Tolessa, 2023)
Poultry	-0.02 (Vs, Kg/d) - [22.9-24.1] (% of TS Kg manure)/ [85-90.8] (% of VS Kg manure) - 0.05 TS Kg/d/h and VS is 47%	(Gabisa & Gheewala, 2019) (Menta, 2020) (Tolessa, 2023)

Table B.6. Total Solid and Volatile Solid Content in Manure – Türkiye

Livestock Type (L_T)	**TS/VS**	**Source**
Cattle/Dairy Cow	- 2.8 (for VS Kg/head in a day) - [20,12,10] (% of TS Kg manure)/ [80,89] (% of VS Kg manure)	(Balcioglu, Jeswani & Azapagic, 2022)
Sheep	- 30 % of TS Kg manure, 20% of VS Kg manure - 37.2 of TS Kg manure - [40-61.4] (% of TS Kg manure)/ [51-81] (% of VS Kg manure)	(Avcioğlu & Türker, 2012) (Melikoglu & Menekse, 2020) (Altan, Orhon & Sozen, 2022)
Goat	- [47.1-51.5] (% of TS Kg manure)/ [79-89] (% of TS Kg manure) - 32% of VS Kg manure	(Altan, Orhon & Sozen, 2022) (Pence, Kumaş, Siseci, & Akyüz, 2023)
Poultry	- [27,35] (% of TS Kg manure)/ [70,80] (% of VS Kg manure) - [20-25] (% of TS Kg manure)/ [55-65] (% of VS Kg manure)	(Dalkılıc & Ugurlu, 2015) (Balcioglu, Jeswani & Azapagic, 2022)

Table B.7. Biogas Yield from Manure - Ethiopia

Livestock Type (L_T)	**m^3/KgVs**	**Source**
Cattle/Dairy Cow	- 0.23 - 0.5	(Tolessa, 2023) (Teferra &Wubu, 2018)
Sheep	- 0.28 - 0.3	(Tolessa, 2023) (Teferra &Wubu, 2018)
Goat	0.290	(Tolessa, 2023)
Poultry	- 0.18 - 0.031	(Tolessa, 2023) (Menta, 2020)

Table B.8. Biogas Yield from Manure - Türkiye

Livestock Type (L_T)	**m^3/Kg VS**	**Source**
Cattle/Dairy Cow	- 0.4, 0.33, 0.31 - 0.39	(GMI, 2012) (Dong et al., 2019)
Sheep	- 0.3- 0.4 - 0.1 0.31	(Melikoglu & Menekse, 2020) (Pence, Kumaş, Siseci, & Akyüz, 2023)
Goat	- 0.1 0.31	(Melikoglu & Menekse, 2020) (Pence, Kumaş, Siseci, & Akyüz, 2023)
Poultry	- 0.6, 0.35 - 0.554	(GMI, 2012) (Pence, Kumaş, Siseci, & Akyüz, 2023)

Table B.9. Average Herd Size per HH

Livestock Type (L_T)	**Herd size per HH (Türkiye)**	**Source**	**Herd size per HH (Ethiopia)**	**Source**
Cattle/ Dairy Cow	- 7.8-9.4 - 2.89-3.9	(Yilmaz & Akbas, 2010) (Gumus, Olgun, & Adanacioglu, 2010)	- 8.3 - 4.5-21.1	(Minase, Masafu, Geda, & Wolde, 2015) (Mekuriaw & Harris-Coble, 2021)
Sheep	4.83	(Gumus, Olgun, & Adanacioglu, 2010)	- 4.3 - 1.1-9.5	(Minase, Masafu, Geda, & Wolde, 2015) (Mekuriaw & Harris-Coble, 2021)
Goat	1	(Gumus, Olgun, & Adanacioglu, 2010)	- 0.5-13.8	(Minase, Masafu, Geda, & Wolde, 2015) (Mekuriaw & Harris-Coble, 2021)
Poultry	- 5.11 - 16.05	(Gumus, Olgun, & Adanacioglu, 2010) (Wilson, 2017)	- 7.6 - 3	(Minase, Masafu, Geda, & Wolde, 2015) (Mekuriaw & Harris-Coble, 2021)

Table B.10. Manure Collection Efficiency

Livestock Type (L_T)	**Collection Efficiency (Türkiye)**	**Source**	**Collection Efficiency (Ethiopia)**	**Source**
Cattle	41% 50%	(Özer, 2017) (Ekinci & Kulucu, 2010)	43%	(Tolessa, 2023)
Sheep	41% 13%	(Özer, 2017) (Ekinci & Kulucu, 2010)	32%	(Tolessa, 2023)
Goat	41% 13%	(Özer, 2017) (Ekinci & Kulucu, 2010)	29%	(Tolessa, 2023)
Poultry	99% 13-19%	(Özer, 2017) (Ekinci & Kulucu, 2010)	68%	(Tolessa, 2023)

APPENDIX C: DATA OBTAINED FROM DATABASES

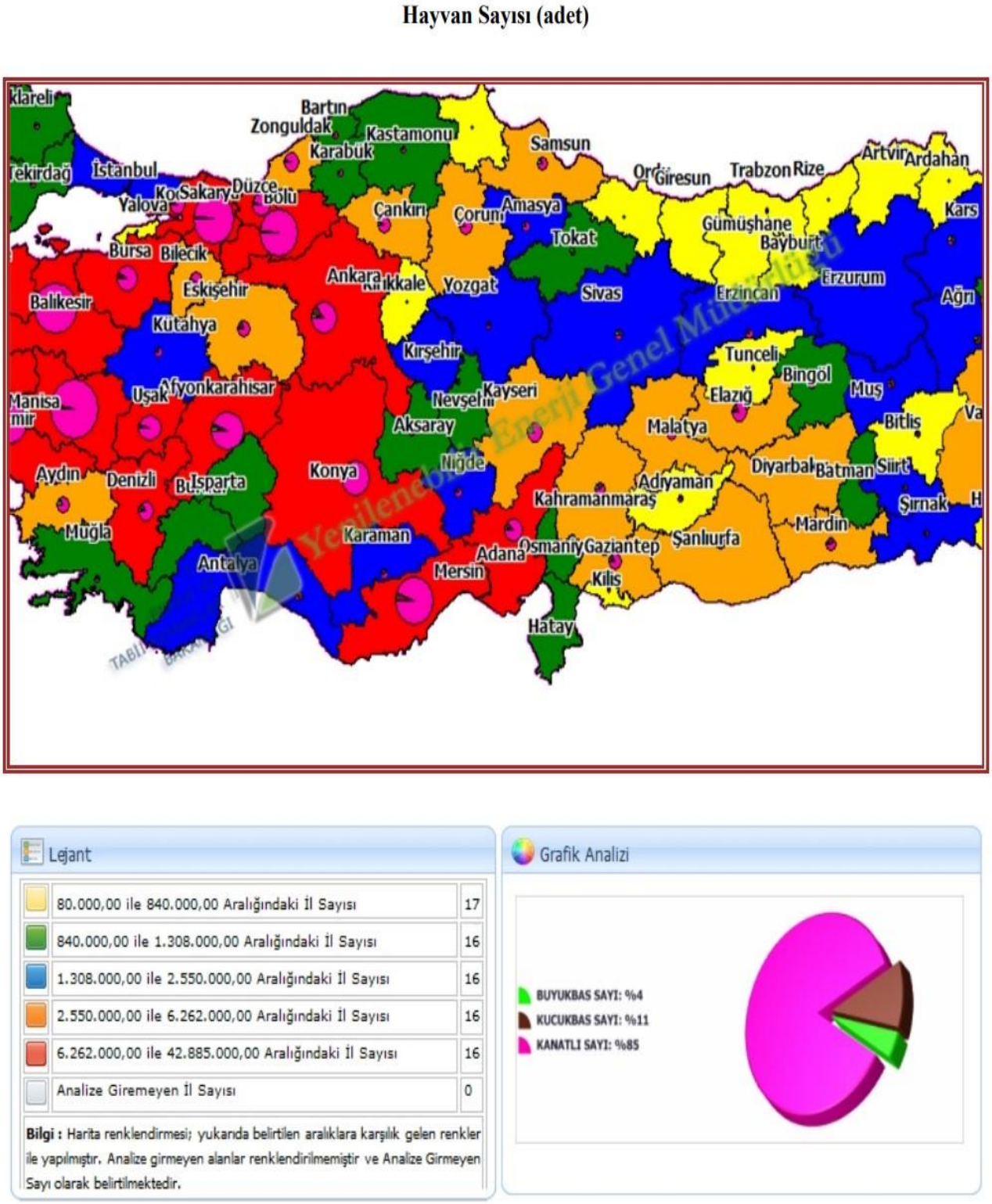

Figure C.1. Livestock Population Across Türkiye

Table C.1. Total N_2O emission from manure management

N_2O Emission (Tonnes of CO_{2eq})	ETHIOPIA 2020	ETHIOPIA 2021	TÜRKIYE 2020	TÜRKIYE 2021
Cattle	335,935.4	322,018.8	144,649.2	143,874.4
Sheep	43,508.0	39,127.4		
Goat	18,416.4	16,628.4		
Poultry	10,012.8	10,400.2	107,697.2	110,587.8

Table C.2. N_2O emission from manure left on pasture

N_2O Emission (Tonnes of CO_{2eq})	ETHIOPIA 2020	ETHIOPIA 2021	TÜRKIYE 2020	TÜRKIYE 2021
Cattle	31,793,441.2	29,988,604.2	10,232,902.8	10,199,795.0
Sheep	3,390,048.0	3,049,970.4	3,361,410.2	3,604,846.4
Goat	5,199,384.8	4,688,642.6	1,199,867.2	1,235,448.4
Poultry	207,020.6	215,126.2	1,278,688.2	1,313,375.4

Table C.3. N_2O emission from manure applied to soil

N_2O Emission (Tonnes of CO_{2eq})	ETHIOPIA 2020	ETHIOPIA 2021	TÜRKIYE 2020	TÜRKIYE 2021
Cattle	528,115.6	546,353.2	283,785.4	282,176.2
Sheep	65,917.6	59,302.0		
Goat	105,045.0	94,734.2		
Poultry	28,548.4	29,651.0	306,910.2	315,224.4