POLITECNICO DI TORINO

Collegio di Ingegneria Energetica

Master of Science Course

in Energy and Nuclear Engineering

Master of Science Thesis

Assessment of a biomethane production route for public transport in the context of the Italian incentivation framework

Tutors:

Chiaramonti David

Noussan Michel

Testa Lorenzo

Candidate:

Platania Mattia

RINGRAZIAMENTI

Prima di procedere con la trattazione, desidero dedicare qualche riga a tutti coloro che mi sono stati vicini in questo lungo percorso di crescita, sia professionale che personale.

Un sincero ringraziamento va al mio relatore, Michel Noussan, per la sua infinita disponibilità e tempestività nel rispondere a ogni mia richiesta. Grazie per avermi fornito tutti i materiali necessari per la stesura di questo elaborato.

Dedico questo traguardo a chi mi vuole bene, mi ama e mi ha sempre amato; in particolare, a due figure che, vedendomi crescere, hanno profondamente influenzato il mio modo di pensare e di vivere: mia madre e mio nonno. Senza il loro costante supporto, non avrei mai potuto celebrare questo piccolo successo.

Un ringraziamento speciale va alla mia famiglia: alle mie due sorelle e ai miei nipotini, che mi hanno insegnato tanto e che spero di poter ringraziare appieno in futuro. Ai miei zii, cognati, cugini, alle mie nonne che non sono più tra noi, e a mio padre.

Dedico questo traguardo anche ai miei amici e compagni più cari: a Francesco e Alessandro, figure importanti nel mio percorso di crescita personale; a Beatrice e Ludovica, ad Alessio e Giovanni, a Matteo e Silvia, a David e Lore e a tutte le altre persone speciali che ho avuto il piacere di conoscere al Politecnico, a lavoro, in Spagna e a Roma. Grazie a tutti voi, senza il vostro sostegno non ce l'avrei mai fatta.

Infine, dedico questo traguardo a me stesso, con la consapevolezza che lungo il cammino della vita avrò modo di raggiungere altri successi.

SUMMARY

ABSTRACT

This thesis work presents a comprehensive assessment of biomethane potential demand for public transportation within the context of the Italian incentivization framework. The study aims to evaluate the energy demand and atmospheric CO_2 savings of integrating biomethane as a renewable energy source for urban transit systems, with a particular focus on the Metropolitan Area of Turin. The research begins by contextualizing global energy production and emissions, highlighting the pressing need for sustainable alternatives to fossil fuels. Biomethane, a renewable form of energy derived from biogas, is identified as a viable candidate for reducing greenhouse gas emissions in the transport sector. The thesis reviews the biomethane production process, detailing the conversion of organic waste into biogas and subsequent upgrading to biomethane. It also examines the current status and future potential of biogas and biomethane in both European and Italian contexts, noting recent legislative developments such as the Italian "Decree Biomethane." A detailed analysis is conducted on the state of biomethane production and demand in the Turin metropolitan area. This includes an examination of existing biogas facilities, potential feedstocks, and the logistical aspects of integrating biomethane into the local public transport system operated by Gruppo Torinese Trasporti (GTT). Various production scenarios are modeled to estimate biomethane supply and match it against the projected demand from the public transport fleet. Furthermore, the thesis includes a well-to-wheel (WTW) analysis to estimate CO_2 equivalent (CO_{2e}) emissions across different fuel types. This analysis provides a comparative assessment of the environmental impact of biomethane versus traditional fossil fuels, considering factors such as fuel production, distribution, and consumption. The findings suggest that biomethane can significantly reduce CO_{2e} emissions of the public transport fleet, aligning with both local and national climate objectives. Economic analyses indicate that, under the current incentivization schemes, biomethane production is financially viable and can compete with conventional energy sources. In conclusion, the thesis advocates for the adoption of biomethane as a sustainable energy solution for public transport in Italy. It provides policy recommendations to enhance the biomethane sector, emphasizing the need for continued financial incentives, infrastructure development, and public-private partnerships to facilitate the transition towards greener urban mobility. This study contributes to the broader discourse on renewable energy integration in transportation, offering valuable insights for policymakers, energy engineers, and stakeholders in the renewable energy sector.

1. INTRODUCTION

1.1. GLOBAL ENERGY AND EMISSION PRODUCTION CONTEXTUALIZATION

ATMOSPHERIC EMISSION PRODUCTION AND REDUCTION: CHRONOLOGICAL CONTEXTUALIZATION

Since the beginning of the First Industrial Revolution around 1760, passing through the Second and up to the present day, humans have exploited and mistreated the environment, generating pollution and greenhouse gas emissions. As demonstrated by the largest opinion of the scientific community, the emission of greenhouse gases, such as carbon dioxide, has negatively impacted the planet and its ecosystems. To monitor the effects of GHG and assess all relevant scientific information to fight global warming, the global community established dedicated organizations, such as the IPCC in 1988. However, the negative effects of greenhouse gases have been recognized scientifically since the previous century. The first study to demonstrate a relationship between the concentration of carbonic anhydride in the atmosphere and the alteration of the Earth's climate was published in 1896 by Swedish chemist and physicist Svante Arrhenius, who developed an explanation for ice ages on Earth directly correlated with fluctuations in atmospheric CO_2 levels and caused an increase in global temperatures [1]. Only at the end of the 20th century, the Governments start to highlight the relevance of this issue adequately; in chronological terms, the first common position taken by the global warming policy can be found in the United Nations Framework Convention on Climate Change (UNFCCC), an international treaty signed at the Earth Summit held in Rio de Janeiro in 1992. The objective of this agreement was to stabilize greenhouse gas concentrations in the atmosphere to prevent dangerous human interference with Earth's climate system. However, this treaty did not impose mandatory limits on greenhouse gas emissions in individual nations, thus making it a legally non-binding agreement. In 1997, a protocol that took its name from the Japanese town of Kyoto was signed, in which over 160 countries participated during UNFCCC COP3. Unlike the Convention of the Rio Summit five years earlier, the Kyoto Protocol set binding emission reduction targets for the first time in history, which are constraints aimed exclusively at nations corresponding to industrialized countries. Entered into force on February 16, 2005, with the ratification of the Russian Federation and Canada, the 37 industrialized countries reduced their emissions of six types of greenhouse gases (CO_2, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride) in the first phase, corresponding to the five years 2008-2012, by at least 5% compared to 1990 levels, and the second phase, completed in 2020, aimed to reduce emissions of the six gases by 18% [2]. The major limitation of this protocol was the failure to include developing countries (especially big polluting nations like China and India) in the transposal of these restrictions, since this category of countries has been subjected to exponential growth in their economy and hence in their atmospheric emission production. This growth, however, appears to be attributable less to strict consumption of energy resources for domestic distribution of goods and more to their marketing to developed countries.

Following the emission production trend, with the advent of the new millennium, both political and public opinion have made progress in understanding the urgency of taking action to combat climate change through the adoption of actions aimed at reducing emissions of gases with considerable environmental impact. Indeed, another fundamental progression of global policy was made during the 21st Conference of the Parties in Paris (COP21) in 2015, in which 197 countries signed the current most ambitious global climate pact, also known as the Paris Agreement. Coming into force in 2016, the Paris Agreement is a global and legally binding action plan that aims to significantly address global warming. Its main objective is to reduce global warming to levels well below 2°C compared with pre-industrial periods, intending to limit the temperature rise to only 1.5 ºC [3].

GLOBAL ENERGY TREND

The success of limiting the global temperature rise in line with the Paris Agreement goals is strictly related to the effectiveness of greenhouse gas emission reduction policies, and hence, to the implementation of energy directives by governments during the following years. Indeed, one relevant goal of the parties is to redesign the energy mix of every country, considering their level of economic development and meeting their predicted growing internal energy demand simultaneously.

Aiming to promote and monitor energy transitions and sustainable development, the International Energy Agency (IEA) provides a comprehensive and analytical view of the global energy market and energy trends through annual publication of the "World Energy Outlook" (WEO) report. Widely used as an authoritative source of information and analysis in the energy sector, the WEO generally describes different scenarios for the future of energy to examine how policy choices and economic trends might affect the global energy and environmental landscapes. The following three scenarios were analyzed in the WEO 2023 edition [4]:

- The Stated Policies Scenario (STEPS) portrays the current trajectory of the energy economy, illustrating existing policies and measures in various sectors, countries, and regions, without assuming the achievement of ambitious energy or climate goals. The STEPS scenario predicts a temperature increase of 2.4°C by 2100 with a 50% probability.
- The Announced Pledges Scenario (APS) assumes that all climate commitments announced by governments, including long-term net zero emissions targets, Nationally Determined Contributions (NDCs), and business commitments, are met in

a timely and comprehensive manner. The APS estimates a temperature increase of 1.7°C by 2100 with a 50% probability.

- The Net Zero Emissions by 2050 (NZE) scenario envisions a limitation of the global temperature increase to 1.5°C above pre-industrial levels by 2100 with at least a 50% probability and limited overshoot.

The growing global population and improved living standards have led to an increase in energy consumption, with the total global energy demand anticipated to rise from approximately 630 exajoules (EJ) to 670 EJ between 2022 and 2030, as outlined in the STEPS scenario report. This represents an average annual growth rate of 0.7%, which is approximately half of the rate of energy demand growth over the past decade. Energy demand will continue to grow from 2030 to 2050, with a 16% increase in emerging markets and developing economies, more than compensating for the 9% decline in advanced economies. In contrast, the Announced Pledges Scenario (APS) predicts a decrease in total energy demand by an average of 0.1% per year until 2030 owing to the accelerated deployment of renewables, increased energy efficiency, and quicker electrification than in the STEPS scenario.

According to the STEPS scenario, the total final energy consumption (TFC) is expected to increase by 1.1% annually by 2030, and continue to rise at a slower pace by 2050. In the APS, the TFC increased until the mid-2020s, before beginning a gradual decline. In the NZE Scenario, TFC is anticipated to decrease by an average of 0.9% annually from the present until 2050.

The global energy consumption and demand increment described by the STEPS scenario are related to the economic and industrial rise that will continue to characterize developing countries. Among these, the BRICS organization was responsible for 40% of the total world energy consumption [5] and 45% of global CO_2 atmospheric emissions in 2018 [6]. In Figure 1, taking a glance at the columns, we can observe the relevant weight of emerging world regions according to the STEPS and APS scenarios concerning energy intensity. However, it can be observed on the dots that these countries are characterized by lower levels of energy consumption per capita than first-world countries. In particular, continents such as Africa, South America, and India, on average, show energy consumption values per capita that are between two and eight times lower than those reported in developed countries.

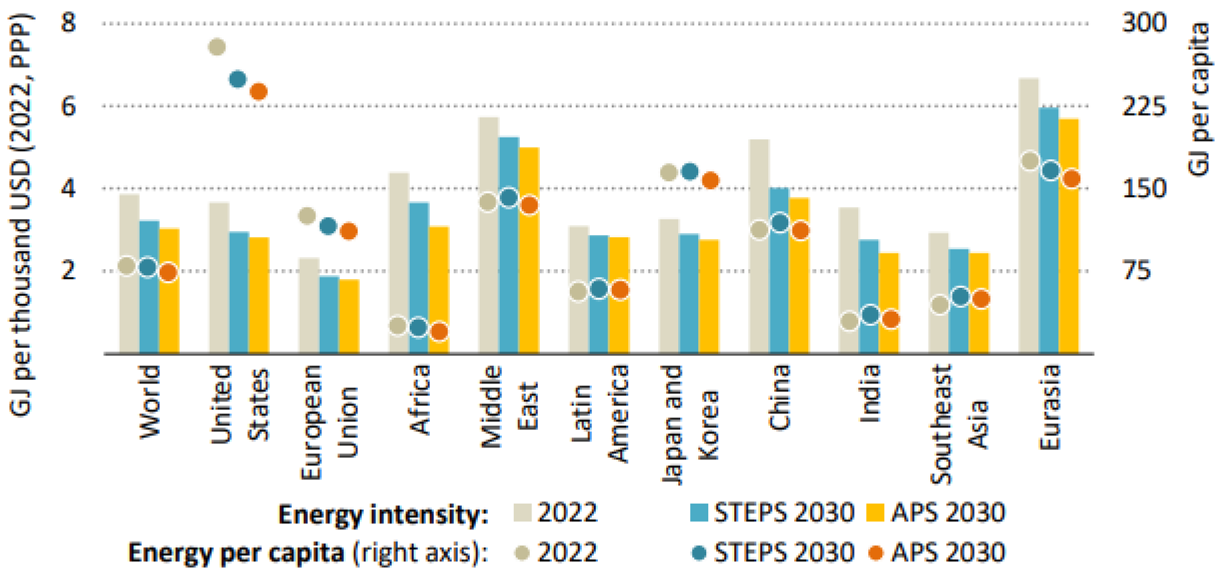

Figure 1: Energy intensity and energy per capita in selected regions trends for STEPS and APS, in 2022 and 2030 [4]

Developed countries have implemented important regulatory steps aimed at reducing the impact of the energy sector on the atmosphere. In contrast to the escalating global trajectory of energy demand, the final energy consumption within the European Union declined from 2010 to 2022, a departure from the prevailing trend in most world regions. The reduction in energy consumption can be attributed to heightened energy efficiency resulting from recent energy policies implemented by the European Union, the increased rate of electrification in final consumption, and the distinctive energy mix of the EU, characterized by a greater share of renewables compared to other geographical areas. Indeed, the EU energy policy has defined future regulations and directives to further improve the energy sector system, with the approval of measures such as the Fit for 55 and RePowerEU frameworks*.

**Note - Fit for 55: the plan, aiming to reduce GHG emissions by 55 percent by 2030, includes interventions in transportation, industry and buildings to accelerate the transition to a low-carbon economy; RePowerEU: the plan aims to reduce dependence on Russian fossil fuels, boost renewable energy and improve energy efficiency.*

TRANSPORT SECTOR: ENERGY CONSUMPTION AND ITS TREND

According to final energy consumptions, in recent decades the transport sector, which is the third most energy-intensive sector in the world, following the industrial and building sectors [4], has attracted the attention of competent governments and organizations, setting goals to reduce energy consumption, increase overall efficiency, and increase the share of energy from renewable sources.

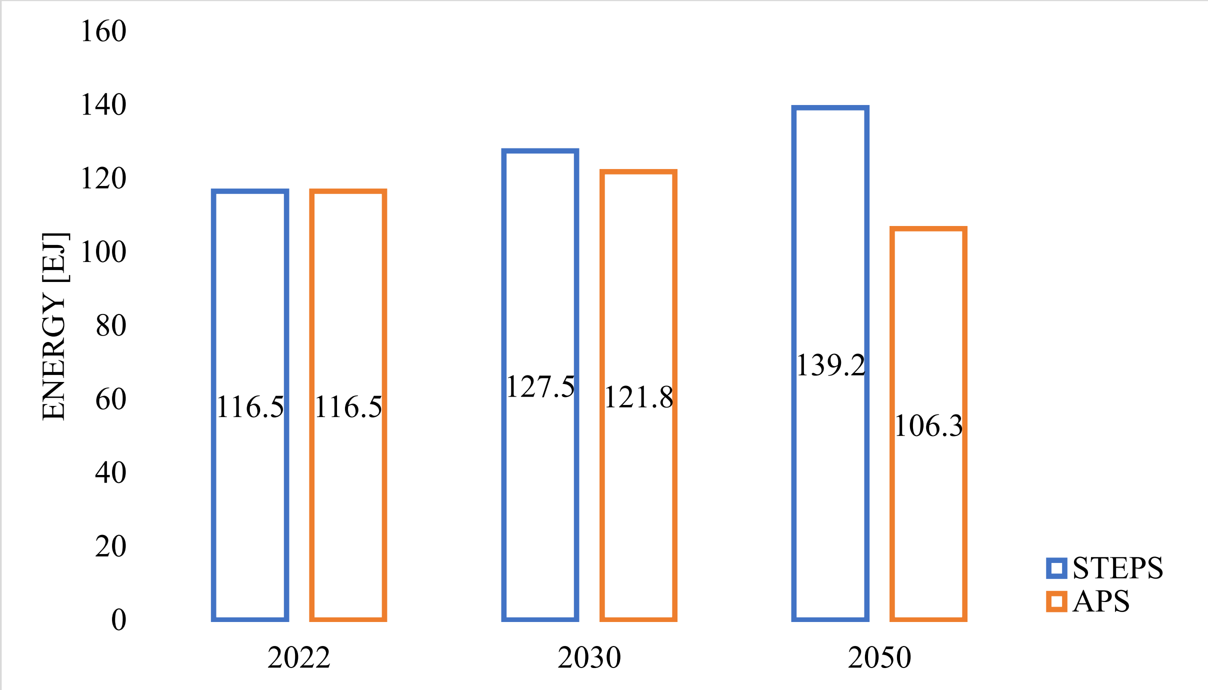

Figure 2: Global transport energy consumption trend, WEO 2023 data processing [4]

The transport sector consumption, which increased globally by 4% in the previous year, accounted for more than a quarter of the total world final consumption in 2022 (26%); the demand increased globally by 4% with respect to 2021 (112,4 EJ), effect due to the recovery of the transportation sector following the restrictions due to the pandemic in 2020 and 2021. As shown in Figure 2, the amount of energy consumed increases by 2030 in both STEPS (+8.6%) and APS (+4.4%) scenarios. In 2050, further growth is expected in STEPS and a fall in APS. In the first scenario, further growth in consumption is expected to be 8.4 percent, whereas in the second scenario, they are expected to decrease in percentage terms by 14.6 percent. The WEO 2023 document does not report any information regarding the expected energy consumption in 2030 and 2050 in the NZE scenario; however, a larger reduction than in the APS scenario is expected due to a more developed electrification of the sector. According to STEPS, the projected energy increases are the result of an increase in the number of vehicles registered in the world, particularly in developing countries, corresponding to a 15% increase in the global car fleet and a similar trend for buses. In addition, over the same period, the truck fleet increased by over 10%, and aviation activity and energy demand doubled from the current level.

As shown in Figure 3, the oil share for road transport in 2022 accounts for 92% of the transport energy consumption, demonstrating the strength of the dependency between the sector and oil consumption. By 2030, this value will decrease to 88% for STEPS, 84% for APS, and 78% for NZE. In the latter scenario, only approximately 7% of the share will come from oil in the NZE by 2050.

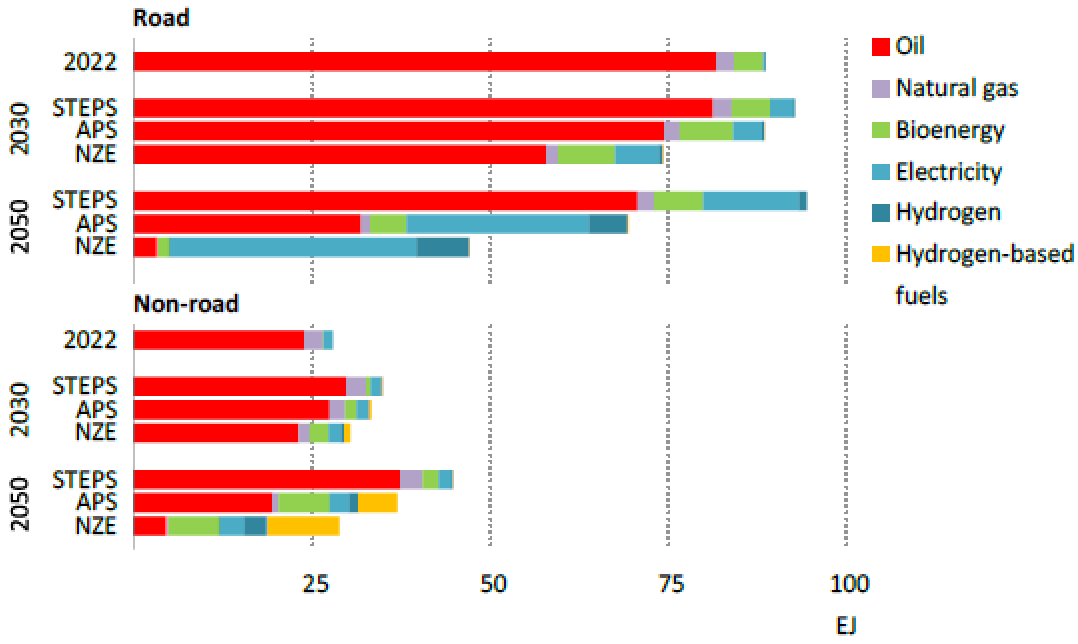

Figure 3: Global energy demand in transport by fuel and scenario, 2022-2050 [4]

According to STEPS and APS, the contribution of biofuels in road transport will play a growing role in the final consumption between 2030 and 2050, while in the Net-Zero Scenario the reduction in energy consumption will be mainly due to the development of electrification of the global vehicle fleet and hydrogen consumption. Considering air and sea transport, the STEPS and APS show increasing global energy consumption until 2050, whereas in the NZE, there is an increase until 2030, followed by a decrease until 2050. The contribution of oil to the energy mix will decrease in the NZE and APS, leaving room for the use of biofuels and e-fuels (both of which fall under the so-called sustainable aviation fuel or SAF).

The future reduction in oil consumption in the global transport energy mix is mainly caused by the increasing use of biofuels and the increase in electric vehicles on the road, which results in a 12 and 15 times increase in the demand for electricity in the transport sector in STEPS and APS, respectively. Electric car sales were up to 55% in 2022, led by China, Europe, and the United States, reaching 14 million units.

Strong policy support, particularly in the EU, the United States, and China, is helping the electric vehicle market grow and become competitive to face a reduction in emissions from the transport sector. Considering the Old Continent, on October 31, 2023, the third directive on renewable energy (RED III) was published, which bound each Member State to the reduction of greenhouse gas emissions by 14.5% (compared to the levels recorded in 1990) or a 29% increase in the share of energy from renewable sources in the final consumption in the transport sector by 2030.

The European Union has set concrete objectives in the political-jurisdictional field regarding the transport sector and its final consumption, including a strategy to increase the share of SAF under the ReFuelEU Aviation package (approved on October 9, 2023); SAF produced from biomass and renewable energy conversion will make up 6% of the fuel supplied at airports by 2030, up to 70% by 2050, year in which the European Commission previews approximately two-thirds of the abatement of the emissions of CO_2 of the aircraft, compared to the present level [7]. It is important to mention the decision of March 25, 2023, by the European Energy Ministers, who ratified with a large majority the stop to the sale and marketing of light-duty vehicles with internal combustion engines by 2035, except for vehicles fueled by synthetic fuels (e-fuel). This sentence raised doubts about the techno-economic feasibility of the measure; This question mark has turned into abstention in the votes of members such as Italy, Bulgaria, and Romania, following requests not granted on the postponement of the deadline for the final decision on their inclusion.

Globally, the Union's complex policy approach to biofuels and their use in the transport sector has been defined with opportune regulations but lacks a long-term perspective, and risks undermining the EU's transport decarbonization goals, as noted in an analysis by the European Court of Auditors [8]; indeed, biofuels play a transitional but crucial role in achieving the climate and energy goals previously set and on schedule.

1.2. BIOFUELS: A USEFUL BRIDGE TO ENERGY TRANSITION

The use of biofuels in the transportation sector dates back to the nascent stages of the automotive industry, when Rudolph Diesel's early experiments on his namesake engines involved the combustion of peanut oil before diesel. Biofuels and their production chains experienced strong commercial expansion until the 1940s, with bioethanol blends finding wide applications in the United States, Europe, and other regions. However, the post-war period saw a decline in the development of bioethanol and other biofuels, owing to the greater affordability of petroleum-derived fuels. Subsequently, the oil crisis of the 1970s rekindled interest in the return of their commercialization on a global scale. Since then, there has been renewed support for domestic biofuel industries in the United States and many European countries driven by rising per-barrel crude oil prices and energy security concerns regarding the wider differentiation of energy sources. This interest has further increased over the past two decades, fueled by climate-change mitigation policies and strategies to reduce greenhouse-gas emissions from the transportation sector. Consequently, more than 60 countries have established biofuel development programs and blending mandates within their fuel pools [9].

Biofuels, derived from renewable biological resources, offer a range of advantages that make them a compelling option for energy transition. They can be produced from various feedstocks, including crops, forestry residues, and municipal waste, making them readily available and geographically diverse, without special difficulties related to raw material supply.

Anyway, it must be mentioned that the wide availability of raw materials contrasts with high transportation costs and additional emission impacts related to their supply; indeed, additional emissions at the Well-to-Tank (WTT) stage mainly include those resulting from the harvesting, transportation, and processing of biomass into biofuel. These emissions include both CO_2 produced during the combustion of fossil fuels used in agricultural machinery and transport vehicles, and other greenhouse gases such as methane (CH_4) and nitrous oxide (N_2O) released during the anaerobic digestion process and residue management. These emissions need to be accounted for to get a complete picture of the environmental impact of biofuel, as they can significantly reduce the overall benefits compared to other renewable energy sources. Another relevant aspect to consider is competition with other land uses. In the case of biomethane, biomass production associated with it may conflict with agricultural use for food production, leading to increases in food prices and potential food security issues. In addition, Direct Land Use Change (LUC) and Indirect Land Use Change (ILUC) pose significant challenges. LUCs include the conversion of forests or other natural ecosystems to agricultural land for biomass cultivation, while ILUCs refer to land use changes that occur indirectly, such as when land previously used for food production is converted for biomass production, pushing food production to new areas and potentially causing further deforestation.

To conclude the overview, biofuels possess a net-zero carbon footprint because their combustion releases carbon dioxide, which was previously absorbed by the plants used to produce them. In addition, most biofuels can be blended with conventional fuels and used in existing vehicles, requiring minimal infrastructure changes, and can help to decarbonize specific transport segments, such as maritime and air transportation, which are technically more complex and challenging. In the realm of economics, the production costs of certain biofuel typologies have almost reached a break-even point compared with traditional fossil fuel costs, allowing for technical improvements and a move to more favorable financing terms.

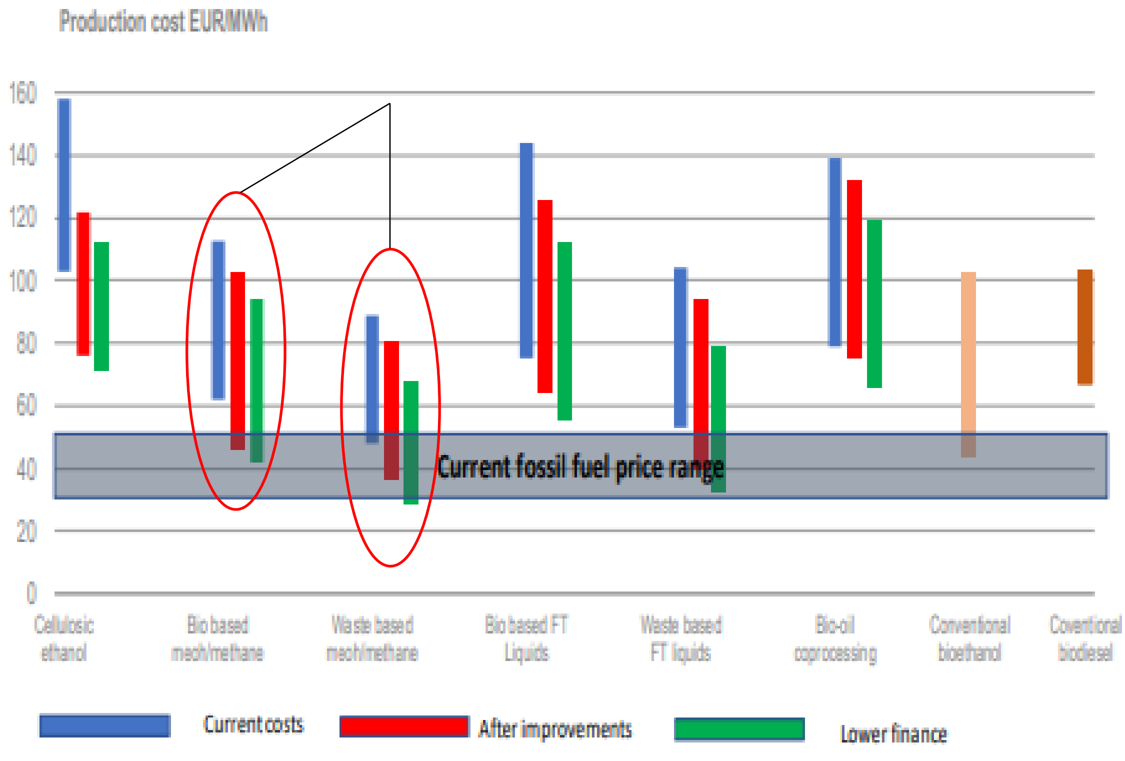

Figure 4: Advanced and conventional biofuels production costs, considering potential cost reductions [10]

As shown in Figure 4, there is globally a consistent gap between the costs of biofuels and fossil alternatives; however, waste-based fuel and bio-based methane processes (highlighted in the Figure) are an exception. The analysis shows that these technologies currently have the potential to compete with fossil fuel prices, where raw material costs are low (e.g., when raw materials can be procured at significantly negative costs). In the long term, the cost gap can be further reduced through experiential learning depending on the learning rate that can be achieved and whether raw materials are available at reasonable prices. In addition, this gap can be closed through policies that increase revenue, such as certificate-based systems, and provide funds to scale up renewable fuels, such as biomethane.

1.3. BIOMETHANE

WHY BIOMETANE?

Biomethane is a renewable natural gas produced through the anaerobic digestion of organic materials such as agricultural waste, sewage sludge, organic household waste and food waste. The production process begins with the collection of biomass, which generally then undergoes anaerobic digestion in digesters, where microorganisms decompose the organic material in the absence of oxygen, generating biogas. This biogas consists mainly of methane (CH_4) and carbon dioxide (CO_2), along with traces of other gases. The raw biogas is then purified through an upgrading process, which removes carbon dioxide, water vapor, hydrogen sulfide and other impurities, resulting in biomethane, which has a similar composition to fossil natural gas and can be used as a fuel for heating, electricity generation and as a vehicle fuel.

Thanks to its wide range of use mentioned above, the urgency to expand biomethane production in Europe has never been greater, especially with the need to decrease reliance on natural gas imports from Russia, combat high-energy prices, and address climate crises. According to IEA investigations, biomethane results to be the most cost-effective and rapidly expandable renewable fuel gas in Europe in 2019 [10]. Consequently, the European Commission, in its recent REPowerEU plan endorsed on May 18, 2022, has set a target to boost the annual EU production and utilization of sustainable biomethane to 35 billion cubic meters by 2030, with an estimated total investment requirement of €37 billion for the period [11]. Additionally, the Commission has introduced the establishment of a Biomethane Industrial Partnership (BIP), where policymakers, industry representatives, and other stakeholders collaborate to facilitate the attainment of the targeted annual production and utilization of sustainable biomethane by 2030 and lay the groundwork for further expanding its potential by 2050. The following paragraph describes the social, economic, and environmental benefits of biomethane production.

- **Greenhouse Gas Emission Impact**: Biomethane is a versatile and renewable energy source that can be utilized in various sectors including transportation, heating, and power generation. It can directly replace fossil fuels in major parts of these industries, and has the potential to significantly reduce greenhouse gas emissions. Furthermore, diffuse emissions from the agricultural sector can be avoided by using manure as a raw material for biomethane production. This is a valuable solution that can support efforts to reduce global methane emissions, such as the Global Methane Commitment aimed at reducing methane emissions by 30% by 2030 compared to the 2020 levels. Similar benefits arise when organic waste streams from other sectors, such as biowaste, are treated using anaerobic digestion. Finally, using digestate instead of synthetic fertilizers can also reduce greenhouse gas emissions because the production of synthetic fertilizers is energy intensive; anyway, it is important to pay attention to the containment of potential methane leakage in its supply chain so that the resulting environmental benefits are not nullified.

- **Energy Security**: Europe relies heavily on energy imports, including natural gas. Considering the recent Russian-Ukrainian and Israel-Hamas conflicts, the need for natural gas imports could be reduced, thereby directly improving Europe's energy independence and security.
- **Provision of biogenic carbon dioxide**: Biomethane production through anaerobic digestion and thermal gasification produces a pure biogenic carbon dioxide (CO_2) stream. Biogenic carbon dioxide can be used as a raw material for a variety of industrial applications, largely replacing fossil sources of carbon dioxide or in new applications, such as renewable fuels, chemicals, and algae production. Alternatively, they can be permanently stored in geological formations (such as a closed saltwater layer on the seafloor) to remove greenhouse gases. Such emission reductions are crucial for achieving net zero targets as they offset unavoidable emissions from other sectors, but their realization appears to be expensive and the technology not commercially scalable yet.
- **Organic waste processing**: Biomethane production from organic waste feedstock provides both waste processing and energy generation services, leading to an increased economic viability. Furthermore, this process is crucial for promoting the circular economy by repurposing organic waste into valuable resources, including renewable energy and nutrient-rich digestates, which can be reintroduced into the soil.
- **Soil Health**: The utilization of anaerobic digestion in the production of biogas results in the generation of nutrient-rich digestates. The application of these digestates to agricultural soil improves a variety of soil health indicators and results in sequestration of organic carbon. Its rich organic content supports the recovery of degraded soils, which is beneficial for long-term sustainability of agriculture. By spreading fermentation residues into the soil, most of the nutrients contained in the raw materials can be recovered, reducing the need for synthetic fertilizers derived from fossil raw materials and promoting a circular economy.
- **Job creation**: Biomethane production is expected to contribute to the creation of between 1.1 and 1.8 million jobs across the value chain in Europe by 2050 [12]. The decentralized production model of biomethane through anaerobic digestion based on agricultural wastes, residues, and sustainable crops is expected to bring new employment benefits, especially in rural regions across Europe. In contrast, biomethane production from thermal gasification is expected to lead to employment benefits in more centralized production facilities located near sustainable forest-based industries or urban areas from which the feedstock will be collected.

According to IEA research data, biomethane “indirect” benefits range in total from 84€ to 175€ per megawatt hour (MWh) for anaerobic digestion and between 80€ and 162€ per MWh for thermal gasification, considering two scenarios of lower and higher externalities, respectively [12]; specifically, the higher externality value for anaerobic digestion largely results from the higher greenhouse impact due to reducing fugitive emissions in agriculture, benefits from the application of digestate (replacing synthetic fertiliser) and organic waste processing, as well as a lower cost of production which increases the overall value of energy security. It must be pointed that fugitive emissions from biomethane production and digestate storage do not make a significant impact to the overall results present in the cited report.

These benefits far exceed the current production costs of biomethane using the technologies shown in Figure 4, which range from 55€ to 100€ per MWh for anaerobic digestion and from 85€ to 110€ per MWh for thermal gasification.

In contrast, in 2023, the cost of fossil-derived natural gas remained stable at approximately 50 €/MWh, according to TTF gas future price in September 2023 [13]. However, biomethane production costs combined with the additional benefits associated with biomethane production make it an increasingly compelling choice for energy generation.

These considerations regarding production technology maturation and government support growth show that biomethane is expected to play a more prominent role in the global energy landscape.

1.4. BIOMETHANE PRODUCTION PROCESS

Biomethane is a renewable energy source obtained from agricultural and agro-industrial biomass and the organic fraction of municipal solid waste (OFMSW). The liquid and solid raw materials are fermented through anaerobic digestion in special digestion chambers to obtain a mixture of gaseous substances called biogas, mostly composed of methane and carbon dioxide. After the pretreatment of this gas mixture, in which other undesired chemical compounds are removed, the next step involves the separation of CO_2 from CH_4 through a process known as upgrading, generating a flue gas stream. Finally, the obtained biomethane (which is mainly composed by 85% methane or more) is either liquefied or compressed and fed into the natural gas distribution network, depending on the intended use that the company wants to assign to its production.

This process, including upgrading, is not the only technologically viable one. Indeed, there are mainly two methods to obtain biomethane from biomass, which consist of gasification and anaerobic digestion; nevertheless, the last method is more widespread in the market, compared to the first one. According to the International Energy Agency (IEA) in 2018, most of the global biomethane production came from biogas upgrading (89.9%), with only 10.1%

obtained through gasification [14]. Anyway, in the coming years, the construction of biomethane plants has almost included the process of biomethane production through biogas upgrading, so a share of production through this process is expected to be higher with respect to 2018 data.

Because no separation technology is perfect, the flue gas stream still contains some methane, depending on the activated recovery technology. Whether it is allowed by regulations that this gas stream can be released into the atmosphere or must be further treated depends on the methane content, the methane "slip" of the upgrading plant (equal to the amount of methane in the flue gas compared to the amount of methane in the raw biogas), and the legal situation at the power plant.

The percentage of methane present in biogas depends on the process conditions and typically ranges from 60 to 70 percent. Therefore, the task of purification processes is to raise the methane concentration to values above 98 percent through high molar recovery, obtained by the removal of all other substances within the raw mixture. It follows that biomethane is nothing more than the final product obtained through a chain of mechanical operations conducted on biogas, as summarized in the Figure below.

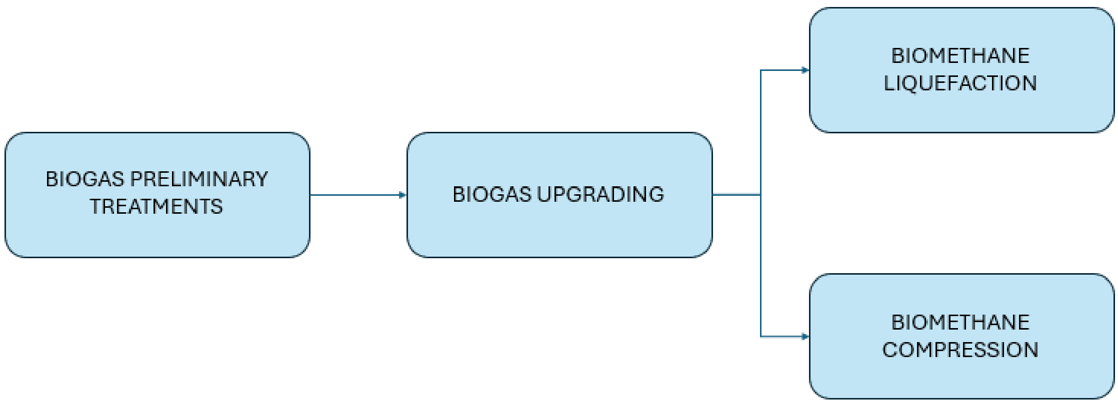

Figure 5: Block summary diagram showing biomethane production macrosteps, concerning biogas upgrading process

PRELIMINARY TREATMENT ON BIOGAS

First, the biogas to be converted must be properly treated and purified so that any external chemicals do not affect biomethane yield. Pretreatment typically begins with dehydration, aimed at removing water vapor because its presence contributes to a significant decrease in the energy content of the biomethane that will be obtained if not removed. This harmful component is then condensed through cooling, conducted between 2 and 5°C, and then removed. Pushing the biogas to cool down to -23°C results, similar to water vapor, in the condensation and removal of ammonia (also highly corrosive) and siloxanes, mainly because the latter may create several problems during combustion in gas engines. Hydrogen sulfide, a dangerous and corrosive gas owing to its acidic nature, is then removed from the gas before any further use, whether feed-in or methane fuel production, through the installation of opportune desulfurization technologies.

THERMAL GASIFICATION

Thermal gasification is a process for biomethane production that involves the conversion of solid biomass into synthesis gas through high temperatures in a controlled environment with little or no oxygen. Biomass is heated to over 700°C, causing the material to decompose into synthesis gas, mainly consisting of carbon monoxide (CO), hydrogen (H_2) and methane (CH_4). This gas is then purified to remove impurities and converted to biomethane through a methanation process, where CO and H_2 react in the presence of a catalyst to form methane and water.

In Europe, anaerobic digestion plants produce on average between 300 and 600 Smc/h [14]. On the other hand, plants that use thermal gasification to produce biomethane tend to be more variable in terms of output, with productions that can reach up to 1000 Smc/h. However, these plants are less common and often more complex and expensive to operate than anaerobic digestion plants. It thus turns out, as described above, that less than 10 percent of biomethane plants make use of the following process, as this technological solution is less commercially mature.

BIOGAS UPGRADING

Currently, there are several technologies at a high level of maturity for upgrading biogas to obtain biomethane. This process is described in the following section according to the data provided by Wien University of Technology [15].

Pressure Swing Adsorption (PSA)

The treatment of raw biogas by this separation technique can be explained by the different adsorption behaviors that the various gas components exhibit at a porous solid surface under high pressure. Certain adsorbent materials selectively capture carbon dioxide from raw biogas, thereby increasing the concentration of methane in the gas stream. In fact, they can selectively retain molecules at different pressures. Because methane has a size of 3.8A°, while carbon dioxide has a size of 3.4A°, said molecules can, for example, be separated by an adsorption process within pores of size 3.7A°. The components with which this process is carried out possess the advantage of being extremely compact and adaptable, even to small-scale plants (up to flow rates of 300 Nm3 /h), as well as being characterized by high simplicity of construction.

Physical washing with pressurized water

It is the most diffused upgrading technology in Europe [15]. The pollutants to be captured are bound to the washing solution, in this case water. CO_2, which has a higher solubility in water than methane, is more captured and dissolved at lower temperatures and higher pressures. Because the air components, oxygen and nitrogen, are dissolved in water during regeneration, the biomethane produced with this technology always contains a minimal percentage of O_2 and N_2. Next, the biomethane stream is saturated with water; therefore, the final upgrading step involves a dryer.

This technology for biomethane production is advantageous if:

- oxygen and nitrogen content in biomethane along with lower calorific value is acceptable
- the plant has a medium or large capacity
- the biomethane stream is used directly at delivery pressure, without any additional compression

Physical washing with organic compounds

Similar to previous techniques, this method uses an organic solvent solution instead of water as the washing liquid. The main advantage of this technology is that carbon dioxide shows higher solubility in these solvents than water, and at the same partial pressure of the process, more CO_2 is dissolved. Consequently, for the same capacity as raw biogas, smaller equipment and less washing liquid circulation are required. To further increase the selectivity of the process, the organic solvent is not used pure, but mixed with water. The latter is responsible for changing the polarity of the formed solution, thereby increasing its affinity for CO_2. Through the following process, the methane content in the output biomethane stream can reach high values close to 98 percent.

Chemical washing with amines

In chemical absorption, the adsorption capacity no longer depends on the partial pressure of the gaseous component to be captured but solely on the concentration of the chemical reagent used to enter the solution. During the process, chemical equilibrium is established in the liquid phase, such that larger amounts of gas (CO_2) can be absorbed even at significantly lower system pressures, which is why chemical absorption is more effective than physical absorption. Regarding the choice of reagents, the solution may consist of inorganic salts or basic agents such as amines. Organic salts, which cause fouling of process equipment, do not prove to be the best choice in terms of determining the reagent. Therefore, the best type of reagent is amines. Chemical adsorption is characterized by an actual chemical reaction between the liquid scavenging components and gaseous components to be removed within the biogas stream for treatment. The binding of undesirable gas components to the washing liquid is significantly stronger, the chemical reaction is highly selective, and the amount of methane absorbed into the liquid is, on the contrary, very low resulting in very high molar recovery of methane and very low methane leakage, with CH_4 losses even less than 0.1%). However, unlike previous technologies, amine wash solutions require a significant amount of thermal energy during regeneration, which must be supplied as the process heat.

Chemical washing with amines for biomethane production is technically and economically advantageous if:

- the capacity of the plant is medium or large in size
- the biomethane stream is almost at atmospheric delivery pressure and no further compression is required
- the infrastructure available at the biogas plant supplants the heat demand of the regeneration phase and the chilled water demand for condensation operations

Membrane technology

As the second most diffused upgrading technology across the European continent [15], the membranes used for the process under consideration consist of materials permeable to carbon dioxide, water, and ammonia. Hydrogen sulfide, oxygen, and nitrogen also pass through the membrane in considerable quantities, whereas methane is largely retained. Typical membranes for biogas upgrading consist of polymeric materials that show favorable selectivity for methane- CO_2 separation and have a constitution such that they do not degrade too easily over time. The degree of purity and productivity of biomethane are parameters closely related to the pressure and operating speed of the compressor and are thus constantly monitored. The disadvantage of this process is that the concentration of methane in the biomethane outflow stream settles under standard conditions around values that are not too high (80-89 percent by volume). If higher values (close to 95 percent by volume) were to be achieved, one would have to work with more modern upgrading systems that rest on a more complex design, as they employ more membrane stages; however, this would cause the energy and economic costs of the overall system to rise sharply. In contrast, unlike all other technologies, exhaust gas is rich in CH_4 (up to 12 percent by volume).

Criogenic technology

Cryogenic technology takes advantage of the different boiling temperatures of methane and carbon dioxide, -160°C and -78°C (corresponding to a pressure of 1 bar), respectively, to carry out separation. Biogas is alternately cooled and compressed to the point where carbon dioxide condenses and is thus easily removed in the liquid phase. The main disadvantage of this technology is that, to compress several times and bring the system temperature to very low levels, it requires large amounts of energy. Only some industries are adopting it (around 25 plants in Europe [16]), creating the possibility to obtain both LNG and liquid-form CO_2. which is still under development and therefore has not yet been seriously considered.

BIOMETHANE OUTPUT CHARACTERISTICS

The prevailing configuration to date is to use part of the biogas to produce the electricity and thermal energy needed to power the upgrading process. As a result, the biomethane stream produced is almost exclusively marketed. Once produced, biomethane can be transported in two physical configurations:

- bioCNG (Compressed Natural Gas), which is intended primarily for the automotive sector and secondarily for civil and industrial uses through its compression and feeding into the grid; in this way, there is no need to use transportation to reach gas stations because existing pipelines are used. If pipelines are not present, the transportation of biomethane by tank wagons would be considered. It is stored and distributed at pressures between 200 and 248 bar, and its volumetric energy density is 25% that of diesel fuel.
- BioLNG (Liquefied Natural Gas), transported via cryogenic tanks. It is primarily used as an alternative to bioCNG for heavy transport, with a 58% higher energy density.

1.5. BIOGAS AND BIOMETHANE IN THE EUROPEAN SCENARIO

BIOGAS

Biogas production differs significantly across the world, as it is influenced not only by feedstock availability, but also by policies that encourage its production and utilization. According to the IEA, Europe, China, and the United States accounted for 90% of global biogas production in 2021[17] . Europe currently ranks as the continent with the largest biogas producers globally, with Germany leading the market and home to two-thirds of Europe's biogas plant capacity. Energy crops initially fueled Germany's biogas industry, but policies have recently shifted towards utilizing crop residues, sequential crops, livestock

waste, and capturing methane from landfills. Other European countries such as Denmark, France, Italy, and the Netherlands have actively promoted biogas production.
In the EU 27, an amount of 15.8 Mtoe of biogas primary energy has been produced in 2022 [18] ; the biogas sector has experienced a steady and relentless increase in its production, reaching 11 times more the biogas energy produced value in 2000, as can be seen from Figure 6.

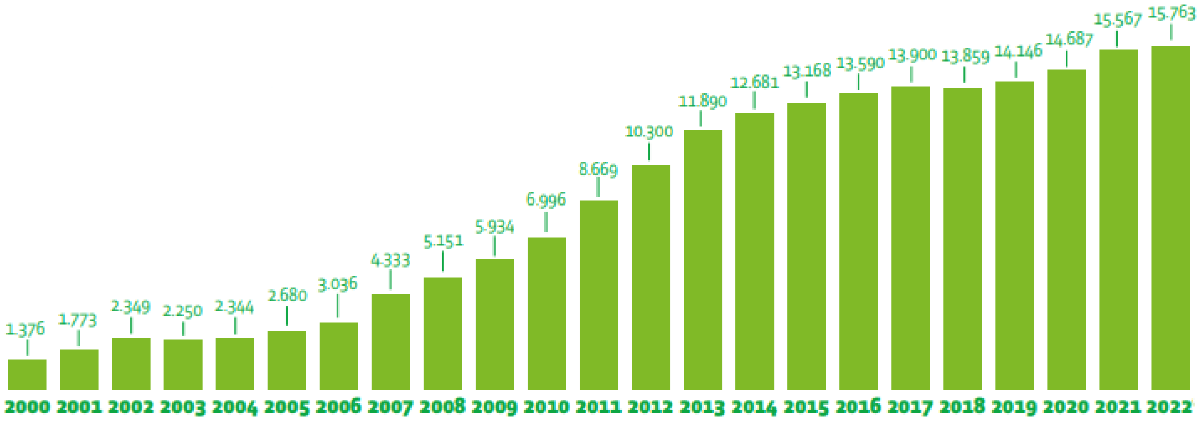

Figure 6: Primary energy production from biogas in the EU-27 (in Mtoe) [18]

According to the EurObserv'ER association, after a slight decrease in electrical energy production between 2021 and 2022 (-0.8%), the European Union biogas sector will have a strong acceleration in electricity production by 2030 (+26.7%), as shown in Figure 7. Considering the strong acceleration in the conversion of European biogas power plants to biomethane production (as it is occurring in Italy in the last years), the following scenario to 2030 therefore predicts a steeper growth in the number of biogas power plants and its global production.

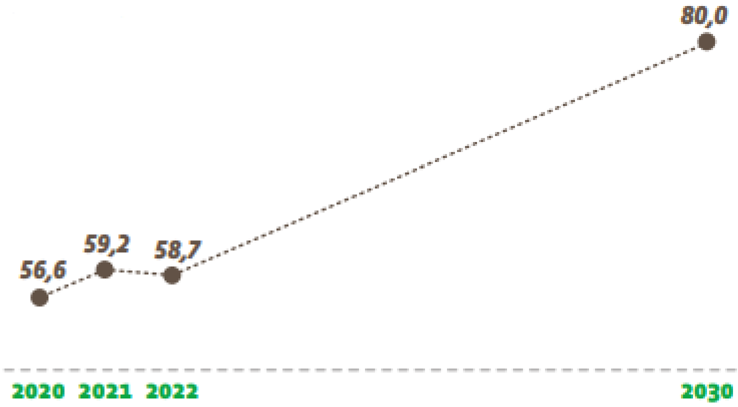

Figure 7: EurObserv'ER projection of electricity production from biogas in the EU-27 (in TWh) [18]

It can be stated that Europe presents a mature biogas industry with expanding markets. Electricity generation has been the primary driver of biogas growth over the past two decades, but recent European policies have promoted the diversification of biogas use and the utilization of biomethane. As a result, Europe's biogas sector is expected to experience significant growth from biomethane generated from both new plants and upgraded existing biogas facilities in the forecast period.

In 2021, 485 petajoules per year (PJ/y) of biogas out of 700 PJ/y (69.3%) were utilized for electricity and heat generation. Additionally, 104 PJ/y of biogas was upgraded and injected into the European natural gas grid, representing 14.9% of primary biogas use; the remaining 15.8% share is destined to residential, commercial and public service use (41 PJ/y), agricultural and forestry use (35 PJ/y), industry use (28 PJ/y) and road transport (5 PJ/y). In terms of volume, considering a standard biogas lower heating value (LHV) equal to 22 MJ/Nm3, this amounts to approximately 13.79 billion cubic meters (bcm) destined for heat and power production facilities and 2.96 bcm converted into biomethane. As reported by the IEA, this conversion of biogas plants to biomethane will be of particular interest for gas production in power and heat plants, which have a significant installed capacity in the European territory, presenting substantial development opportunities [19].

BIOMETHANE

Policies and regulations at the European and national levels are trying to build a framework conducive to the growth of the biomethane industry, given its potential as a contributor to the transition, reduction in dependence on non-EU energy sources, and the circular economy. As with other energy sectors affected by EU transition policies, ambitious targets are set for biomethane, considering the current development of the production chain, which is unlikely to be achieved within the time frame considered. This implies major capital deployments, the demand to create very favorable and efficient support measures, and the need to overcome technical and economic criticisms.

Currently, Europe is characterized by the spread of a substantial number of biomethane production facilities in its territory, which has been growing steadily, particularly in the last 15 years. According to statistics provided in the latest annual statistical report and the European Biomethane Map by the European Biogas Association [16], a figure of 1222 operating plants in the 25 European countries that are members of the association was reached in 2022, an increase of 15 percent over the previous year. Compared with 2011, when only 182 installations were operational, each subsequent year saw growth of between 10 and 30 percent, as can be seen in the Figure below.

Figure 8: Number of biomethane plants across Europe [16]

The REPowerEU Plan published by the Commission in May 2022, as part of the set of measures to achieve independence from Russian gas and push on the accelerator of the transition, raised the European 2030 targets for annual biomethane production contained in the "FIT for 55" package, increasing them from 18 to 35 bcm. This would be a tenfold increase in the current union production. Trying to pursue these goals will require upgrading the biomethane of many existing biogas plants and the direct construction of new biomethane production capacity, for which it is estimated that 5,000 new plants need to be installed, a goal that to date is still far off.

The increase in the number of European plants has implied substantial growth in biomethane production, as can be seen in Figure below; the latest disclosure shows an increase in production of 0.7 bcm in 2022 over the previous year (+20%), reaching the production of 4.2 bcm annually or 6 times that of 10 years earlier.

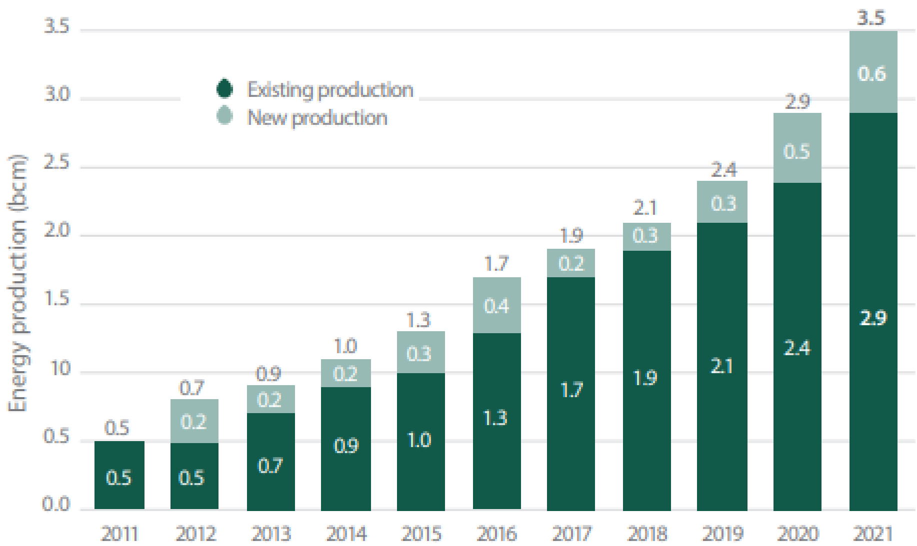

Figure 9: Biomethane production according to EBA [16]

As declared by the EBA, reaching 35 bcm of biomethane production requires a sustained annual growth rate of the biomethane production capacity of approximately 30 per cent, an annual growth value that has not yet been achieved.

Furthermore, Europe generated 31 million metric tons (dry matter) of digestate in 2022. This amount is sufficient to fulfill 15 percent of the European Union's demand for nitrogen fertilizer, resulting in a reduction of 10 million metric tons of carbon dioxide equivalent and 2 billion cubic meters of natural gas consumption, which would otherwise be required for the production of artificial fertilizers.

Regarding the types of plants with respect to the characteristics of the biomethane produced, according to the map, most of them produce, compress, and feed CNG fuel into the grid, as shown in the following chart. Almost 10 times fewer CNG production plants that distribute gas with other transport methods are present in Europe, whereas currently installed LNG plants make up a small percentage of the total.

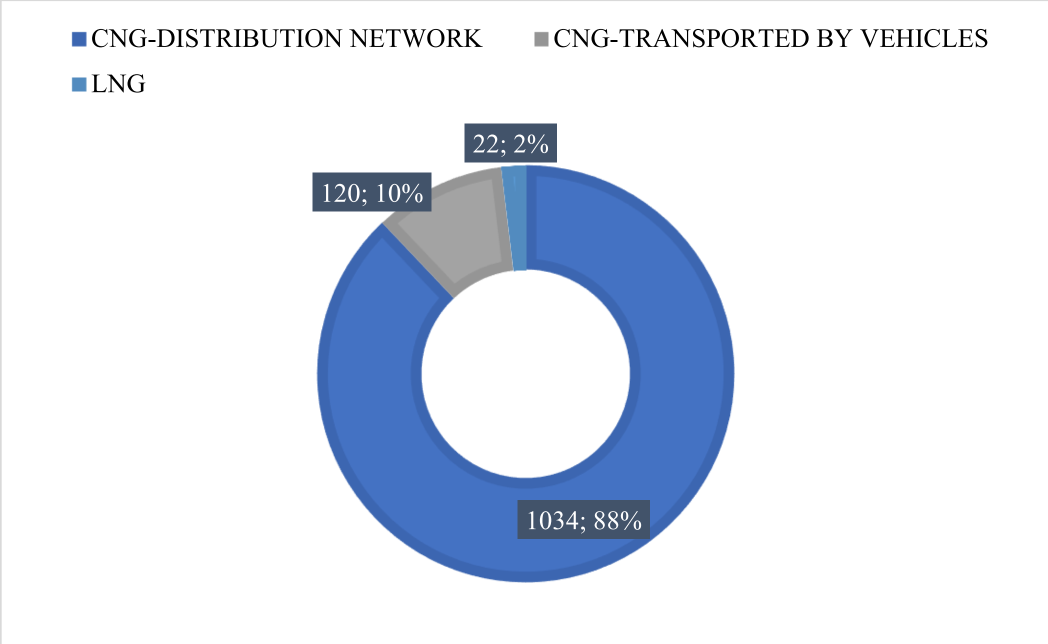

Figure 10: Number and percentage of biomethane plants according to their injection characteristics [16]

France and Germany, with 477 and 254 installations respectively, account for approximately 62 percent of the share of the total number of installations [16]. Of the 155 new installations built in 2022, 140 (90 percent) were in France, demonstrating the importance of government support in the biomethane production chain. Of the 25 member nations of the Association, the majority produce biomethane in one particular injection characteristic: seven countries (Denmark, France, Germany, Holland, Switzerland, and the UK) produce CNG biofuel to be fed into the distribution and transportation network with a percentage of more than 90%; three countries (Estonia, Finland, and Sweden), on the other hand, are characterized by a prevalent production of CNG destined for vehicle transportation.

1.6. BIOGAS AND BIOMETHANE IN THE ITALIAN SCENARIO

BIOGAS

The Italian biogas sector has undergone significant development in the recent decades. According to the "Biogas Barometer" study compiled by EurObserv'ER, Italy appears to be the second largest country for biogas production in the European Union [18].With its 2033.0

ktoe produced in 2022, it contributes 12.9% to continental production, albeit second to the German contribution of 51.4%. In terms of volume, considering a standard biogas lower heating value (LHV) equal to 22 MJ/Nm3, 2.42 bcm of biogas was generated in Italy; 12.8 percent of Italy's production came from refining landfill gas (261.1 ktoe, 0.31 bcm) and only 2.8 percent turned out to be sewage sludge gas (48.7 ktoe, 0.06 bcm),while the largest share comes from other gases' anaerobic digestion (1723.1 ktoe, 84.4%, and 2.05 bcm).

As of April 2024, according to data provided by the Atlaimpianti software managed by the GSE, there were 2010 biogas-fueled power plants active in Italy, with a total installed output electric capacity of 1.34 GW and an average size of approximately 670 kW. According to Terna, as of December 2022, the gross efficient generating capacity was 123.3 GW [20]; therefore, the capacity of biogas plants appears to be 1.1 percent of the Italian total.

However, according to EurObserv'ER, gross electricity production from biogases as of 2022 was found to be equal to 7.84 TWh, equivalent to 2.5 percent of the overall national electricity demand as of 2022 (315 TWh) [20]; 30.6 percent of 7.84 TWh energy was found to be generated by power generation plants only (2.4 TWh), while the rest (69.4 percent) was produced by combined cycle plants (5.44 TWh).

Despite the strong growth known since the turn of the century, a decrease in the installed capacity is expected in the coming years, with a consequent reduction in power generation. As illustrated in the graph below, after experiencing a slight decrease in electricity generation from bioenergy (combining the contribution of solid biomass, biogas, and bioliquids) between 2020 and 2021, there will be a collapse in generation by 2025, subsequently realizing its own stabilization by 2030. This fall leads to a similar decline in the bioenergy contribution in the Italian renewable energy scenario, from 17% detected in 2020 to only 4% in 2030. According to the [21], this decline is caused by the extensive conversion to biomethane of biogas plants planned by 2026, in accordance with Ministerial Decree 15/9/2022 also referred to as the "Biomethane Decree."

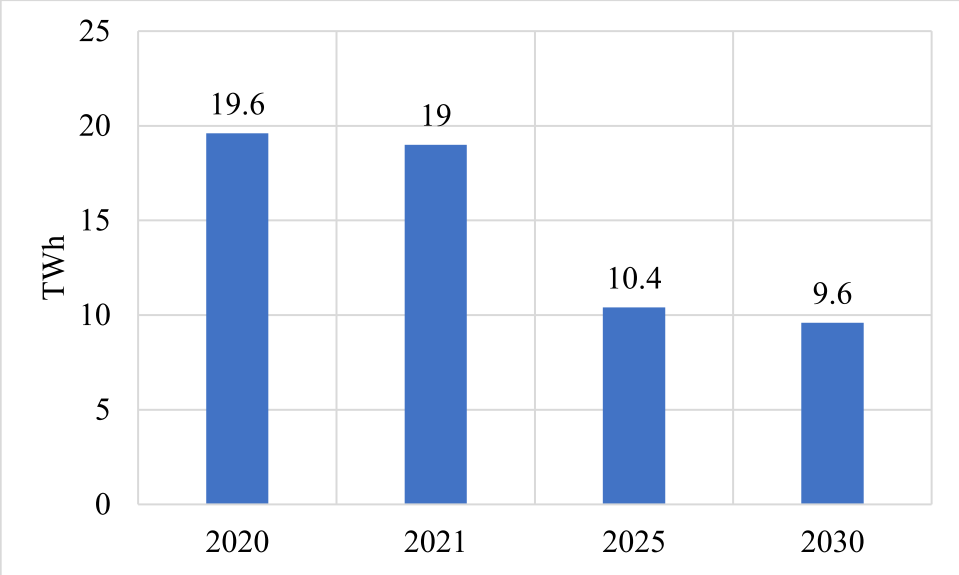

Figure 11: Required electric energy to be produced from bioenergy during the considered years, according to 2023 PNIEC scenario to 2030 (in TWh) [21]

BIOMETHANE

The abundance of raw materials from agri-food markets combined with the need to manage municipal waste means that biomethane produced through the use of biomass grown in Italy can be considered a significant factor in the security of supply (see the potentially producible biomethane, described with detailed data in section 4.1) and, with a view to full decarbonization, a tool for the coverage of renewable sources in sectors that are difficult to electrify, including transportation. Today, there is no comprehensive list showing the effective number of plants producing biomethane; however, for producers of biomethane released for consumption in transportation, through road, highway or private distribution facilities, the issuance of Certificates of Release for Consumption (CICs) is envisaged: in 2021, only 22 plants were issued CICs for biomethane incentives, namely those reported by the EBA. Cross-referencing the data provided by the latter association and those produced by Snam [22], as of June 2023, there are 85 active biomethane production plants in the Italian territory, with expected annual productivity between 572 million smc and 746 smc, and the expected production values at 6000 h and 8000 h per year of operation of each plant, respectively. Although biomethane production appears in almost all plants to be continuous throughout all hours of the year, a lower expected production scenario (6000 h) was considered as a more precautionary scenario.

Source	Number of plants	Expected production- Low Scenario (MSmc/y)	Expected production- High Scenario (MSmc/y)
Agricultural biomass	23	139.2	182.5
Organic matrix waste	45	271.9	347.8
Other	17	160.9	215.6
Total	85	572.0	745.9

Table 1: List of biomethane production facilities in Italy by input materials [22]

The most commonly used source of biomethane is municipal waste with an organic matrix, followed by agricultural biomass (Table 1). Considering the provincial territorial context, the northern Italian provinces of Bergamo and Vicenza stand out at the top of the ranking; the first generates 72 mcm annually, while the second generates 51 mcm (assuming 6000 h/year of operation).

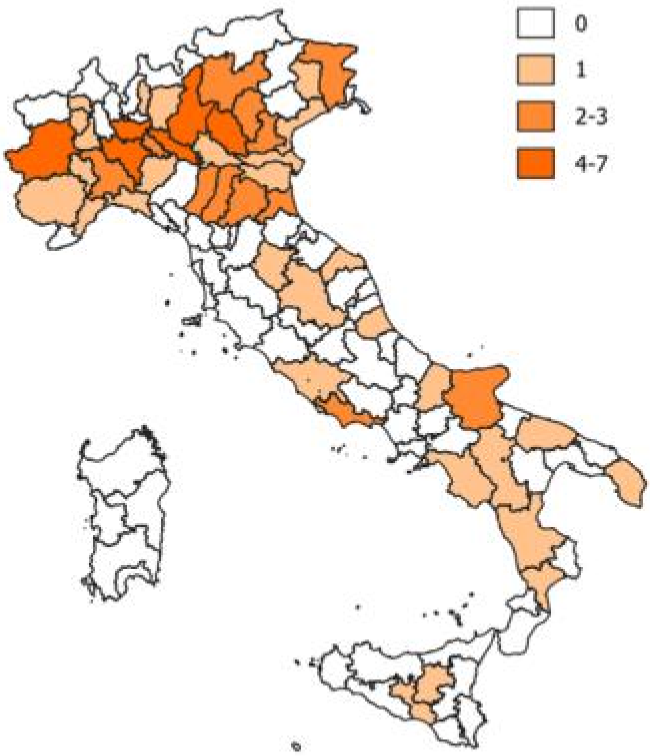

Figure 12: Map showing the number of biomethane plants by province [22]

In general, however, as shown in Figure 12, the highest density of plants, and thus biomethane production, comes from northern Italy. Most central and southern provinces have only one biomethane plant, except for Foggia and Latina, which have two plants. Anyway, observing the results of the first three auctions of the DM 15/09/2022 "Biomethane", the distribution of funded plants appears homogeneous along Italy, with a fair concentration even in the southern regions.

Italy's goal, in line with European targets, is to increase biomethane production to reach 10 billion cubic meters by 2030, according to ministerial projections. Reaching that target would mean developing new capacity capable of generating 1.4 billion cubic meters annually, which is markedly higher than what has been observed to date. In Italy, by 2050, production is expected to be 13 billion cubic meters, and by 2030, no more than 5.5 billion cubic meters, a value that is 10 times higher than the current level. It is estimated that the main feedstocks used to support the development of new biomethane production are mainly crops, animal manure, industrial wastewater, agricultural by-products, and food industry waste, which is consistent with the framework for the organic matrix waste segment for biomethane production; all these feedstock categories are included in Decree Biomethane. The Ministerial Decree of 02/03/2018, which incentivizes the use of biomethane and other advanced biofuels in the transportation sector, has provided a strong boost to plants. Information on the authorized capacity fed by organic matrix waste suggests a supply quantitatively adequate to the treatment needs, at least nominally, in light of the numerous entrepreneurial initiatives in the pipeline also incentivized by the resources made available by the PNRR.

1.7. DECREE BIOMETHANE

PNRR

In response to the difficulties arising from the significant impact of the COVID-19 pandemic on the Italian economy and society, in order to allow the recovery and sustainable and digital development of the country on 13 July 2021, the Council for Economic and Financial Affairs (ECOFIN) of the European Union has approved the Italian National Recovery and Resilience Plan (NRRP in english, PNRR in italian). Forming part of the broader Union program known as Next Generation EU, it contains a set of investments and reforms planned for 2022-2026 period for an amount of 191.5 billion, of which 70 billion are in non-repayable grants and 121 billion in loans [23]. Furthermore, a sum of 30.62 billion from the Italian government is added to the European resources, as this is the Complementary Plan, and has the aim of both further financing some measures of the Plan and carrying out new interventions for a total of

54 of the 292 overall economic investments. Until December 2023, the European Commission provided Italy with the first four installments of the Plan, for a total of 101.9 billion euros. The European regulatory framework that regulates the drafting of PNRRs, their implementation, and the sending of resources is defined in EU Regulation 2021/241. In addition to the following document, the Italian state has adopted its governance, made up of a series of ad hoc bodies and rules of the plan, so that interventions on the agenda are completed within the expected timescales. Some of the main passages in the regulation include the following:

- the obligation of states to EU institutions to complete deadlines and measures within the established deadlines, under the penalty of non-disbursement of funds. Each measure has different deadlines to complete per quarter, from year to year, until June 30, 2026.
- the possibility for countries to modify the plan at any moment of its implementation, respecting the precise conditions that the commission will always evaluate. In November 2023, the EU Commission approved the remodulation of part of the PNRR proposed by the Meloni government, bringing it to 194.4 billion (2.9 billion more, of which 1.3 in non-repayable funds and 1.6 in loans) and adding the RePowerEU chapter;
- The obligation for beneficiary countries to invest at least 37% of the resources received in environmental and climate measures and 20% for digital transition, with the first contribution reaching 39.5%, while the share for digital transition is equivalent to 25.6%.

The European PNRRs focus on milestones and targets that describe in a granular way the progress and results of the reforms and investments they propose to implement. Milestones generally define relevant administrative and procedural steps. They are qualitative targets to be achieved through a given measure of the Plan (reform and/or investment) and often identify key steps in the implementation of the measures, such as the legislation adopted. The targets, on the other hand, represent the expected results of the interventions, quantified with measurable indicators; they are quantitative goals to be achieved through a specific measure of the PNRR and are measured through well-specified indicators (such as the number of buses purchased and the number of students who have completed training). After the revision of the Italian Plan was approved in 2023, the total number of milestones and targets increased from 527 to 614. The new Plan includes seven new reforms, five of which are within the REPowerEU chapter, in addition to the existing ones, for a total of 66.

The PNRR investment projects can be grouped into seven missions:

- M1- Digitalization, innovation, competitiveness, culture, and tourism
- M2- Green revolution and ecological transition;
- M3- Infrastructures for sustainable mobility;
- M4- Education and research;

- M5-Inclusion and cohesion;
- M6-Health;
- M7-RePowerEU.

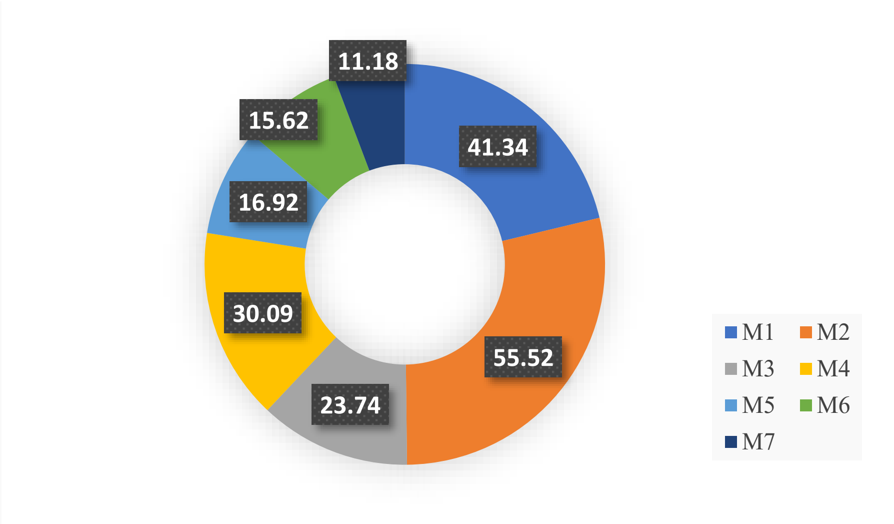

Figure 13: Total resources granted by the European Union earmarked for investment for each Mission under the PNRR [23]

To cope with the current and future impacts of climate change, improve energy efficiency in various sectors, and especially promote the transition to sustainable mobility, the plan envisages, with Missions M2, M3, and M7, a total allocation of 90.44 billion euros. In particular, the M2 Mission, with more than 55 billion euros, represents the main investment item of the PNRR and has four components (categorized with letter C):

- M2C1-Sustainable agriculture and the circular economy
- M2C2-Energy transition and sustainable mobility;
- M2C3-Energy efficiency and building upgrading;
- M2C4-Protection of land and water resources.

With regard to the transport sector in the Italian national context, intervention areas 1 (Increasing the share of energy produced from renewable energy sources) and 4 (Developing more sustainable local transport) encompass the largest and potentially most significant investment sums for an increasingly sustainable transition of local public transport, namely Investments 4.4 (Renewal of green bus and train fleets) and 1.4 (Biomethane development); in particular, second Investment calls for the expenditure of 1.92 billion euros to provide for an increase in the use of biomethane in order to be able to meet the Community targets set for 2030 by the RePowerEU.

INVESTMENT 1.4: DECREE BIOMETHANE

Italy, being part of the main states promoting the creation of the Global Biofuel Alliance in 2023, firmly believes in the development of a technology that can open up great opportunities for development in the automotive sector, without dismembering endothermic engine production, with serious economic and social environmental impacts, and taking into account flexibility in the timing of implementation of measures. Evidence for this is the large amount of money made available by the PNRR for the development of the biofuel supply chain, especially in Investment 1.4.

The investment line has five main objectives:

1. The conversion and improvement of the energy efficiency of existing agricultural biogas plants towards the total or partial production of biomethane for use in both the industrial and residential heating and cooling and the tertiary and transportation sectors, targeting an increase in production of 0.8 to 0.9 billion cubic meters, for total production from conversion expected to be between 1.6 and 1.8 billion cubic meters;
2. Supporting the construction of new biomethane production facilities with the same uses, expecting an additional production of 0.7 billion cubic meters;
3. Promote the dissemination of environmentally friendly practices at the biogas production stage, reduce the use of synthetic fertilizers, increase the supply of organic matter in soils, and create consortium hubs for the centralized treatment of digestates and effluents with the production of fertilizers of organic origin.
4. Promote the replacement of obsolete and low-efficiency mechanical agricultural vehicles with biomethane-powered vehicles;
5. Improve efficiency, in terms of heat utilization and emission reduction, of existing agricultural biogas plants for which conversion measures cannot be implemented.

The implementation plan for the five goals includes a total investment of 1.92 billion euros over the five-year period 2022-2026, according to the allocation plan described in the following table:

GOAL	2022	2023	2024	2025	2026	TOTAL (Mln €)
1. Reconvert and improve the efficiency of existing agricultural biogas plants	70	133,6	324,8	424	78	1030,4
2. Support the construction of new biomethane production facilities	161	154	175	175	35	700

Table 2: Breakdown of funds allocated in the Biomethane Decree [23]

The sum of the resources allocated to the first two investment objectives turns out to be equal to 1.73 billion euros, which is 90 percent of the resources allocated in investment 1.4, so this study will analyze the distribution and outlook related to the first two economic measures. For 2024 and 2025, the Plan allocates most funds. For the conversion and upgrading of the biogas plants in question, 31.5 percent and 41.1 percent of the funds will be made available in 2024 and 2025, respectively, whereas for the construction of new biomethane plants, 50 percent of the resources will be used in the biennium in question.

The delegated implementing entity for investment is the Gestore dei Servizi Energetici (GSE), an Italian joint-stock company founded in 1999 and wholly owned by the Ministry of Economy and Finance, which is entrusted with the promotion and development of renewable energy sources and energy efficiency in the country. Through a defined online portal made available by the company, it is possible to submit the notice of entry into operation for access to the incentives under the plan only for the plants that resulted in a useful position in the rankings of special public competitive procedures drawn up by the GSE, based on specific access requirements and priority criteria.

The targets defined at the definition of the Plan turn out to be the increase in biomethane production of 0.6 billion smc by the fourth quarter of 2024 and 2.3 billion smc by the second quarter of 2026.

GENERAL PRINCIPLES AND HIGHLIGHTS OF BIOMETHANE DECREE

Continuing with the Ministerial Decree of March 2, 2018 [24], which promoted the use of biomethane and other advanced biofuels in the transportation sector through special incentives provided by the GSE and consistent with the investment support measures provided in the PNRR, the Ministerial Decree of September 15, 2022, defines the provisions for the development of biomethane production facilities. Published in the Official Gazette on October 26, 2022, and commonly known as the "Biomethane Decree," it aims to promote the first two objectives contained in Investment 1.4, namely, the promotion of biomethane conversion interventions (total or partial) of existing agricultural biogas power plants and the development of newly established agricultural or waste-based biomethane production plants. The Decree grants all plants involved capital support, equal to a maximum of 40 percent of the expenses incurred, and an energy account incentive, through the definition of an incentive tariff applied to the net volume of biomethane production: in addition, according to the document, the biomethane produced may have two distinct uses depending on the permitted feedstocks:

- The transportation sector, provided that biomethane is produced through double-counting feedstocks defined in Annex VIII of Legislative Decree 199/2021, excluding animal fats and used cooking oil;
- Other uses, that is, use in the industrial, residential, tertiary and agricultural sectors, excluding the thermoelectric generation sector.

The two types of facilities to be implemented were defined in turn through the guidance provided in the document:

- Agricultural plants, producing biomethane from refining biogas from a farm or using materials from non-waste agricultural, forestry, livestock, food, and agro-industrial activities;
- Organic waste plants, producing biomethane from biogas refining fed to OFMSW (Organic Fraction of Municipal Solid Waste) as well as to animal manure and sewage sludge.

The decree does not allow the conversion of plants fed with organic waste, but only their new construction. For the production of biomethane, the processes of biomass gasification, hydrogen and CO_2 methanation, and use of landfill gas as feedstock were excluded.

INCENTIVE MECHANISM DESCRIPTION

In order for the economic resources made available by the Plan to be distributed in a functional manner, the investment provides participating companies with two types of support:

- Capital support;
- Energy bill incentives.

The contributions are defined by the decree, taking into account the type of plant and the category of intervention, staggering the contribution according to biomethane production capacity (Cp), which represents the nominal hourly output of biomethane, expressed in standard cubic meters per hour (Smc), as a result of the nameplate of the biogas purification and refining device present. The following table shows the different capital contribution brackets in detail:

TYPE OF BIOMETHANE PRODUCTION FACILITIES	Biomethane production capacity Cp [Smc/h]	Maximum specific investment cost for new facilities [€/Smc/h]	Maximum specific cost investment for riconversion [€/Smc/h]	Percentage of capital contribution[%]
Agricultural plants	Cp<100	33000	12600	40%
	100<Cp<500	29000	12600	40%
	Cp>500	13000	11600	40%
Plants fueled by organic waste	Any	50000	None	40%

Table 3: Capital contribution brackets depending by Cp [24]

As described in Table 3, in each case, the capital grant is up to 40% of the expenses incurred, provided that the commissioning of the plant and payments of expenses covered by the benefit occured by June 30, 2023. The types of expenditure covered by support are defined in DM 2022 in Article 8.

1) The costs of plant implementation and efficiency include the infrastructure and machinery required for the management of biomass and the anaerobic digestion process, storage of digestate, construction of the biogas purification plant, processing, compression, storage of biomethane and CO_2, and construction of facilities and equipment for farm self-consumption of biomethane.
2) Biomethane, flue gas, and fugitive emission monitoring and oxidation equipment.
3) Costs of connecting to natural gas grid
4) Costs of purchasing computer programs for plant management
5) Design expenses to the maximum total extent of 12 percent of the total eligible expenditure;
6) Costs of digestate composting phase.

More complex regulations refer to the definition of the energy account incentive: the Biomethane Decree provides for the creation of an incentive tariff recognized with respect to the amount of net biomethane produced and fed into the grid, that is, for the amount of gross biofuel produced deducted from the energy absorptions of the plant's auxiliary services that are not self-supplying. The decree provides for differentiation between the two types of support:

- All-inclusive tariff, payable to plants with up to 250 Smc/h of production capacity connected to a grid with a third-party connection obligation;
- Premium tariffs are intended for grid-connected plants characterized by a production capacity value above 250 Smc/h or having any capacity in the case of no grid connection. The tariff is calculated based on the value of biomethane production, considering the average monthly gas price in the markets, and the guarantees of origin (GO) that the producer holds and values in the market through trading on the PB-GO platform managed by the Gestore dei Mercati Energetici (GME), which is wholly owned by the GSE.

	PREMIUM TARIFF (TP)	ALL-INCLUSIVE TARIFF (TO)
Calculation mode	TP=due tariff -monthly average price of natural gas-GO average monthly price	TO=due tariff
Natural gas sales	Sale in the availability of the Applicant	Withdrawal by the GSE
GO Management	Issued to the Applicant and in its availability	Issued to the Applicant and transferred free of charge to the GSE

Table 4: Premium tariff and All-inclusive tariff prerequisites [24]

In both cases, the incentive tariff is recognized from the date of commercial operation for 15 years.

The average monthly price of natural gas is defined periodically by the GSE and is calculated by running the average transaction prices recorded on the MGP-Gas and MI-Gas markets, reduced further by 5 percent; for 2023, the average value stood at 39.98 €/MWh, down sharply from the 2022 value of 133.19 €/MWh, which was very high due to the political-economic problems generated by the Russian-Ukrainian conflict [25]. The average monthly price of Guarantees of Origin at auction base turns out to be €3.64/MWh for the last 10 months of 2023, with an average price defined by the M-GO negotiated market of €6.10/MWh. Energy suppliers, sustainable companies, and government agencies are required to purchase Guarantees of Origin (GO) to certify the use of renewable gas; M-GOs are traded at low prices mainly due to oversupply, low demand, low awareness, and insufficient policies that limit their attractiveness and perceived value [26].

The reference tariff, set as the basis for the auction, is the same regardless of whether the biomethane is destined for the transportation sector or for uses other than transportation; however, even in this case, it is differentiated between plants fueled by agricultural matrices and those fueled by waste. Annex 2 of the Biomethane Decree provides the reference values of the incentive tariffs for the plants admitted to the ranking lists in good position, which were put on the auction basis in the competitive procedures of the years 2022 and 2023. In the document, a 2% reduction is provided for competitive procedures in 2024, and possibly in 2025 and 2026.

TYPOLOGY OF BIOMETHANE PRODUCTION PLANTS	Production capacity [in Smc/h]	2023 procedures	2024 procedures and next
Small-scale agricultural plants	Cp<=100	115	112.7
Other agricultural plants	Cp>100	110	107.8
Plants fueled by organic waste	Any	62	60.76

Table 5: Reference tariffs put up for auction [in €/MWh] [24]

To determine the tariff payable to the plant, that is, the net tariff that the biomethane-producing company is awarded, successive steps of curtailment take place, as described in the following diagram:

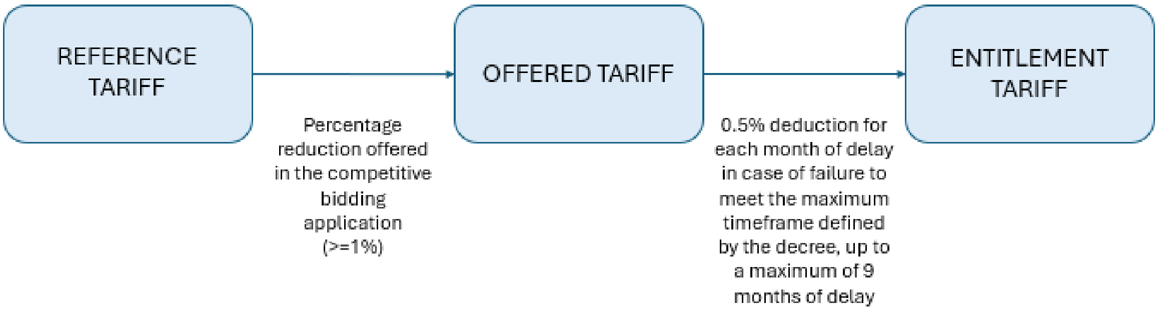

Figure 14: Illustration of the link between reference tariff, offered tariff, and entitlement tariff [24]

Incentives under this decree may not be combined with other public incentives or support schemes intended for the same projects, while other public incentives or support schemes may be received for works outside the control volume of the biomethane production process, subject to the impossibility of accumulation with the capital grant (e.g., CO_2 liquefaction plant, biomass pretreatment systems that do not involve biogas production and capture).

In addition, biomethane production, depending on the intended use of the fuel, requires a reduction in GHG emissions. In the case of use in the transportation sector, through the use of biomass, a reduction of at least 65% of emissions shall be verified, in addition to the mandatory use of advanced feedstocks in Annex VIII, Part A of Legislative Decree 199/2021; In the case of other uses, the plant must instead achieve at least an 80% reduction in GHG emissions through the use of biomass.

Importantly, access to incentives for biomethane plants for transportation use was allowed until an annual production of 1.1 billion cubic meters is reached.

ENTRY REQUIREMENTS FOR COMPETITIVE PROCEDURES

The entry requirements for companies participating in the call as applicants can be divided into subjective and objective. In the first type, the Applicant must basically not be a "firm in difficulty" and must not fall on the list of firms for which a recovery order is pending for incentives received and declared illegal and incompatible by the European Commission. Regarding the objective requirements, the most significant ones appear to be

- Compliance with sustainability requirements dictated by the decree

- In the case of conversion, interventions must be carried out in existing agricultural facilities.
- In the case of agricultural facilities, at least 40 percent by weight of livestock manure is required for use in the overall feeding plan of the facility if applicable;
- Digestate storage tanks were established with a volume equal to that of at least 30 days.

As mentioned earlier, access to incentives occurs through participation in competitive procedures with an opening period of 60 days. According to the GSE schedule, at least five procedures are planned, including three for 2023 and two for 2024, so the annual capacity quotas put out to tender are equivalent to 162000 Smc/h and 95000 Smc/h for the first and second years, respectively.

Originally, the five procedures designated by the decree divided the quota allocation in the following order shown in the table:

	2023			2024	
Opening date	30/1/2023	14/7/2023	22/12/2023	3/6/2024	18/11/2024
Procedure number	1	2	3	4	5
Contingent [Smc/h]	67000	71250	23750	71250	23750

Table 6: Contingent allocation and procedures opening dates [24]

If the total quota of available production capacity is not exhausted with the fifth procedure, the Biomethane Decree provides the possibility of opening new procedures until the available resources are exhausted, in any case no later than 01/01/2026. To maximize the rate of implementation of interventions, specific arrangements are made for the reallocation of the share of unallocated quotas, as was the case in the first and second procedures.

In the first announcement, the quota allocated through special ranking equals 29977.7 smc/h compared to the available 67000 smc/h, failing to allocate 55.3% of the volumes. A large proportion of the winning plants were newly constructed agricultural plants (37 out of 60 projects), 14 involved the conversion of biogas plants, and the remaining nine were newly constructed organic waste plants. For a total of 11 plants, all waste plants and two agricultural plants will use the biomethane produced for transportation, while the remaining 49 will use their production for other uses.

The resources advanced in the first procedure were reallocated in the second, resulting in the tendering of a total available quota of 108272.3 Smc/h; only 25881.4 smc/h were allocated to applicants, resulting in the non-utilization of 76.1% of resources.

With the third procedure, 58119.3 Smc/h (44.1% of the total) were allocated to 132 applicants, of which 11 will build new organic waste plants, 61 will build new agricultural plants, and 60 will convert agricultural plants. In the third round, therefore, a considerable increase in allocated quotas can be seen, due to the increased attractiveness of the incentives due to the announcement of their future adjustment and thus increase; in fact, it seems that the incentives shown in Table 5 will increase by 11.6 percent, economically penalizing the winning companies of the first and second procedures.[27]

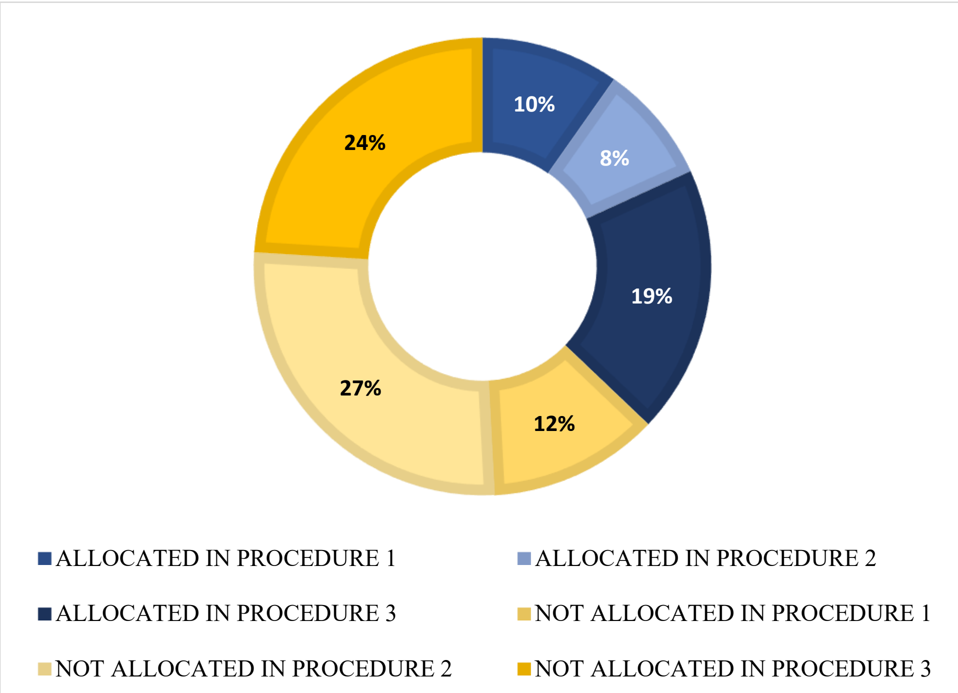

Figure 15: Percentages of contingent allocation in procedures 1, 2 and 3 [24]

1.8. CONTEXTUALIZATION OF PUBLIC TRANSPORT

NATIONAL MOBILITY DEMAND SCENARIO

The European Strategy for Low Emission Mobility, published by the European Commission in July 2016, sets the goal of achieving a level of greenhouse gas emissions from transport of at least 60 percent below the 1990 levels by 2050, progressively increasing the share of low- and zero-emission vehicles in line with the commitment made in the Paris Agreement on Climate Change and the 2030 Agenda for Sustainable Development.

The main elements of this strategy are as follows:

- The efficiency of transportation systems should be increased by making the most digital technologies and further encouraging the shift to low-emission modes of transportation.
- Accelerate the deployment of alternative energy sources, such as biofuels and electricity, and transition to low- and zero-emission vehicles.

This Strategy was reaffirmed by the Commission in a communication to the European Parliament in 2020, in which it raises the strategic goal of reducing greenhouse gas emissions from transport from 60 to 90 percent of the European Green Deal's greenhouse gas emissions from transport to enable the EU to become a climate-neutral economy by 2050, while working towards the goal of "zero pollution." Recently, concerning the PNRR, it was determined that 68.6 billion euros were allocated in the plan for ecological transition, and within this measure, resources useful for the renewal of local public transport were included. The strengthening and improvement of local public transport appears to be particularly functional in achieving the goals set by the European Commission in Italian and EU soils.

According to the 2023 National Integrated Energy and Climate Plan (PNIEC) drafted by the Ministry of Environment and Energy Security, the final energy consumption of the transportation sector in Italy appears to be significant; in 2021, the transportation sector determines 32.5 percent of the energy demand. In addition to the tertiary sector, the transportation sector appears to be the only sector with an increasing trend in energy consumption between 2021 and 2025. However, as shown in Figure 16, it is projected to decline by 2040 [21].

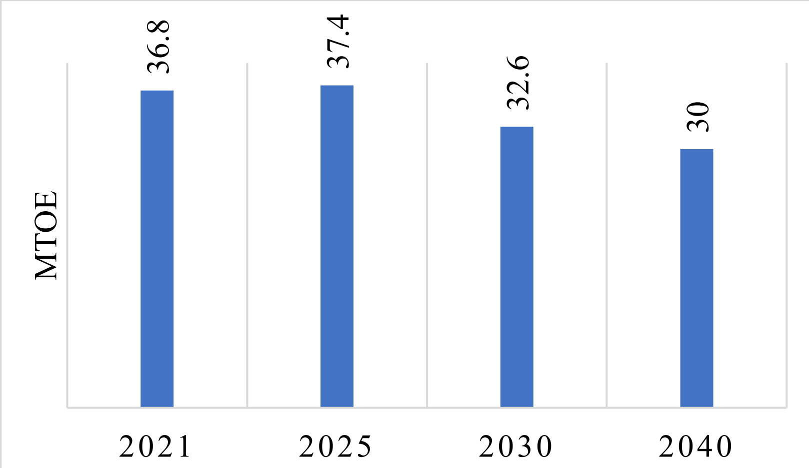

Figure 16: Final energy consumption for the transportation sector (Mtoe), RSE data processing [21]

A similar downward trend can be seen in greenhouse gas emissions from the transportation sector, which are projected by the ISPRA to be nearly halved in 2040, compared to the value found in 2021 (-52.4 percent). Similar to the share of final consumption by sector type, 30.9 percent of the total emissions in 2021 came from the transportation sector [21].

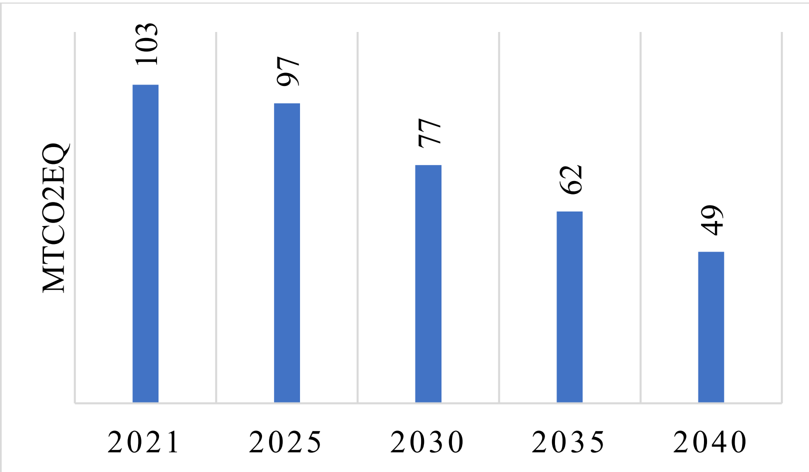

Figure 17: Greenhouse gas emissions according to the PNIEC scenario for the transportation sector ($MtCO_{2e}$), ISPRA data processing [21]

LOCAL PUBLIC TRANSPORT DEMAND IN ITALY

Referring to the 20th Report on the Mobility of Italians published by ISFORT on November 30, 2023, as of 2019, the mobility services offered in Italy by local public transport amount to a total of 1.65 billion bus*km [28]. Among road vehicles, bus fleets produce the least amount of climate-altering emissions, with only 2.9 percent of the total emissions in 2021; however, this decreased from 3.1 percent in 2019 owing to improved vehicle profiles. In addition, the bus, by replacing the circulation of more than 20 cars each, offers a large reduction in emissions and in the fuel consumed, assuming that the vehicles reach a certain rate of attendance depending by the territory and its context.

Figure 18: Total passengers*km and travels in Italy (in millions, 2000-2022) [28]

In Italy, the total number of passengers*km for all types of mobility fluctuates around 1- 1.2 billion/day, with a significant reduction between the beginning of the millennium and today; anyway, this decrease is lower with respect to travel-alone trips by private cars (just over 10%). Moreover, the passenger*km curve follows a quite different trend from that of travel, with vertical growth from the beginning of the historical series until 2008 (1.561 billion, +28.4% from 2000) and an equally sudden fall to a low point in 2020 during the pandemic crisis, only partially recovering in the following two-year period (1.074 billion in 2022, or -31.2% from 2008).

Figure 19: Passengers*km and travels for collective mobility (in %, 2000-2022*)* [28]

Among all types of mobility, collective mobility has suffered a marginal demand coverage position over the years; the modal share of aggregate public transportation averaged just under 10 percent, with a positive peak in 2012 (11 percent) and a negative peak in 2020 (5.4 percent) brought about by the pandemic, only partly reabsorbed in the following two years; in terms of travel, on the other hand, the weight of collective mobility is much higher, practically double (around 20 percent), although, as for the travel share, it tended to decline due to a post-Covid recovery that was laborious and partial.

SITUATION AND EVOLUTION OF THE BUS FLEET

In 2022, buses on the road in Italy remained above the 100-thousand-vehicle threshold, a figure that has remained essentially stable since 2018. When compared with 2002, there was a growth of approximately 9 percentage points, and the distribution of buses by environmental class allowed us to assess the growth in the number of the latest generation of vehicles (Euro 6 and Zero Emission Vehicles). As shown in Figure 20, in 2022, they account for nearly 30 percent of the total, approximately six points more than in the previous year. However, approximately 44 percent of buses have a class no higher than Euro 3, which, with unchanged regulations and considering only vehicles used for local public transport services and excluding so-called school buses, will not be able to circulate from January 1, 2024, according to Article 4 of Decree-Law 121/2021 [29]. This highlights the need to produce an urgent accelerate the renewal process of the Italian vehicle fleet.

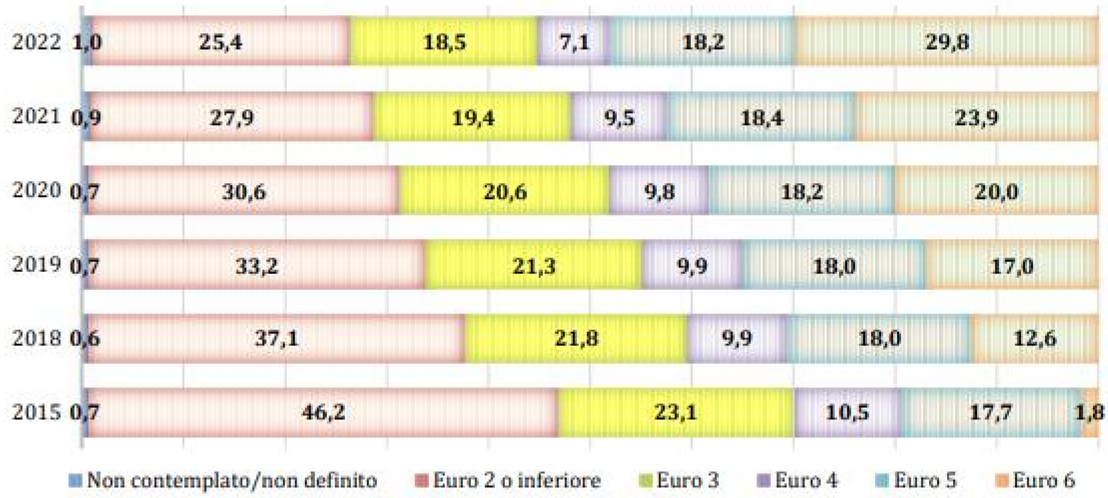

Figure 20: Evolution of the bus fleet in Italy by emission standard (in %) [28]

In 2022, diesel-powered buses comprised the majority of M2 and M3 vehicles on the road, accounting for 92.7 percent of the total. Alternative fuels, from natural gas to pure electricity, represent a minority share and are concentrated in the country's urban areas. Moreover, when one considers that in 2015, the percentage stood at 5.5 percent, just 1.8 points lower than that in 2022, and that at that time the penetration of all-electric buses was completely insignificant, it became clear that the electrification process still appears particularly slow. The ban on buses with emission standards will particularly affect public-use vehicles, accounting for 52.7 percent of the total in 2022, a percentage that in absolute terms translates to 52,752 vehicles, 0.5 percent more than in 2021, and +4.6 percent in comparison with 2016. Finally, vehicles no less than 15 years old account for nearly half of the entire fleet on the road in 2022 (47.3%), while buses no more than two years old account for only 7.5 percent of the total, a lower percentage than that in 2019 (8.7%).

BUS FLEET IN PIEDMONT AND METROPOLITAN CITY OF TURIN

In contrast to the stable trend in the number of buses registered in Italian territory over the last five years, the Piedmont Region has experienced a significant decrease in the number of registrations since 2015. According to the data provided by the Open Parco Veicoli website, managed by Automobile Club Italia (ACI) [30], 5537 private and public buses were registered in 2023, equivalent to 5.5 percent of the total number of buses in Italy (100078 buses), which decreased sharply from 6211 registered in 2015 (6.3 percent of the national total) and slightly from 5771 present in 2021 (5.8 percent of the total). In particular, the latter decrease comes from plans to decommission buses by age, especially belonging to the Euro 2 (279 divested compared to 2021), Euro 3 (279), and Euro 4 (387) categories. Their divestment was only partially offset by the registration of new buses in the last two years, including 547 in the Euro 6 category and 76 electric buses.

As already seen for the existence of biomethane and biogas plants, the Metropolitan City of Turin also leads the statistics for the total number of buses registered in Piedmont: in 2023, 52.2% of the total is registered in Metropolitan City, of which 180 are electric vehicles (94.2% of the total in the region) and 249 are methane-fueled (78.3% of the total in the region).

The consistent presence of electric and methane buses registered in the Metropolitan City can be explained by poor air quality concerns, as local pollution is a major problem in Northern Italy, and Turin ranks among the most polluted cities in the country [31]. From 3190 total units registered in the Metropolitan City in 2015, this decreased by 10.3% to 2909 in 2021 and 2892 in 2023.

As shown in Figure 21, the replacement of older vehicles has also been substantial in the Metropolitan City over the past two years. In the foreground, the number of Euro 4 vehicles decreased by 254 units (-63.2%) and Euro 2 vehicles by 154 units (-43.8%) compared with an increase of 256 Euro 6 vehicles (+30.7%) and 75 zero-emission vehicles (+41.7%). As mentioned before, this trend is mainly due to the mandatory decommissioning by the beginning of 2024 of diesel and gasoline-powered buses having Euro 3 category or lower and operating in the local public transport sector, especially in Turin municipality territory.

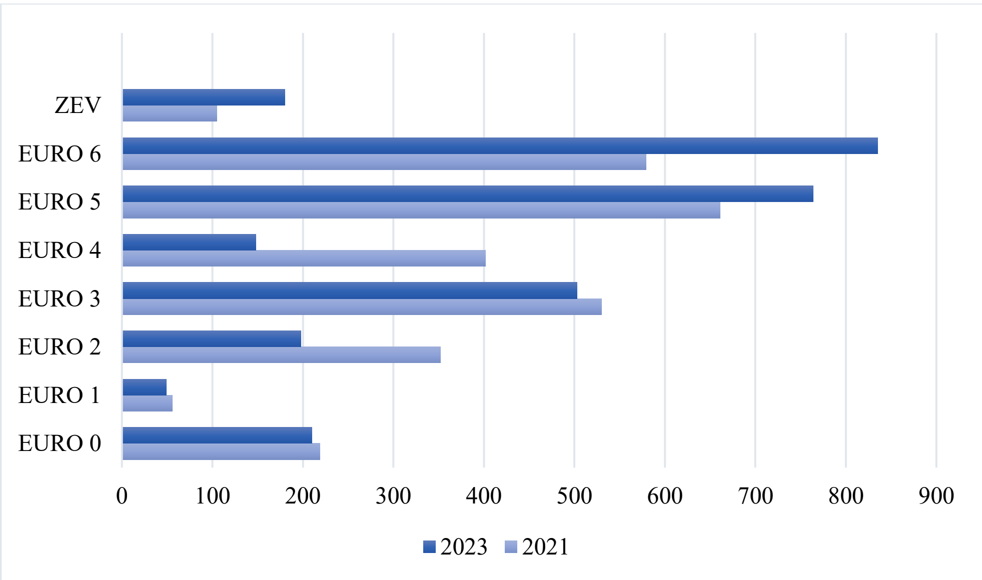

Figure 21: Trend in the number of buses present in the Metropolitan City of Turin according to their emission category [30]

As shown in Figure 22, as of 2021, 86.8 percent of the fleet is diesel-powered. Similar to the Italian context, this figure decreased from 89.2 percent (-281 units) in 2015 and continues to decline (as of 2023, it is 84.1 percent). In contrast, electric buses have seen a significant increase in number, rising from just 30 in 2015 to 105 in 2021, and reaching 180 in 2023, with an increase of +600%. Nevertheless, they account for only 6.2 percent of the total in 2023, although their numbers are growing significantly (up to 0.1 percent in 2015). Finally, methane-powered buses have experienced a smaller but steady increase in recent years, accounting for 8.6 percent of the share in 2023 compared with 5.7 percent in 2015.

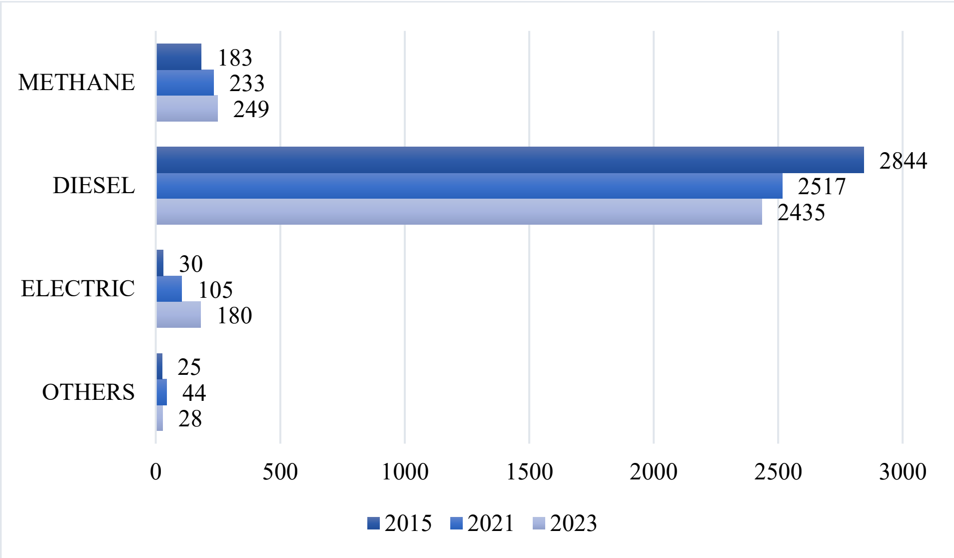

Figure 22: Trend in the number of buses in the Metropolitan City of Turin according to their power supply [30]

The statistics illustrated are the result of the application of European, national, and local policies aimed at encouraging the purchase of public vehicles that have less environmental impact and are powered by more sustainable alternative fuels, including electricity and natural gas. Notably, these policies have involved the gradual transformation of the fleet, characterizing local public transport companies, which have largely contributed to the renewal. In fact, these companies mainly cover the demand for transportation within short urban routes, an ideal scenario for the use of methane, electric, and/or hybrid vehicles with a current limited range, and they own most of the buses in provincial and regional territories.

2. ANALYSIS OF THE SITUATION IN THE METROPOLITAN CITY OF TURIN

2.1. BIOGAS PRODUCTION CHAIN

The Piedmont region, particularly the area around Turin, is home to many biogas plants with assigned to power generation. According to data provided by the Atlaimpianti website of the GSE and the Metropolitan City of Turin, on its provincial territory the number of plants reaches 59, out of a total of 235 plants distributed over the regional territory. The nominal electrical power of Piedmont's plants reaches a magnitude of 153.1 MW in total, of which 36% was installed within the boundaries of the Metropolitan City (55.03 MW). Approximately 31 percent of the installed capacity (16.93 MW) uses municipal organic waste (MSW) as raw material input, whereas the remaining 69 percent is fed with farming and agricultural waste (38.10 MW).

Until May 2024, a total of 8 plants in the Metropolitan City were admitted in the first three procedures, including 3 in the first call (1 reconversion) and 5 in the third round (including 2 reconversions), described in detail in Table 7 below; this trend results in only 3.7 percent of Turin's installed capacity being converted.

2.2. BIOMETHANE PRODUCTION CHAIN

As mentioned in previous chapters, most existing biomethane plants are present in northern Italy. Specifically, as of 2023, the top three regions by the number of plants owned more than half of the Italian total (48 out of 85). Piedmont ranks second as the Italian region to host the most, tied to Emilia-Romagna (11), and behind only the Lombardy region (26) [22].

In the first three regions, distribution was heterogeneous at the provincial level. In the Piedmont region, seven out of eight provinces contain at least one plant within their boundaries, but only the province of Alessandria and the Metropolitan City of Turin have at least two, with two and four plants, respectively. This is related to the higher population and population density of the province of Turin, its high number of industrial settlements, stronger and economically extensive farms, and easier infrastructure and logistics network.

	Cp (Smc/h)	CO_2 liquefaction	Upgrading technology	Self-consume by biogas combustion	Marketing type	Raw material input
Pinerolo	800	No	Membrane	Yes	CNG+feed-in	FORSU
Candiolo	350	Yes	Criogenic	No	LNG	Agricultural and zootechnic
Piverone	400	No	Membrane	Yes	CNG+feed-in	Agricultural and zootechnic
Villareggia	380	Yes	Membrane	Yes	CNG+feed-in	Agricultural and zootechnic

Table 7: Technical characteristics of biomethane plants in the Metropolitan City of Turin [32]

The Piedmont biomethane supply chain has experienced strong technological developments in recent decades, considering both biofuel production and distribution. In fact, October 2020 saw the inauguration of the first production plant in Italy fueled by organic waste (OFMSW), located in the municipality of Pinerolo. In March 2021, the first plant in Italy producing liquid biomethane, obtained through cryogenic upgrading technology and whose production is entirely intended for the transportation sector, began operation a few kilometers from the previous site. In addition, in February 2020, the first fueling station in the Northwest to deliver exclusively biomethane, in the form of bio-LNG and bio-CNG, was opened near the CNH Industrial Group's industrial headquarters.

At the end of 2023, the total hourly production capacity of the Metropolitan City is equivalent to 1930 Smc/h, resulting in an annual output of between 11.58 and 15.44 mcm (considering 6000 and 8000 hours of plant operation per year, respectively).

In the ranking list of Call for Proposals 1 of Ministerial Decree 15/09/22, published on 11/24/2023, three business names based in the Metropolitan City of Turin are eligible for the incentive, out of a total of 51 successful applications (5.9% of the total). The plants under construction or reconversion will have a production capacity equivalent to 1200 Smc/h, out of a total of 25881.4 Smc/h allocated (4.6% of the total).

Considering the third Call of Proposals, five companies result to be eligible for the incentive (3.8% of the total applications number). Anyway, it is necessary to say that two companies out of five refused the assignment in Procedure 1 and were in Procedure 3, due to the different incentivization system previously described; in fact, it appears that around 70% of the companies in Italy refused the assignment in the first procedure, to show up on the third and guaranteeing higher incomes.[27]

In Piedmont the realization of new or reconverted plants will result add an additional production capacity of 900 Smc/h (excluding the two plants that were present in first Procedure), resulting in a total 67.4% increase in the current provincial production capacity.

	Cp (Smc/h)	Category of intervention	Feedstock typology	Intended use of biomethane	Offer of percentage reduction on the reference rate
Rondissone*	300	New realization	OFMSW	Transport sector	1.50%**
Piobesi Torinese*	500	New realization	OFMSW	Transport sector	1.02%**
Piverone	400	Reconversion	Agricultural	Other uses	1.00%
Favria	250	New realization	Agricultural	Other uses	1.50%
Candolo	250	Reconversion	Agricultural	Other uses	1.00%
Scalenghe	400	Reconversion	Agricultural	Other uses	1.00%

Table 8: Characteristics of the plants present in the Metropolitan City of Turin admitted in the first and third rankings of the Ministerial Decree 15/09/2021, reprocessing of data provided by GSE [24]

* *Assigned plants in the first Procedure that waived the incentive, and were found to be assigned to the third Procedure. ** This percentage reduction value coincides with the one reported in the third Procedure.*

As evidence of the low competition among the participating companies and the wide availability of quotas in the ranking list, all 51 winning applicants offered a percentage reduction in the benchmark tariff slightly above the minimum (with an average reduction of 1.05 percent), which offers substantial opportunities for development and profit to willing parties to invest in the Italian and Turin biomethane supply chains, although not a consistent number of subjects have applied to access the incentive especially in the first two Calls.

2.3. THE MAIN LOCAL PUBLIC TRANSPORTATION COMPANY IN TURIN: GTT

Gruppo Torinese Trasporti S.p.A., under the FCT Holding S.r.l., is a holding company controlled by the City of Turin. Today, it is the leading local public transport (LPT) company in the provincial and regional scenario. Gruppo Torinese Trasporti plays a key role in the mobility of the metropolitan city of Turin. In particular, GTT operates a significant part of local public transport, with a fleet that accounts for about 40 percent of the buses in service in the province of Turin. Analyzing GTT in this thesis work is therefore essential to understanding the dynamics of Turin's public transport, both in terms of operational management and its impact on environmental sustainability.

According to the data crossing between the operating budget document as of December 31, 2022 [33], "Parco Veicoli-Schede tecniche" document, (published by the Group in April 2021 [34]) and “Analisi dei dati di consumo ai fini della diagnosi energetica del "sito virtuale" di GTT” thesis work [35]. In 2023, the company controlled 795 buses used for urban and suburban transport and 240 extra-urban buses, and the total number of fleet compositions is equivalent to 18.7 percent of registered buses in Piedmont and 35.8 percent in the Metropolitan City of Turin. In 2022, in the post-pandemic period, the entire company-owned fleet covered a total of 37.9 million kilometers in Turin's urban and suburban areas, of which 32.8 million kilometers were covered by buses, a figure that is down sharply from the 40 million kilometers covered within the suburban area in 2019, of which 34.5% were from its own bus fleet (4.9%), due to extended lockdowns aimed at the citizenry between 2020 and 2021 [33].

DESCRIPTION OF THE URBAN AND SUBURBAN FLEET AND NETWORK

The surface network served by buses in the city of Turin and the suburban area is served by 88 lines, distributed in the Capital and the municipalities of the metropolitan belt: Alpignano, Baldissero, Beinasco, Borgaro, Cambiano, Caselle Torinese, Chieri, Collegno, Druento, Grugliasco, Leinì, Moncalieri, Nichelino, Orbassano, Pecetto Torinese, Pianezza, Pino Torinese, Rivalta Torinese, Rivoli, San Mauro, Santena, Settimo Torinese, Trofarello, Venaria Reale.

Bus networks can be divided into the following categories:

- "force" lines: those designed to operate on strong mobility routes not covered by tram service;

- "integrative" lines: they have the function of integration and adduction towards the fixed-plant system and force lines. On the force lines and other lines characterized by high load levels, articulated vehicles with a length of 18 m are in service.

In addition to the regular lines, there are 21 special lines serving industrial estates and school hubs, which have few runs that coincide with the entry and exit of schoolchildren.

In addition, a night service (Night Buster) served by 10 bus lines with hourly passes operates every Friday, Saturday, and pre-holidays.

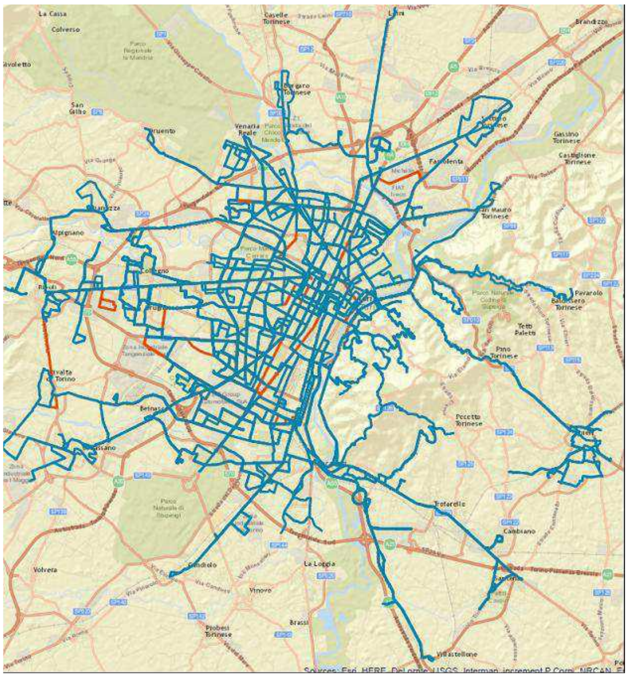

Figure 23: Map showing urban and suburban lines served by GTT buses [36]

In total, the surface road network operated by GTT covers a length of 1,068 km along the axis, equivalent to 2,136 km in round trips plus returns [34].

The following table presents a detailed illustration of the composition of buses operating in the urban and suburban areas of the company in 2023.

	MODEL	REGISTRATION YEAR	NUMBER	SUPPLY	CATEGORY
10 m	EPT - CACCIAMALI "ELFO" ELETTRICO	2003	23	EV	ZERO
	BYD K7 ELETTRICO	2019	8	EV	ZERO
	BMC NEOCITY	2020	6	DIESEL	EURO6
12 m	IRISBUS 491E.12.29 - CITYCLASS E4	2006	15	DIESEL	EURO4
	IRISBUS 491E.12.27 CNG - CITYCLASS	2008	87	CNG	EEV
	IRISBUS CITELIS 12.29 DIESEL EEV	2010	81	DIESEL	EEV
	IVECO CITELIS 12.29 DIESEL EEV	2013	81	DIESEL	EEV
	BYD K9UB ELETTRICO	2017	20	EV	ZERO
	MERCEDES CONECTO E6	2019	40	DIESEL	EURO6
	MERCEDES CONECTO CNG	2020	40	CNG	EURO6
	BYD K9UB ELETTRICO	2021	50	EV	ZERO
	BYD K9UB ELETTRICO	2023	70	EV	ZERO
	BYD K9UB ELETTRICO	2022	30	EV	ZERO
	IVECO URBANWAY CNG 12m	2023	52	CNG	EURO6
18 m	IRISBUS 491E.18.31 CNG CITYCLASS	2005	24	CNG	EEV
	IRISBUS CITELIS 18m DIESEL EEV	2010	10	DIESEL	EEV
	IRISBUS CITELIS 18m CNG	2010	4	CNG	EEV
	IRISBUS CITELIS 18m DIESEL EEV	2012	65	DIESEL	EEV
	IRISBUS CITELIS 18m DIESEL EEV	2014	5	DIESEL	EEV
	MERCEDES CONECTO G E6	2020	34	DIESEL	EURO6
	IVECO URBANWAY CNG 18m	2023	50	CNG	EURO6

Table 9: Description of buses owned by GTT in 2023, broken down by year of registration, number, power supply and emission category, data elaboration [33], [34], [35]

Logically, the company's most significant local emissions are caused by its road bus fleet, which is used for urban and suburban services. To limit emissions and improve the service provided, GTT responds to the aging bus fleet with substantial investment in the purchase of new vehicles, continuing to implement further improvements beyond those already achieved in the years leading up to the pandemic.

- During 2022, 30 new electric vehicles produced by the BYD, with a length of 12 m, gradually entered service.
- During 2023, another 70 new electric vehicles produced by BYD with a length of 12 m gradually entered service, effectively concluding the delivery of vehicles by the Chinese supplier that won the respective 2020 tender.
- During 2023, 52 CNG buses produced by Iveco with a length of 12 m and 50 CNG buses produced by Iveco with a length of 18 m were integrated into the urban fleet.
- In 2022, in addition to the 334 vehicles purchased through funding from PNMS resources and other sources, the company has drawn up a plan for the purchase and commissioning of another 300 electric buses, funded by the PNRR.
- During the two-year period 2021-2022, the entire fleet of Euro 2 and Euro 3 buses, in accordance with the obligations imposed by Decree Law 121/2021 [29], was decommissioned from services carried out in urban and suburban circulation, and as many as 58 Euro 2 buses and 55 Euro 3 diesel-powered buses were set aside over the said period.

As shown in Figure 24, the percentage distribution curve of vehicles by year of registration appears heterogeneous. However, one can note the commitment placed by the company to adhere to the bus fleet renewal plan, with the introduction of 172 vehicles only in 2023 (constituting 21.6 percent of the total). The average year of registration as of 2023 was equal to 2016, with an average seniority of buses in service of 7.5 years. This value is drastically lower than the average life of service in 2021, which is equal to 11.3 years and higher than the average seniority of buses in Italy as of 2021 (10.1 years) [28].

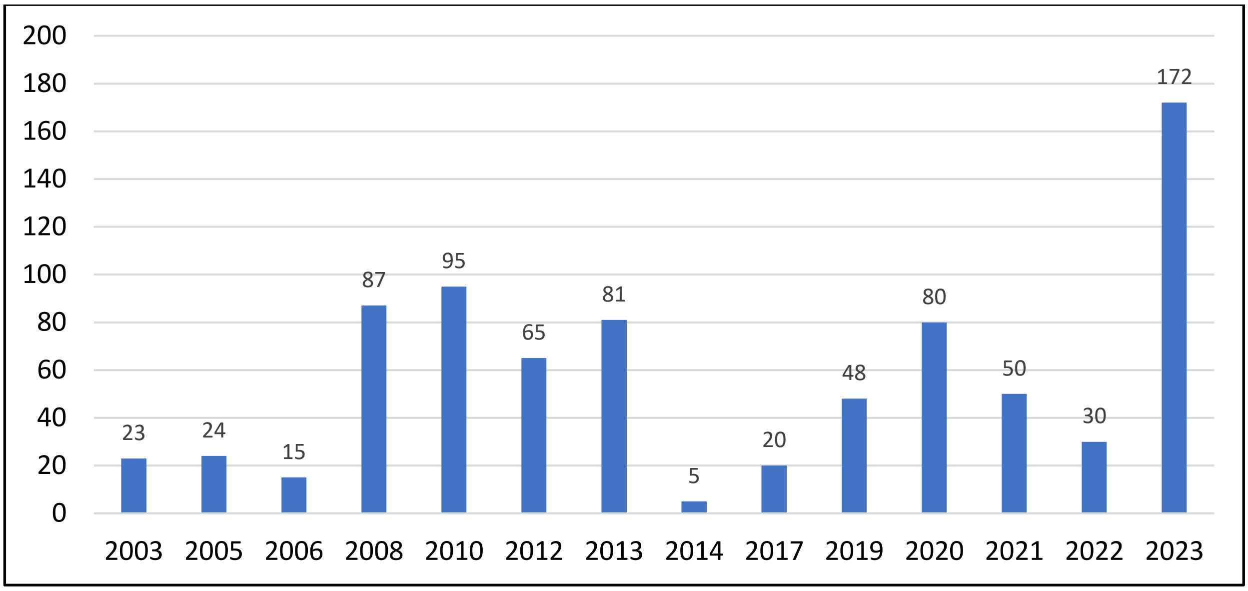

Figure 24: Registration year with respect to number of buses in 2023, data elaboration [33], [34], [35]

Regarding the breakdown by fuel type of the fleet, in 2021, more than half of it was powered by diesel (52 percent), 36 percent by CNG, and 12 percent of the buses were electric. If these figures are compared with the bus fleet operating in the entire territory of the Metropolitan City of Turin, the percentages of CNG- and electric-powered vehicles are slight higher (8 percent and 3.6 percent of the provincial fleet, respectively). Despite the high seniority of vehicles, these data showed a more differentiated composition with respect to the fuel used.

As a result of the introduction of electric vehicles and the decommissioning of impactful diesel-powered buses, at the end of 2023, the latter were found to comprise 43% of the fleet (-9%), CNG buses 32% (-4%), and electric vehicles a quarter of the total (+13%).

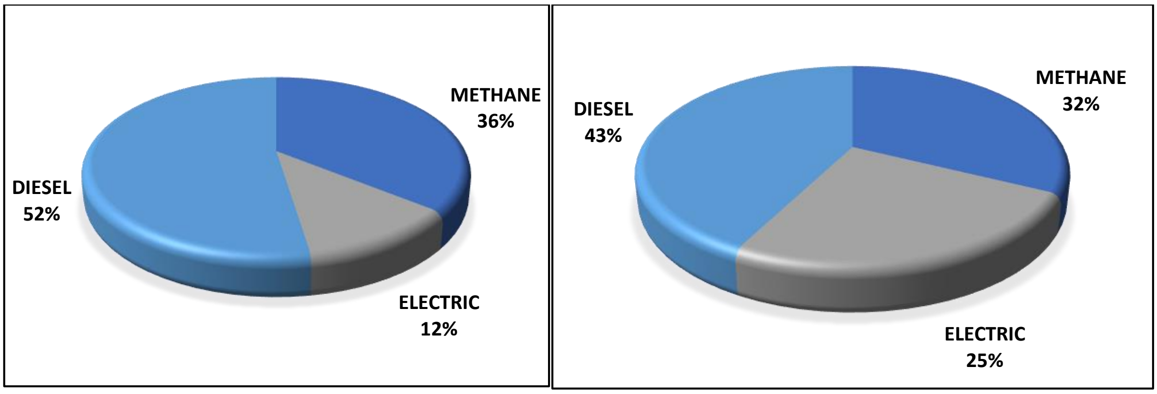

Figure 25,26: GTT buses fuel distribution in 2021 (left) and 2023 (right), data elaboration [33], [34], [35] According to the data provided by the GTT and described in Figure 27, in 2021, as many as 58 percent of the vehicles were found to belong to the enhanced environmentally friendly vehicle (EEV) emission class, an unconventional emission class identifiable between the Euro 5 and Euro 6 standards, whose emission constraints can also be met by older vehicles through their conversion by installing specific anti-pollution technologies (as in the 97 buses registered between 2004 and 2005, but belonging to the EEV class). In 2021, a total of 120 buses (12.8 percent of the total) were found to be part of the Euro 2 and 3 categories; the vehicles falling into these emission categories are found to be decommissioned from the fleet as of 2023, in compliance with the increasingly stringent Italian regulations mentioned above.

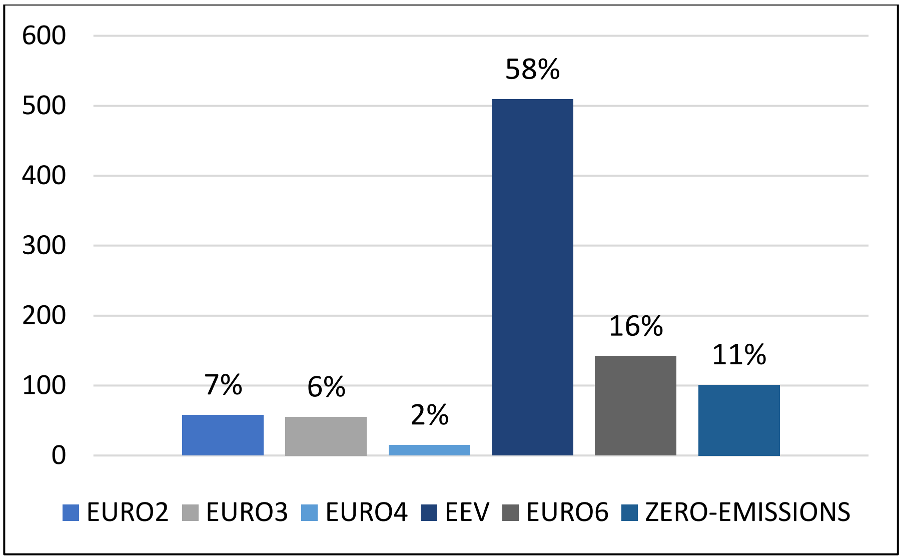

Figure 27: Vehicle emission standards in 2021, data elaboration [33], [34], [35]

In Figure 28, a predominance was observed in the presence of vehicles in the EEV category, which constituted almost half of the total share, albeit with a sharp reduction in number (-152 vehicles). The number of vehicles registered as Euro 6 is growing (+80) and those falling under the Zero-Emissions category (+100), while only 15 diesel-powered buses appear to belong to the fleet, as reported in 2021.

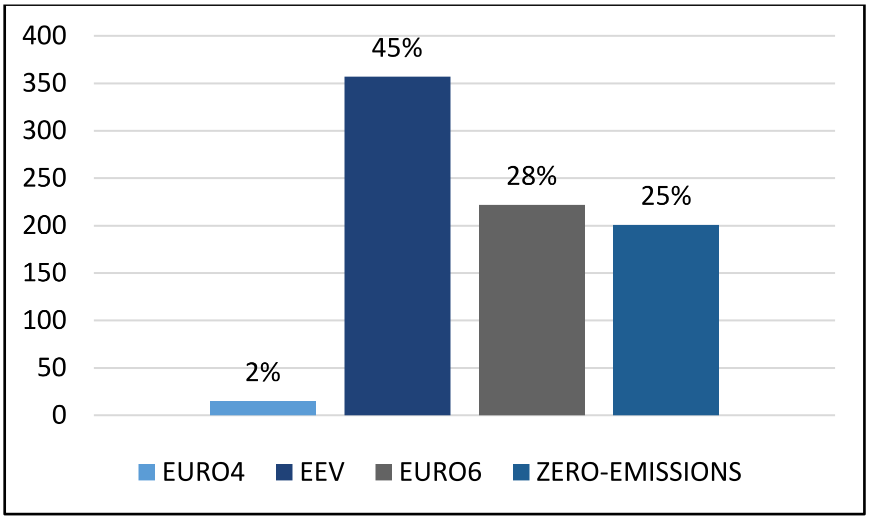

Figure 28: Vehicle emission standards in 2023, data elaboration [33], [34], [35]

GTT FLEET OUTLOOK TO 2027

Between now and 2027, the strategy decided by the city includes a robust turnaround in fleet composition, as defined by the newly formed New Transport Turin (NTT), an association with the purpose of defining future investments related to metropolitan mobility through the collaboration of the City of Turin, GTT, Infra.TO, and the Piedmont Mobility Agency; by 2027, the entire GTT fleet will consist of 63% electric vehicles and 24% CNG vehicles, resulting in a reduction in the number of diesel-powered vehicles (13%) [37]. As stated by Councillor for Mobility Chiara Foglietta in the NTT group presentation, one of the priority goals is to reduce particulate matter and carbon dioxide emissions released into the atmosphere, starting precisely with the revision of the local public transport plan.

The new plan appears to have been developed according to four main guidelines:

- The strengthening of the tramway network, with the recovery of currently unused tracks and the creation of new tracks (with an increase in track kilometers from 70 to 100, thus an increase of approximately 40 percent).

- Extension of Metro 1 to the Cascine Vica.

- The introduction of 18 Bus Rapid Transit vehicles starting in 2025, 18-meter-long electric buses with a declared transport capacity of two thousand passengers per hour and featuring a dedicated transport infrastructure that does not interfere with city traffic [37].

- The renewal of the urban fleet, including 150 12-meter-long electric buses, 62 articulated electric buses (18 m), and 22 electric minibuses, which are less than 10 m long [37]. In addition, an additional 31 articulated CNG buses (18 m) will be introduced [38].

In accordance with the plans drawn up and approved by the Group, by 2027, 283 vehicles will be introduced, which will inevitably be followed by a massive decommissioning plan of obsolete and energy-consuming vehicles, powered primarily by diesel and secondarily by natural gas. The Tables below show the means introduced and those being decommissioned.

	MODEL	REGISTRATION YEAR	NUMBER	SUPPLY	CATEGORY
10 m	INDCAR E-B6	2024	10	EV	ZERO
	INDCAR E-B6	2025	12	EV	ZERO
12 m	NEW BUSES FROM IVECO	2024-2025	150	EV	ZERO
18 m	NEW BUSES FROM IVECO (SNODATI e BRT)	2024-2025	95	EV	ZERO
	NEW BUSES EXPECTED	2025-2026	31	GNC	EURO6

Table 10: Description of buses added during the four-year period 2024-2027, data elaboration [37], [38]

	MODEL	REGISTRATION YEAR	NUMBER	SUPPLY	CATEGORY
10 m	EPT - CACCIAMALI "ELFO" ELETTRICO	2003	23	EV	ZERO
12 m	IRISBUS 491E.12.29 - CITYCLASS E4	2006	15	DIESEL	EURO4
	IRISBUS 491E.12.27 CNG - CITYCLASS	2008	87	CNG	EEV
	IRISBUS CITELIS 12.29 DIESEL EEV	2010	81	DIESEL	EEV
	IVECO CITELIS 12.29 DIESEL EEV	2013	71	DIESEL	EEV
18 m	IRISBUS 491E.18.31 CNG CITYCLASS	2005	24	CNG	EEV
	IRISBUS CITELIS 18m DIESEL EEV	2010	10	DIESEL	EEV
	IRISBUS CITELIS 18m CNG	2010	4	CNG	EEV
	IRISBUS CITELIS 18m DIESEL EEV	2012	65	DIESEL	EEV

Table 11: Description of buses decommissioned during the four-year period 2024-2027, data elaboration [37], [38]

Lacking detailed information regarding the plan to decommission vehicles in the coming years, following the Group's methodology over the past decade of decommissioning vehicles with an average of 20 years of service, vehicles characterized by 15 or more years of operation were assumed to be taken out of service, in accordance with the company's intentions to rejuvenate the fleet. To achieve the goals announced in the plan, the GTT will divest 380 vehicles over the four-year period 2024-2027, compared with the 2023 composition [37]. This provision will affect 242 vehicles with diesel propulsion, 115 with natural gas propulsion, and 23 with electric propulsion. The last 15 Euro4 vehicles and almost the entirety of the EEV buses will be decommissioned; the first 23 "Elfo" electric vehicles, now operating for more than 20 years, will also most likely be gradually replaced by more modern and efficient minibuses. As described so far, the following plan will see a total of 713 vehicles as of 2027, affecting a 10 percent reduction in number from the total in 2023. This can be justified by the greater modernity of the fleet, and thus, the greater reliability and efficiency characterizing the recently introduced vehicles, and by the gradual reduction of mileage according to the Service Agreements and provisions of the commissioning entities [39].

By 2027, the fleet will have an average age of as much as 4.5 years, with an average year of vehicle introduction of 2023 As can be observed in Figure 29, there is an inhomogeneity in the distribution of data; only a fraction of the vehicles will be registered before 2023 (116 vehicles, or 34.1% of the total), with the majority of buses introduced in the three-year period 2023-2025.

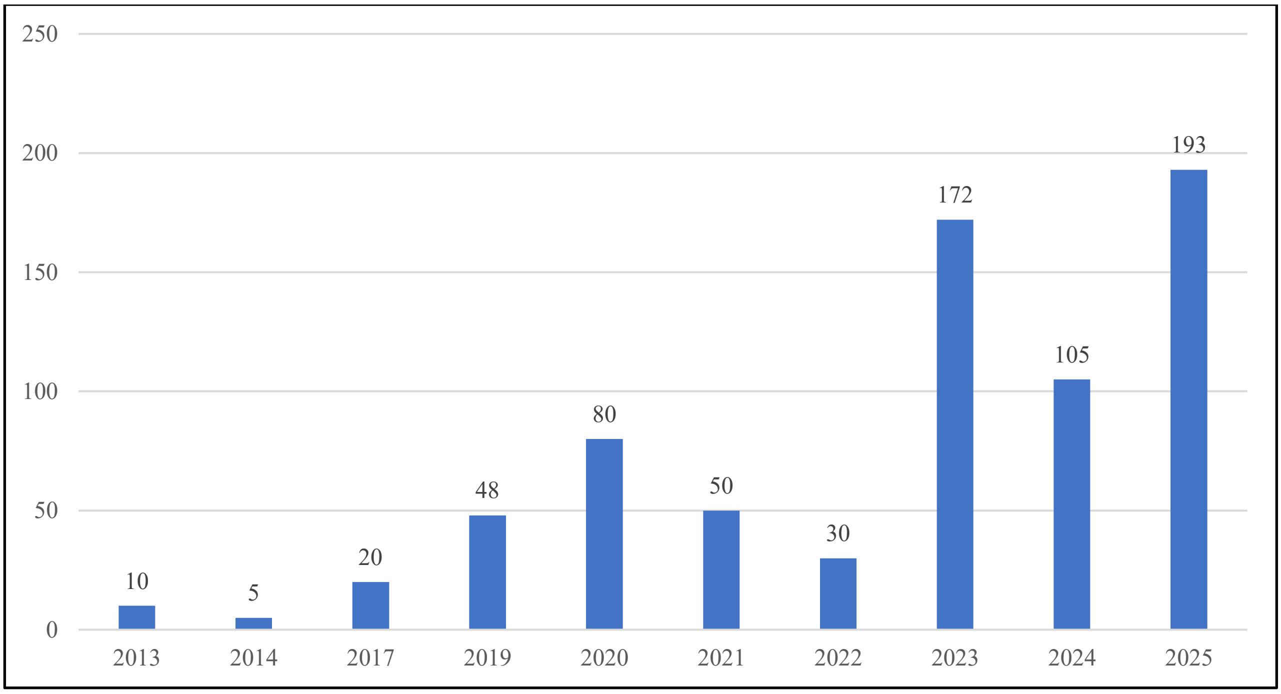

Figure 29: Registration year with respect to number of buses in 2027, data elaboration [37]

As described above, starting in 2027, the company will have no Euro4 vehicles and only 15 vehicles belonging to the EEV category will be operational. Thus, 445 buses will be classified as Zero-Emission Vehicles (ZEV), inevitably lowering CO_2 and PM10 emissions in the metropolitan environment. In addition, the peak of registered Euro6 bus vehicles will be approaching, and the environmental category will be replaced by the more stringent Euro7 in 60 months from April 2024, starting around April 2029 [40].

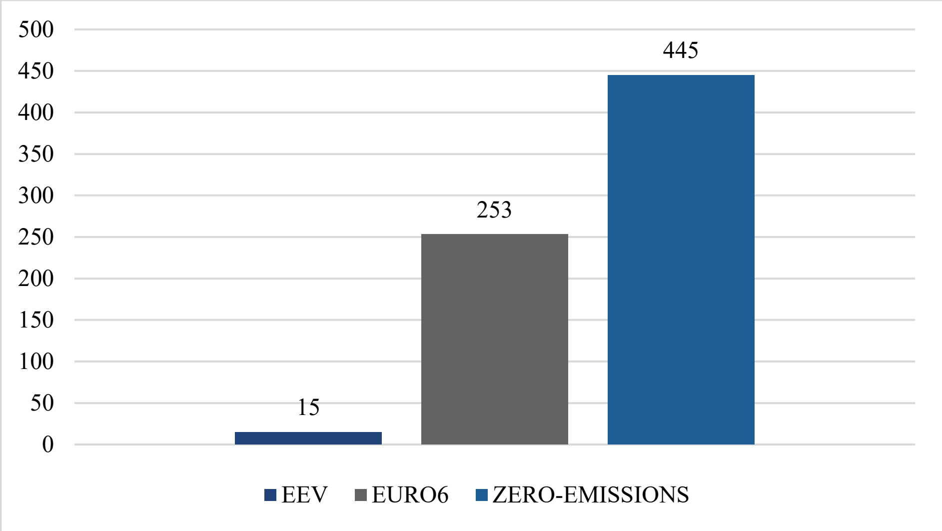

Figure 30: Vehicle emission standards in 2027, data elaboration[33], [37]

It is interesting to note that the trend in fleet composition between 2021 and 2027 sees a fourfold increase in the number of electric vehicles (101 from 445), and a doubling from 2023 (201 units). Diesel-powered vehicles will make up only a small part of the Turin fleet, reaching 95 vehicles in 2027, down sharply from 450 in 2021 and 337 in 2023. Finally, the number of CNG-fueled vehicles in 2027 appears to be decreasing compared to previous years (173 units in 2027, 257 in 2023, and 307 in 2021).

These trends describe a centralization of resources in the purchase of mainly electric vehicles, at the expense of an inevitably negative trend related to diesel vehicles and their phasing out. In addition, although the company 's recent calls for tenders call for new CNG vehicles, they will be insufficient to maintain a CNG composition share at the current level because of the decommissioning of as many as 115 CNG vehicles.

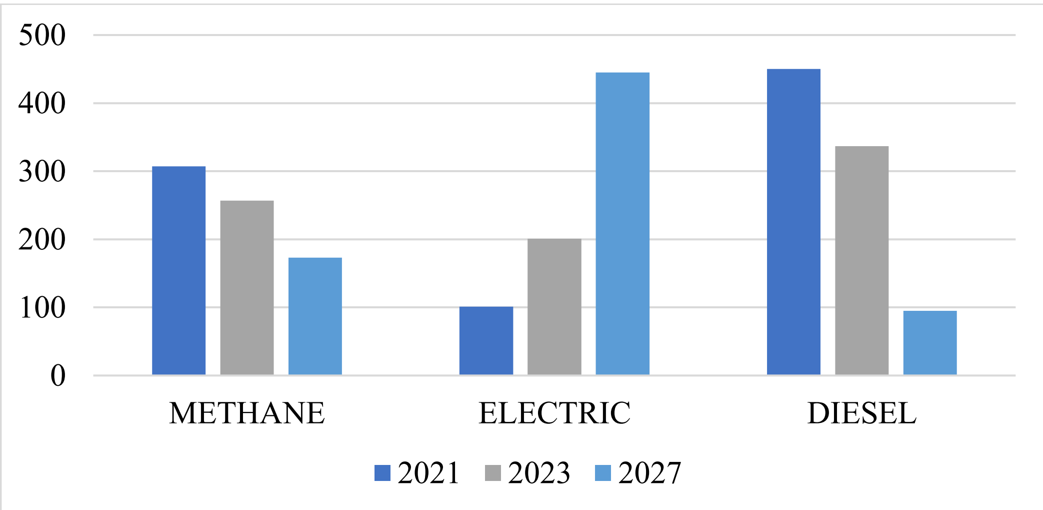

Figure 31: GTT buses fuel distribution trend [33], [37]

URBAN BUSES OFFER

The Company, although a decline in production compared to data reported in the early 2000s, appears to have maintained a generally stable mileage offered by its surface cars in the urban sector in the post-pandemic period. As the public health emergency disappeared, with changes in public mobility management gradually arranged in previous years from April 2022, the standard service offered in the years prior to 2020, as shown in Figure 32, came back into effect. Analysis of the reported data shows that 74.4 percent (27.6 million km) of the distance offered by surface vehicles is covered by city and suburban buses, compared to 9.5 by streetcar vehicles.

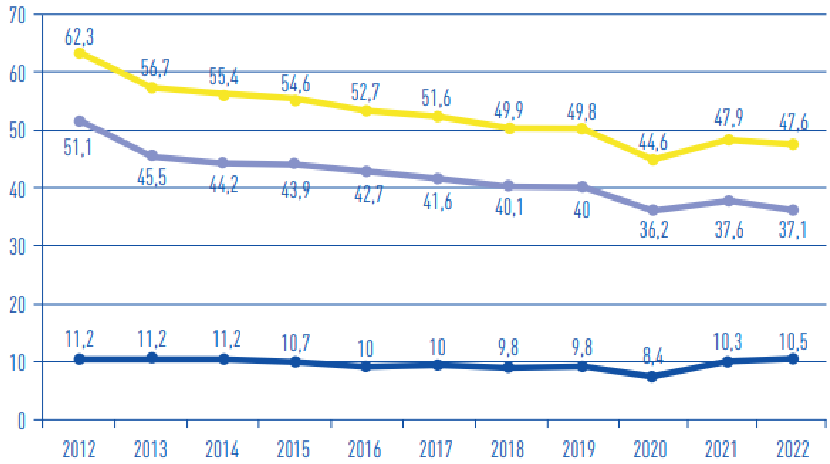

Figure 32: Milions of kilometers related to urban transportation (in blue the metro system, in grey the urban surface vehicles, in yellow the total offered distance) [39]

According to the Company, of the reported kilometers related to buses, most are offered by diesel-powered vehicles, as depicted in Figure 33. Following the acquisition by incorporation of the company Canova in 2022, which operated lines under subcontract to GTT, the kilometers offered are up compared to 2021. Because of this offer trend, the fleet of diesel buses serving the urban network is increased in number, thus covering 10% of the kilometers compared to 2021 and approaching 17 million, compared to 15.4. As a result of the divestment of many CNG vehicles during 2022, the kilometers offered by the following motorization are down 12 percent (7.2 million compared to 8.1 in 2021), while electric vehicles dramatically increase their production from 2.0 million in 2021 (8 percent of the total) to 3.4 in 2022 (12 percent of the total), an increase of 75 percent.

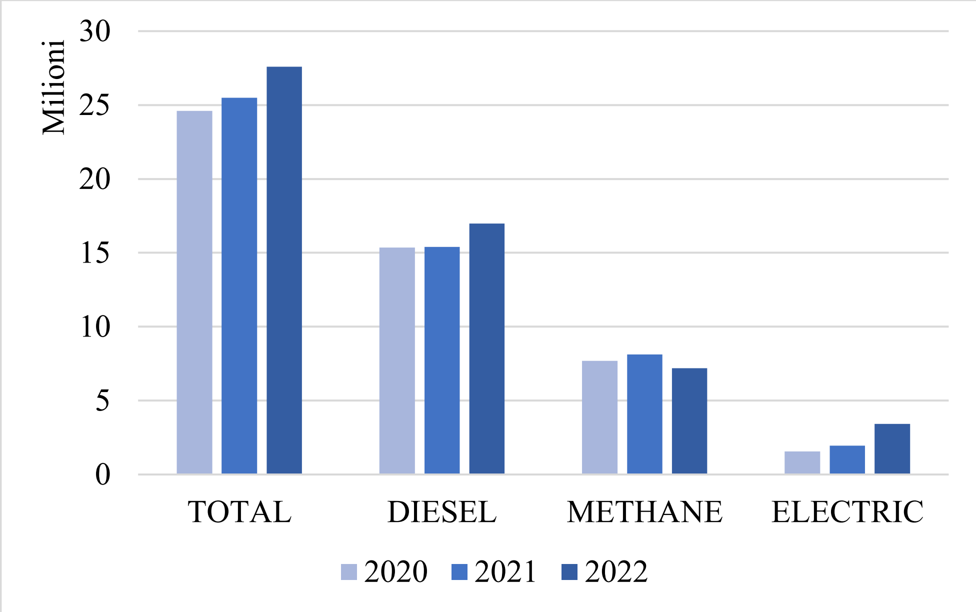

Figure 33: Kilometers distribution by fuel type of GTT-owned city buses, GTT data processing [39]

ENERGY CONSUMPTIONS OUTLOOK OF GTT BUSES

According to the Turin Action Plan for Energy (TAPE), updated as of December 2021 and relying on data for 2019, in the pre-Covid period, Turin's local public transport contributed a non-negligible share of final energy consumption to the total provincial transport sector, with approximately 781.9 TJ consumed by public transport (8.2 percent of the total detected) compared with about 8733.2 TJ consumed by private transport [41]. Consumption appears to decrease sharply from past surveys conducted by GTT, highlighting a difference of approximately 392.4 TJ between 1991 and 2019 (-33%). Specifically, energy consumption by fuel type for urban surface transportation sees in public transport a demand for about 290.9 TJ of energy from natural gas and about 540.7 TJ from diesel fuel during 2019 (electricity consumption for bus transportation is not reported in the document). Regarding private transportation, it is driven by diesel and gasoline consumption (4327.6 TJ and 3569.8 TJ, respectively), while only to a small extent by natural gas (226.8 TJ). Specifically, 45.7 percent of the methane energy demand is for industrial vehicles (approximately 103.3 TJ) and the remainder from cars registered in the City of Turin; 56.6 percent of diesel demand is for industrial vehicles (2450.5 TJ), while the remainder is for privately owned cars and buses. When comparing the CNG and diesel consumption data between public and private transport, it was found that the GTT demand for diesel fuel was significantly lower than that of private vehicles, primarily for industrial purposes (Figure 35). In contrast, approximately half of the total consumption derived from methane is covered by GTT buses, demonstrating the weight that local public transport holds regarding the supply of natural gas destined for the transportation sector (Figure 34). Assuming that the share of methane destined for public transport is derived from the process of upgrading biogas from production plants in the territory of the Metropolitan City of Turin, according to the present situation this would help increase the sustainability of GTT reducing CO_2 emissions into the atmosphere, in line with its business strategy.

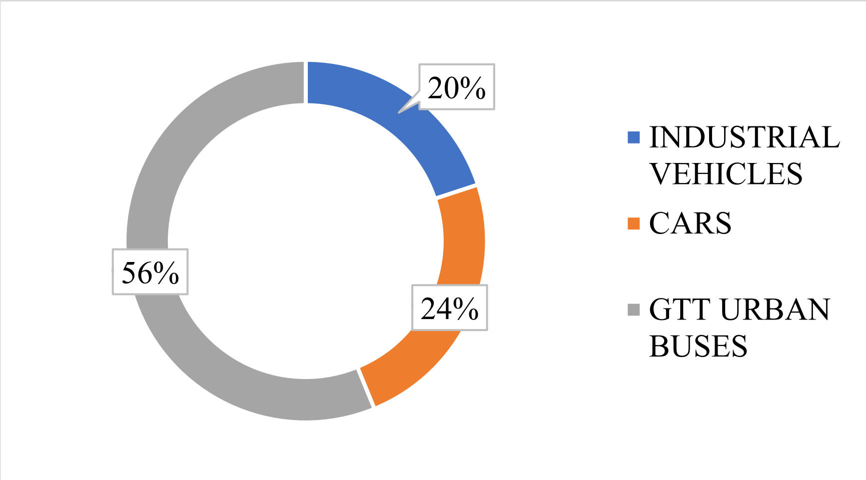

Figure 34: Breakdown of natural gas demand for transport in the City of Turin as of 2019, GTT and TAPE data processing [39], [41]

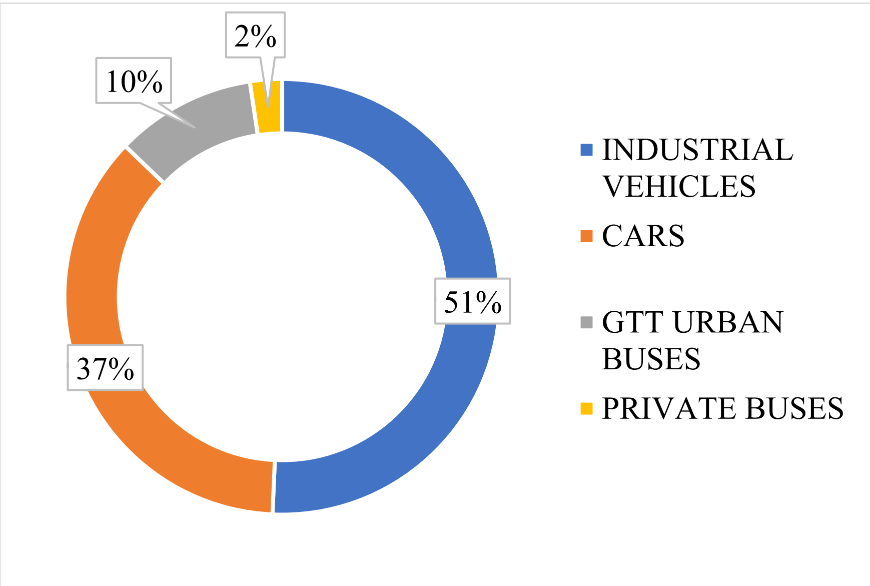

Figure 35: Breakdown of diesel demand for transport in the City of Turin as of 2019, GTT and TAPE data processing [39], [41]

The following Table shows the quantities of natural gas and diesel consumed by the types of vehicles treated so far (in kg and liters, respectively). The data shown were calculated by applying the numerical proportionalities between the mass of methane/volume of diesel and energy content in TJ, applied to calculate the consumption described in the Turin Action Plan for Energy, and agreed with the conversion factors arranged by the Italian Federation for the

Rational Use of Energy (FIRE) [42]. Anyway, in the Table the natural gas and diesel consumptions are shown also in TJ, in order to compare the quantities in energy terms.

	INDUSTRIAL VEHICLES	CARS	GTT PUBLIC BUSES	PRIVATE BUSES	TOTAL
Natural gas (thousands of kg)	2090	2498	5883	-	10471
Natural gas (TJ)	113	135	319	-	568
Diesel (thousands of litres)	83159	59801	17131	3897	163988
Diesel (TJ)	2949	2121	607	138	5815

Table 12: Volumes of diesel, natural gas and their associate energy quantity consumed by Turin vehicle categories in 2019, TAPE data elaboration [41]

GTT FLEET CONSUMPTIONS TREND

GTT represents the largest, and therefore energy-intensive, local transportation company in the Turin Metropolitan Area. With the gradual return to business as usual, its overall energy consumption in 2022, the most recent figures provided by the company, showed an increase from 2021, while remaining below consumption prior to the health crisis (down 8 percent from 2019) [39]

However, automotive CNG consumption has plummeted to approximately 4.49 million kg (equivalent to around 244 TJ) , down 11.2 percent from 2021, and as much as 23.7 percent from 2019. This trend can be explained by the major divestment of natural gas-powered vehicles over the past five years, their consequent reduction in numbers, and the reduction in vehicle fuel consumption owing to the gradual introduction of new and more efficient buses. Obviously, the trends represented in the following Figures about the two fuels (kg and litres) and electricity (in MWh) follow the same trends with respect to energy terms in TJ.

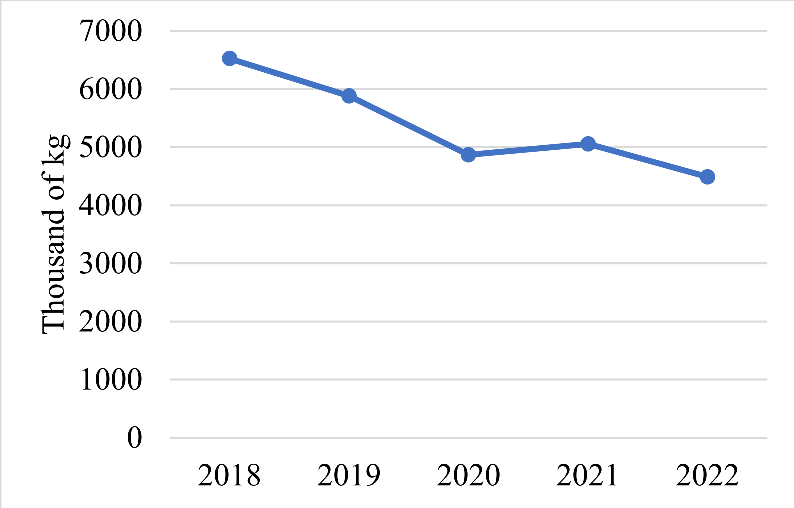

Figure 36: GTT natural gas consumption for urban buses propulsion (in thousands of kg) [33]

Similar to CNG consumption trends, diesel consumption trends in 2022 were affected by a sharp decline compared to pre-COVID levels (-9.1% compared to 2019 levels); however, since 2020, there has been a rebound in consumption, with a partial recovery in reference to values recorded in 2020-2021.

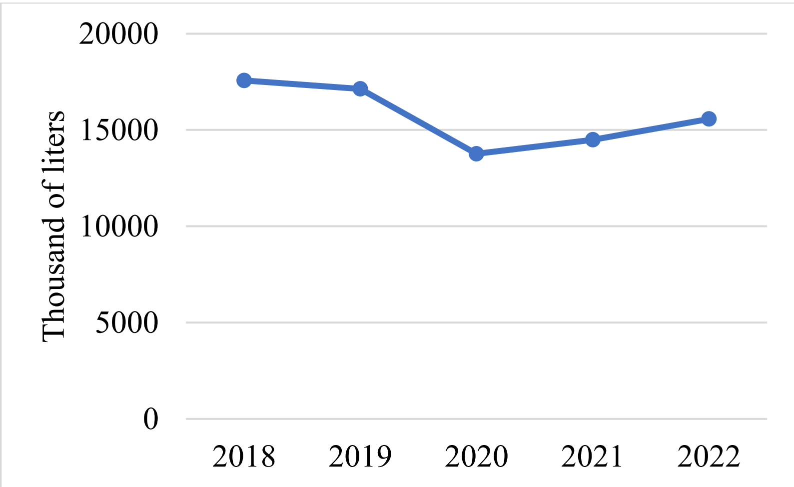

Figure 37: GTT diesel consumption for urban buses propulsion (in thousands of liters) [33]

In contrast to fossil fuels, the demand for electricity for transportation has increased sharply since the beginning of the survey in 2018. Following a slight increase at the beginning of the pandemic period, a steep increase was observed in consumption (+49.7% between 2020 and 2022, equal respectively to around 11 and 21 TJ) because of the wide introduction of electric buses in accordance with the company's Plan for Fleet Renewal and Reduction of Air Pollutant Emissions.

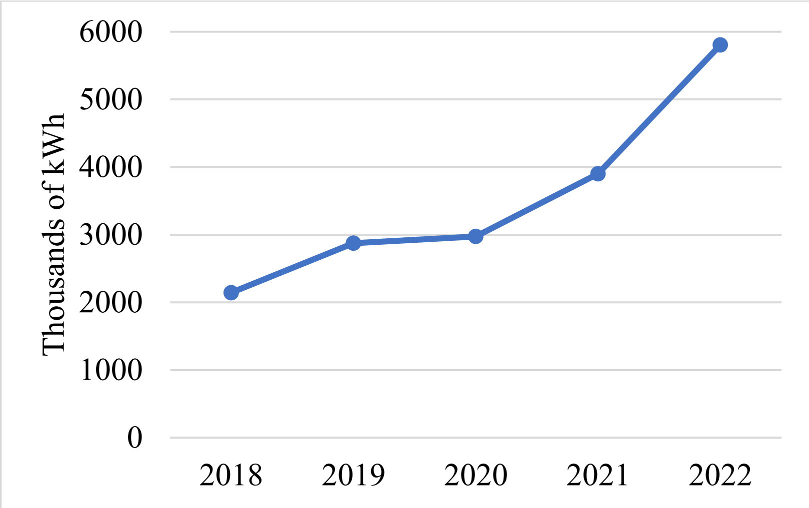

Figure 38: GTT electric energy consumption for urban buses propulsion (in thousands of kWh) [33]

Thus far, the total fleet consumption and production data by fuel type reported in previous non-financial and financial statements of the Turin Transportation Group have been illustrated. For a more accurate calculation of the actual energy consumption levels after 2022, the consumption levels per kilometer of each bus model, as of 2018, are catalogued in this thesis. This year, consumption data collected from each type of vehicle belonging to the fleet are available and reported in the thesis paper [35]; however, we chose to report the consumption data reported in the data sheets provided by the various manufacturers, as most of the vehicles present as of 2018 were antiquated and therefore decommissioned in the subsequent years under analysis.

However, to put this in context, the consumption measured and reported in the thesis [35] appears to be in line with the natural gas consumption calculated from the data sheets per 100 km in the 2018 fleet composition (62.7 and 61.2 kg/100 km, respectively, +2.5%), higher in diesel vehicles (67.0 and 58.4 litres/100 km, respectively, +14.7%) and lower in electric vehicles (85.8 and 99.2 kWh/100 km, -13.5%). The variation in values related to EV vehicles can be found in the small number of vehicles as of 2018, so it is more reliable to work out our calculations relative to the present data sheets.

Without the consumption data per kilometer of bus models introduced after 2021, a reduction in consumption levels of 5% was assumed compared with newer vehicle models with the same fuel type, similar length (<10 m, 12 m, and 18 m), and age difference from the reference means of less than 5 years, and the reduction was assumed to be 10% when the age difference from the reference means was greater than 10 years.

	MODEL	REGISTRATION YEAR	NUMBER	CONSUMPTION	UNIT
	DECOMMISSIONED BUSES				
10 m	EPT - CACCIAMALI "ELFO" ELETTRICO	23	EV	95.0	kWh/100 km
12 m	IRISBUS 491E.12.29 - CITYCLASS E4	15	DIESEL	51.0	l/100 km
	IRISBUS 491E.12.27 CNG -CITYCLASS	87	CNG	56.0	kg/100 km
	IRISBUS CITELIS 12.29 DIESEL EEV	81	DIESEL	50.9	l/100 km
	IVECO CITELIS 12.29 DIESEL EEV	71	DIESEL	50.0	l/100 km
18 m	IRISBUS 491E.18.31 CNG CITYCLASS	24	CNG	67.0	kg/100 km
	IRISBUS CITELIS 18m DIESEL EEV	10	DIESEL	64.1	l/100 km
	IRISBUS CITELIS 18m CNG	4	CNG	64.2	kg/100 km
	IRISBUS CITELIS 18m DIESEL EEV	65	DIESEL	65.9	l/100 km
	BUSES INTRODUCED				
10 m	INDCAR E-B6	10	EV	90.3	kWh/100 km
	INDCAR E-B6	12	EV	90.3	kWh/100 km
12 m	NEW BUSES FROM IVECO	150	EV	86.5	kWh/100 km
18 m	NEW BUSES FROM IVECO (18 m and BRT)	95	EV	104.7	kWh/100 km
	NEW BUSES EXPECTED	31	GNC	54.9	kg/100 km

Table 13: Nominal consumption of decommissioned and introduced buses from 2024 to 2027, GTT data elaboration

By running the calculations for the 2018, 2021, 2023, and 2027 fleets, it has been observed a general decreasing trend in the average consumption of CNG, diesel, and electricity for urban and suburban vehicle propulsion, as shown in Figure 39. Similar declines were found in the consumption levels of CNG and diesel, whose vehicles registered in 2022 were characterized by an increase in energy efficiency of 42.3 percent and 16.6 percent, respectively, in 2018. A negative trend also appears to characterize the consumption per kWh of electricity over the decade in question, with, however, a stabilization of the value between 2023 and 2027, due to the first introduction of electric vehicles 18 m in length and therefore more energivorous than those present before 2023.

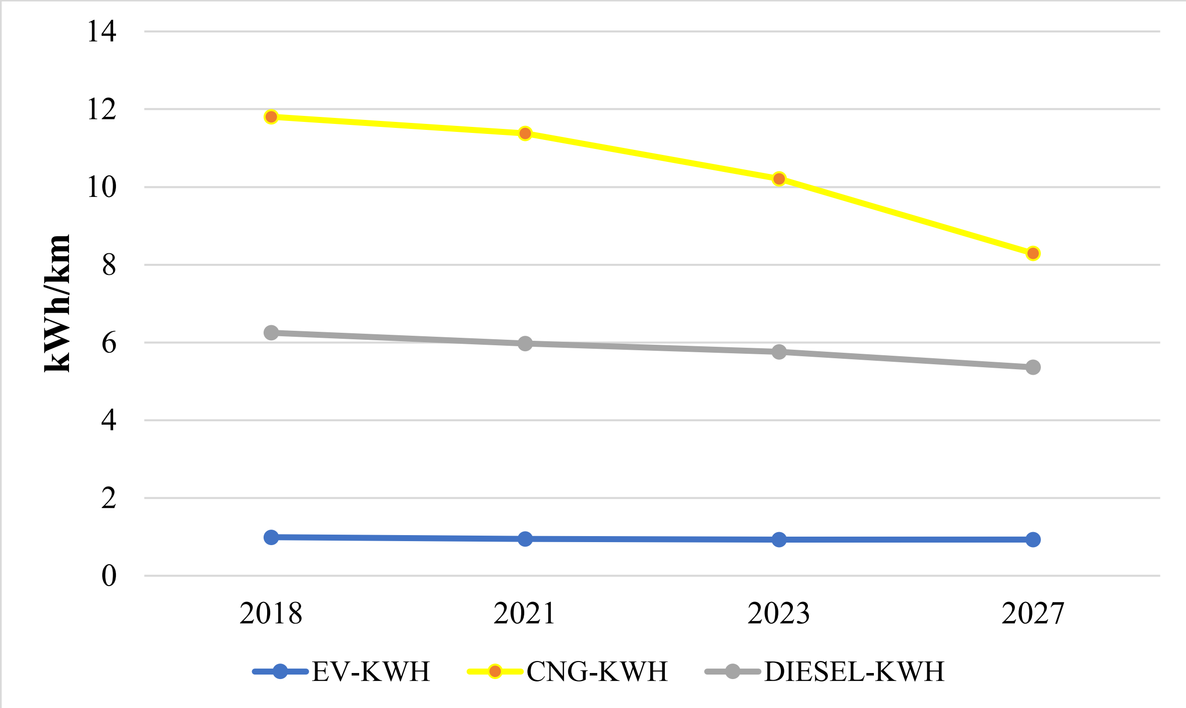

Figure 39: Average bus energy consumption trend by feed typology, GTT data elaboration. For the conversion, natural gas is characterized by 13.9 kWh/kg, meanwhile diesel owns 10.7 kWh/litre.

As mentioned above, the average fuel consumption of diesel and CNG vehicles found in the thesis paper mentioned above was higher as of 2018 than that reported in the data sheets, namely 67.0 liters/100 km for diesel vehicles (+15%) and 62.7 kg/100 km for CNG vehicles (+2%). On the contrary, the average consumption of electric buses is lower than the data from the data sheets (-13%, with a value of 85.8 kWh/100 km); this can be explained by the fact that during 2016 the replacement of the battery packs of the "Elfo" vehicles took place, thus improving their energy performance.

As a result of what has been demonstrated, the reported total consumption figures of GTT's budget can be considered overestimated for diesel consumption, consistent for the purpose of calculating energy demand related to methane consumption, and lower for automotive electricity consumption.

EXPECTED GTT FLEET CONSUMPTION IN 2027

Continuing the analysis, the energy demand for the autotraction of urban and suburban surface vehicles projected for 2027 was calculated. Thus, the results are as consistent as possible with reality; the kilometers produced by the city bus fleet as of 2027 are assumed to be equal to the distance offered in 2022, equivalent to 37.1 million [39].

Taking into account that in terms of offer supply in kilometers of travel, according to GTT's projections reported in the DNF 2022, electric vehicles will provide 81% of the share (22.35 mln km), CNG vehicles 14% (3.86 mln), and the remaining share diesel vehicles 5% (1.38 mln). By multiplying the nominal fuel consumption per 100 km in 2027 already calculated above with the kilometer distances by fuel type, it has been obtained the total energy consumption figures expected in 2027, the last year of the Renewal Plan drawn up by the Group. The conversion factors provided by FIRE were used to obtain the following results in terms of energy [42]

	OFFERED DISTANCE (mln of km)	NOMINAL CONSUMPTION (kg-litres-kWh/100 km)	NOMINAL CONSUMPTION (GJ/100 km)	TOTAL CONSUMPTION (thousands of kg-litres-kWh)	TOTAL CONSUMPTION (TJ)
METHANE BUSES	3.86	42.96	2.33	1659.79	90.03
DIESEL BUSES	1.38	50.09	1.78	691.17	24.51
ELECTRIC BUSES	22.35	93	0.33	20788.82	74.84

Table 14: Description of total and unitary consumptions of the bus fleet predicted in 2027 by fuel, GTT data elaboration

As shown in the table above, a relative collapse in diesel consumption and more than a halving of methane demand are projected at the expense of a nearly three-and-a-half increase in electricity demand for ZEVs. This scenario describes the total downsizing that the transportation company will have to deal with by divesting from the bulk of its diesel fueling stations, increasing the funds dedicated to building more electric charging columns, and entering into power supply contracts better suited to its energy needs. Wanting to compare the nominal fuel consumption of the vehicles for the three fuel types, by 2027, electric buses will be the most efficient, compared with diesel engines (approximately six times more energy consumption on average) and CNG (about 8 times) engines. Indeed, although almost all kilometers will be produced by electric vehicles, the highest energy consumption in terajoules (TJ) turns out to be by CNG vehicles (47.54%), compared to a kilometer coverage of 14%.

GTT CONSUMPTION ANALYSIS: ROAD TO 2040

An analysis of the composition of the fleet and its consumption (average and total) was carried out, starting from the pre-Covid period and ending with a description of the statistical forecast to 2027, thanks to a detailed analysis of the data provided by the Company in its annual reports:

- Scenario 1: As projected as 2027, 63 percent of city and suburban buses are electric-powered, whereas diesel buses are replaced by CNG engines (37 percent).
- Scenario 2: The total number of buses was reported to be electric.
- Scenario 3: All vehicles were reported to be CNG-powered, except for vehicles with a length of less than 10 m (minibuses).

Although implementing Scenario 3 in GTT's reality is unrealistic, the following Scenario was considered as a limiting case of total methanization of the urban fleet. To determine the average consumption by vehicle category and composition of the fleet endowment as of 2040, the following assumptions were adopted:

- For all Scenarios, it has been assumed the disposal of vehicles aged 15 years or older.
- For all Scenarios, the same number of buses belonging to GTT in 2040 was assumed to be 713, as in 2027.
- In all Scenarios, for ease of calculation, new vehicles are assumed to be introduced by 2030, 2035, and 2040.
- In all Scenarios, a 5% reduction in the fuel consumption of newly introduced vehicles was assumed compared with the most recently introduced buses every five years, characterized by similar lengths (<10 m, 12 m, or 18 m) and having the same power supply. This reduction trend appears to be in line with what Kibok Kim, Jinil Park, and Jongwah Lee report in their article in MDPI [43].
- In Scenario 1, decommissioned CNG and electric vehicles are replaced by vehicles with similar length (<10 m, 12 m, or 18 m) and same power supply, while diesel vehicles are replaced by CNG vehicles (with the exception of the BMC-labeled "Neocity" minibuses, which by sempificative assumption are replaced by new electric minibuses whose nominal consumption is known);
- In Scenario 2, CNG and diesel vehicles were gradually replaced by electric vehicles.
- In Scenario 3, diesel and electric vehicles were gradually replaced by CNG vehicles (with the exception of minibuses, whose total will continue to be electric).

Scenarios 1 and 2 turn out to be the most realistic, in line with the plan to abandon the fleet's dependence on diesel and its gradual electrification, adopted starting in 2021 and financed by substantial Italian and European investment funds (PNRR, first and foremost).

Nonetheless, Scenario 3 is reported so that an analysis of the GTT's maximum demand for natural gas can be carried out, with a view to studying the potential production of biomethane (from new or converted plants in the Metropolitan City) required to fully fuel the fleet.

The following table shows the nominal consumption calculated following the assumptions considered and the calculation factors provided by the FIRE [42]. According to Scenarios 1 and 3, the average consumption of CNG vehicles is expected to decrease further, by -2.1% and -6.9%, respectively, compared to the projected energy consumption in 2027. Following Scenarios 1 and 2, electric vehicles will also experience an improvement in their energy performance, reducing the average per capita consumption by as much as 15.2 percent and 12.1 percent, respectively, compared with 2027.

	METHANE NOMINAL CONSUMPTION (in kg/100 km)	METHANE NOMINAL CONSUMPTION (in GJ/100 km)	ELECTRIC NOMINAL CONSUMPTION (in kWh/100 km)	ELECTRIC NOMINAL CONSUMPTION (in GJ/100 km)
2040-SCENARIO 1	42.10	2.28	77.89	0.28
2040-SCENARIO 2	/	/	79.98	0.29
2040-SCENARIO 3	40.03	2.17	78.06	0.28

Table 15: Expected nominal consumption of GTT fleet by fuel type in 2040, GTT data elaboration

To calculate the total energy consumption of the two engines, the fleet mileage production in 2040 is assumed to be equal to the distance offered by 2022. As shown in Table 16 in Scenario 1, the distance previously covered by diesel-powered vehicles is considered to be covered by CNG vehicles. In Scenario 2, the entire distance was covered by electric vehicles, whereas in Scenario 3, almost the entire distance was covered by CNG vehicles. The following scenario considers the offered distance of electric minibuses to be 5 percent of the total, a percentage similar to the composition of electric vehicles in the total fleet (36 minibuses out of 713 vehicles).

	PRODUCED DISTANCE BY METHANE BUSES (in mln of km)	PRODUCED DISTANCE BY ELECTRIC BUSES (in mln of km)
2040-SCENARIO 1	5.24	22.35
2040-SCENARIO 2	0.00	27.60
2040-SCENARIO 3	26.22	1.38

Table 16: Assumed offered distance by methane and electric buses in 2040, GTT data elaboration

The total consumption values for the different scenarios were obtained and are listed in the following Table. In particular, a significant increase in methane consumption (+33.0%) was observed in Scenario 1, and a decrease in the demand for electricity for automotive use (-16.2 percent) compared to those recorded in 2027, a reduction that can be seen due to the introduction of new vehicles and the resulting increase in fleet energy efficiency.

	TOTAL METHANE CONSUMPTION (in thousands of kg)	TOTAL METHANE CONSUMPTION (in TJ)	TOTAL ELECTRICITY CONSUMPTION (in MWh)	TOTAL ELECTRICITY CONSUMPTION (in TJ)
2040-SCENARIO 1	2207.46	119.74	17412.14	62.68
2040-SCENARIO 2	/	/	22071.19	79.46
2040-SCENARIO 3	10493.99	569.21	1077.07	3.88

Table 17: Expected total annual consumption in 2040 of GTT fleet, GTT data elaboration

Looking at consumption in terms of quantity (in TJ), there is a gradual decrease from 2018, with a total decrease of 17.1% to 2022; in particular, there is a sharp decline in the five-year period 2023-2027 due to the almost total planned decommissioning of diesel-powered vehicles, which is far more energy intensive than the average consumption per unit of electric vehicles (see Table 14). Electric vehicles are generally characterized by energy efficiencies in excess of 90 percent, which is an order of magnitude vastly higher and unattainable in the endothermic engines. By making up 63.3% of the fleet energy consumption, diesel will make up about 12.9% in 2027, giving way to a boom in electricity consumption (from 0.8% recorded in 2018 to 39.5% in 2027). As described above, a decrease in energy consumption from natural gas is also expected; however, despite setting aside a portion of natural gas vehicles, the share of total consumption is increasing (from 35.9 percent in 2018 to 47.5 percent in 2027) owing to the more impactful disappearance of diesel as a fuel in GTT fleet.

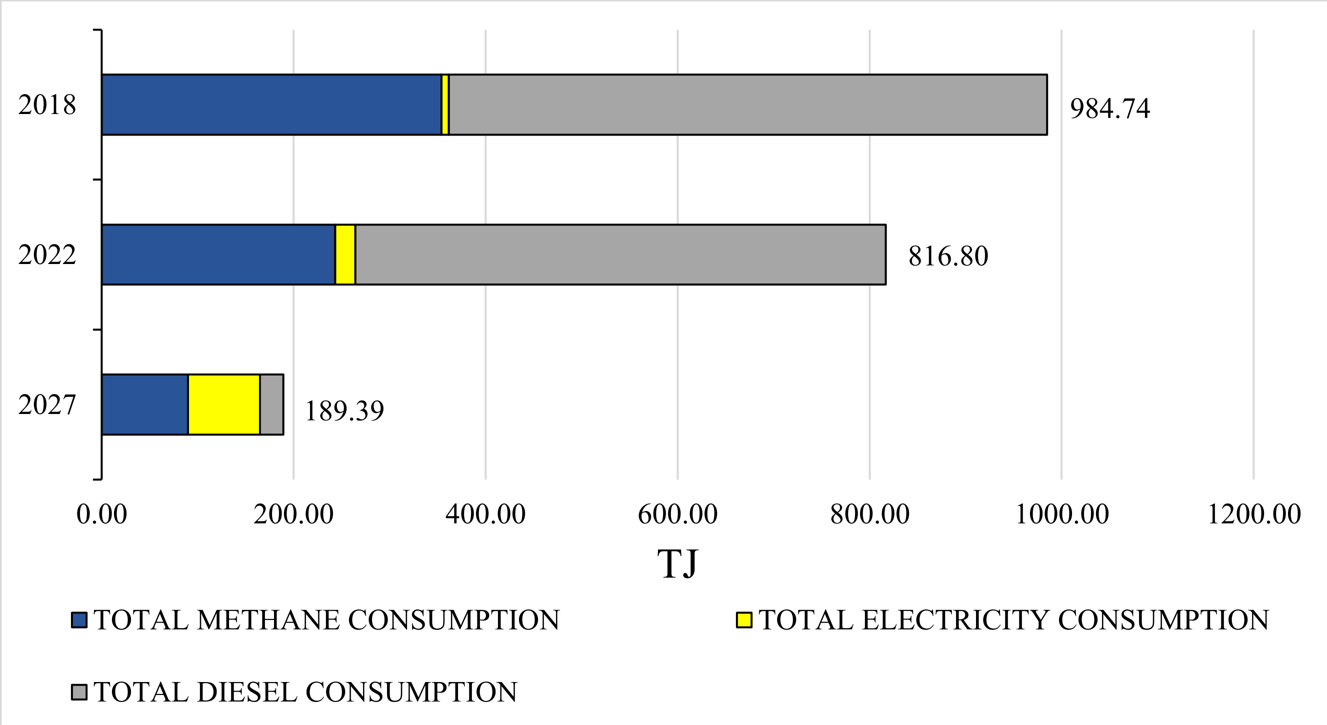

Figure 40: Bar graph describing the annual energy consumption trend of GTT urban buses, GTT data elaboration

For comparison in terms of the demand for methane and electricity in the three scenarios described above, it is interesting to note a further lowering of energy demand in Scenario 1 compared to 2027 (-3.7 percent), despite the fact that the electric composition of the fleet appears to be the same, which can be justified by the increase in efficiency projected for buses to 2040. As might be expected, Scenario 2 (100% electric vehicles) if realized would predict a 58.0% reduction in consumption compared to 2027, and as much as 90.3% compared to 2022, prioritizing maximum savings in GTT's energy consumption. Wanting to compare in terajoules the demand for methane and electricity in the three Scenarios described above as well, it is interesting to note a further lowering of energy demand in Scenario 1 compared to 2027 (-3.7 percent), despite the fact that the electric composition of the fleet appears to be the same; in contrast, Scenario 3 predicts an equally predictable growth in consumption compared to 2027.

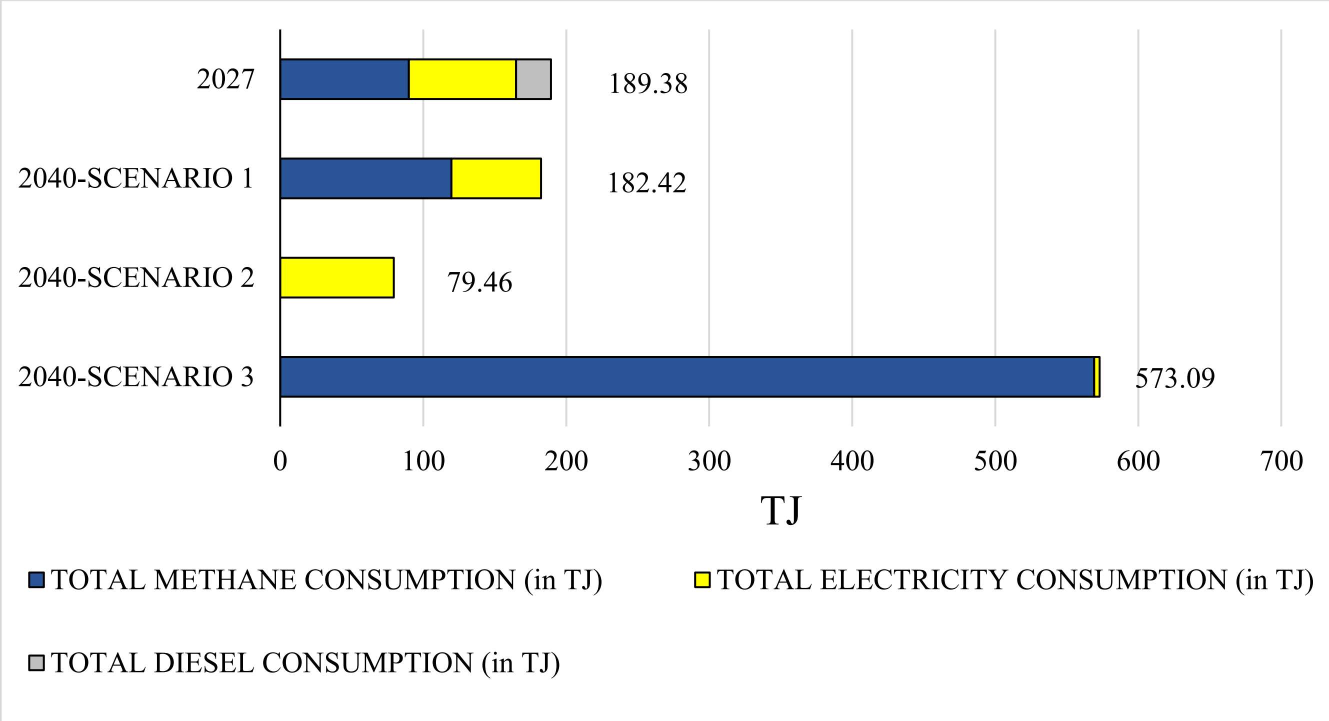

Figure 41: Bar graph describing the annual energy consumption trend of GTT urban buses for the considered 2040 scenarios compared to 2027, GTT data elaboration

To date, the annual and nominal energy consumption for each type of vehicle engine have been described. Instead, in this section, it has been discussed energy consumption relative to the individual passenger so that the three powertrain types can be compared in more detail and normalized. To perform this analysis, data on the maximum capacity of each vehicle in the fleet in the years considered, described in the data sheets provided by the company, were taken into account [34]. With the following data only for vehicles prior to and including 2027, the maximum fleet capacities in 2027 were considered.

As described in their Strategic Plan to 2027, the main Turin Public Transport Company has set its ultimate goal of extensive electrification of its fleet. The following analysis also shows a willingness to gradually introduce more capacious vehicles, improve transportation service offerings, and optimize energy consumption. As described in the table below, the average maximum passenger capacity of city buses appears to be increasing for electric and CNG fuels, with average capacity increases of 29.4 percent and 14.4 percent, respectively, between 2021 and 2027, while diesel engines, which are being phased out, see stabilization in numbers.

	2021	2023	2027
EV	68	73	88
CNG	111	115	127
DIESEL	126	124	127

Table 18: Average of the maximum capacity trend of all GTT urban buses (in passengers), GTT data elaboration

In this analysis, a filling rate equal to the declared maximum capacity of city buses in the GTT equipment was considered. As shown in Table 19, the calculations show that the average per capita energy consumption per 100 km driven is higher for diesel and especially CNG engines compared with much lower consumption for electric vehicles, which is in line with the data of nominal average consumption per vehicle, as described in Table 14. By 2027, per capita energy consumption is projected to decrease by 26.2 percent for electric vehicles and by as much as 35.0 percent for CNG vehicles (through the acquisition of new CNG buses and the major plan to decommission most of the present vehicles in 2022 and 2023) , while consumption from diesel-fueled production is also more stable.

	2021	2023	2027
EV	5.00	4.61	3.69
CNG	28.96	23.92	18.82
DIESEL	15.66	15.40	13.96

Table 19: Average energy consumption trend for passenger per 100 km, considering a bus fill rate equal to 100% (in MJ/(passenger*100 km), GTT data elaboration

Owing to the gradual improvement in the fuel consumption of vehicles introduced in the future, the consumption per passenger is expected to fall further in the three scenarios, as shown in Table 20.

	2040-SCENARIO 1	2040-SCENARIO 2	2040-SCENARIO 3
EV	3.19	3.31	3.19
CNG	18.01	/	17.06

Table 20: Average energy consumption trend for passenger per 100 km for the different Scenarios, considering a bus fill rate equal to 100% (in MJ/(passenger*100 km), GTT data elaboration

In conclusion, it can be stated that transportation by electric vehicles requires approximately six times less energy per passenger than transportation by CNG vehicles, despite the latter having a higher capacity. In fact, it would be more likely to consider higher transport capacities to 2040 of electric vehicles (in line with the company's plans); however, it was chosen to consider related capacity to 2027 for simplification hence lower numbers.

2.4. BIOMETHANE PRODUCTION SCENARIOS

A detailed analysis has been conducted on trends in the demand for fuel and electricity (total and per passenger) needed to power the urban and suburban fleets of GTT, the main local public transport company operating in the Metropolitan City of Turin. Therefore, quantities of methane and electricity up to 2040 were derived to transform the composition of vehicles to save energy and reduce air pollution.

In this section, it has been analyzed the potential production of biomethane from the conversion of biogas plants present in the Metropolitan City of Turin using the incentives present in the Biomethane Decree (described in detail in Section 1.6). The utilization of biomethane in transportation not only decreases carbon emissions, but also enables the harnessing of a regional resource, often sourced from waste streams. Hence, it is imperative to ensure that projected demand is adequately aligned with the production capacity of the area.

As reported in Section 2.1, the nominal electrical power of the Turin Metropolitan City area reaches a magnitude of 55.03 MW, with 31 percent (16.93 MW) fed with MSW and 69 percent (38.10 MW) fed with farming and agricultural waste. Currently, 59 biogas power plants are in operation, with approximately 25% having an output power of approximately 1 MW [44]. Based on the assumption of converting existing biogas facilities to utilize agricultural waste, the estimated biomethane potential served as the basis for this study. This approach aligns with the criteria for accessing incentives provided by the Biomethane Decree. However, a comprehensive evaluation of each plant is necessary to assess the financial feasibility of such conversion, considering the distance from the natural gas grid. Simultaneously, the construction of new plants is anticipated to increase, motivated by current incentives, which will lead to an even larger biomethane potential in the territory. When estimating the conversion potential, it is presumed that an existing biogas plant with a power output of 1 MW can be transformed into a biomethane plant with a capacity of 250 cubic meters per hour (Smc/h), which is consistent with the values reported in other studies [45], [46]. Unlike the latter studies and in line with [22], two types of annual operations for biomethane plants were considered in this study:

- Low-Case Scenario with an activity of 6000 h per year.
- High-Case Scenario with an activity of 8000 h per year.

Although all plants possess anaerobic digesters that are operated continuously for biological reasons, the Low-Case Scenario was considered so that a more “conservative” biomethane production scenario is assumed.

2.5. BIOMETHANE SUPPLY AND DEMAND MATCHING: RESULTS AND PROSPECTS

The following table shows, for each scenario considered, the portion of capacity related to the biogas plants (present in the Metropolitan City) to be converted for the GTT's demand for methane to be fully met. In line with the requirements of the Biomethane Decree, the percentage values refer to the total installed capacity of existing plants fueled exclusively by farming and agricultural wastes. In addition to the share derived from plants fueled by MSW, the capacity of the Piverone plant, an incentive grantee and producer of biomethane destined for sectors other than transportation, was also excluded from the convertible power.

	GTT METHANE DEMAND (in thousands of Smc/year)	LOW-CASE SCENARIO	HIGH-CASE SCENARIO
2027	2474	5%	3%
2040-SCENARIO 1	3290	6%	5%
2040-SCENARIO 3	15639	29%	22%

Table 21: Percentage of biogas capacity required to be converted to satisfy the GTT methane demand for transport related to the different Scenarios, GTT and TAPE data elaboration

The results are encouraging, as the biomethane production potential was much higher than the estimated demand in different scenarios. Calculating a modest demand for CNG requested by the Public Transport Company in 2027 and in Scenario 1, only a small percentage (on the order of 5 percent) of the total capacity would have to be converted to confer GTT to permanently zero the fossil fuel dependence of its vehicles. In Scenario 3, a hypothetical total biomethane-fueled fleet would require a conversion of 29 percent of the capacity in the Low-Case Scenario and 22 percent in the High-Case Scenario. However, it is important to note that other transport segments may also consume biomethane, including private cars and industrial vehicles, as described in Table 12. If the consumption data recorded in 2019 for cars and industrial vehicles registered in the City of Turin are held constant, fully meeting the CNG requirements of these two vehicle categories would require a conversion of 13% more according to the Low-Case Scenario and 9% more according to the High-Case Scenario. As shown in Table 22, to eliminate the dependence on fossil natural gas destined for all vehicles on the road in the City of Turin, the percentages were required to be equivalent to 42 percent in the Low-Case Scenario and 31 in the High-Case Scenario.

	TOTAL METHANE DEMAND (in thousands of Smc/year)	LOW-CASE SCENARIO	HIGH-CASE SCENARIO
2027	9311	17%	13%
2040-SCENARIO 1	10127	19%	14%
2040-SCENARIO 3	22477	42%	31%

Table 22: Percentage of biogas capacity required to be converted to satisfy the Turin Municipality methane demand for transport related to the different Scenarios, GTT and TAPE data elaboration

In conclusion, this technical analysis provides optimistic results regarding the cut-off in urban bus energy demand and highlights concrete possibilities for accelerating the process of decarbonization of GTT fleet endowments and city consumption resulting from the transportation sector in general.

3. ESTIMATION OF CO2e EMISSIONS

After conducting an analysis of the energy consumption related to GTT's city bus fleet (with a focus on total annual consumption and per passenger/100 km), this chapter aims to conduct a second analysis regarding the amount of equivalent CO_2 emitted to the atmosphere (CO_{2e}*, in CO_{2e}/year and CO_{2e}/passenger*km) for each scenario considered. As described in the following pages, the calculation is grounded in particular emission coefficients for each unit of fuel, which are derived from the literature and applied to the fuel consumption of the bus fleet, taking into account the local territorial context. This approach was extended to the different fuels under examination, such as biomethane (bioCNG), fossil-derived diesel, fossil-derived CNG, and electricity, by distinguishing between the WTT (Well-To-Tank) and TTW (Tank-To Wheel) phases.

** CO_2 equivalent (CO_{2e}) is a measure that quantifies the impact of greenhouse gases other than CO_2 by converting them into carbon dioxide equivalent quantities based on their global warming potential (GWP).*

3.1. FUELS CO2e INTENSITY

BIOMETHANE

Because biogas upgrading is produced by a range of organic materials with very different physicochemical characteristics, the production of biomethane and its distribution (WTT phase) generate CO_{2e} emissions that are highly dependent on the feedstock mix considered.

According to a study conducted by ENEA in 2021 [47], the potential production of advanced biomethane derived from feedstock that are currently incentivized (all fermentable residual biomass that is best suited for the production of advanced biomethane by anaerobic digestion process) in Italy in 2016 turns out to be about 6.2 billion Smc, which is double the value in comparison with the 2023 production of fossil-derived natural gas (about 3.0 billion Smc) and which is about 10.1% of total consumption (61.5 billion Smc in 2023) [21]. This study discretizes the production of each raw-material type.

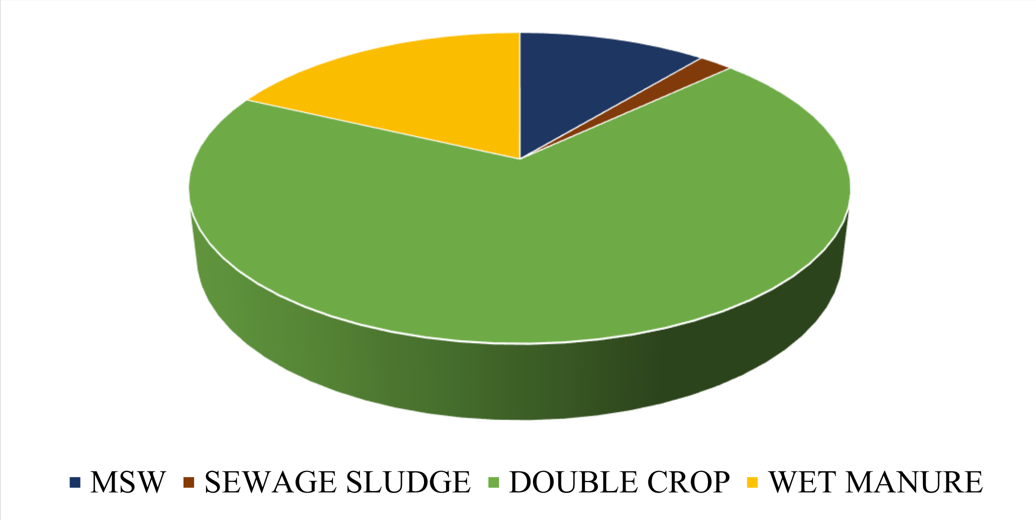

Figure 42: Breakdown of the Italian maximum potential production of advanced biomethane by feedstock type [48]

Owing to the lack of references regarding feedstock quantities in the provincial context, the subdivision described in Figure 42 depicts the feedstock supply for biomethane production in Italy that will be considered in our study, according to the considered "Medium" scenario in "The potential role of biomethane for the decarbonization of transport: An analysis of 2030 scenarios in Italy" paper [48]. Consequently, the biomethane feedstock mix will be characterized by a scenario including 69% volume from double crops, 18% from wet manure, 11% from OFMSW (Organic Fraction of Municipal Solid Waste), and 2% from sewage sludge. Other studies provide alternative reference feedstock mixes, that are reported in the Section 2 of the Annex [45].

For a CO_{2e} emission value related to the well-to-tank phase of biomethane, which is consistent with the feedstock mix characteristics of the area, the following assumptions were adopted

- All raw materials include carbon intensity, which considers their digestion, upgrading, transport, grid injection, and eventually cultivation.
- The entire amount of produced biomethane was fed directly into the gas grid.

It is essential to consider additional factors when evaluating emission savings of biomethane produced from wet manure. If wet manure is left unused or stored, it undergoes natural anaerobic digestion, which results in the production of CH_4 and N_2O emissions. However, by controlling this process in closed tanks and collecting the gas produced, these emissions can be avoided [49]. Therefore, the production of biogas from manure via anaerobic digestion is a more favorable option than the traditional use of manure as a fertilizer when considering its climate impact. According to the RED II Directive and a recent JRC study [49], the avoided emissions are estimated to be 107.2 $gCO_{2e}/MJ_{biomethane}$ when considering closed digestate storage and the injection in the grid. Consequently, this value can be viewed as a credit that can be applied to the share of biomethane produced from manure in the considered scenarios.

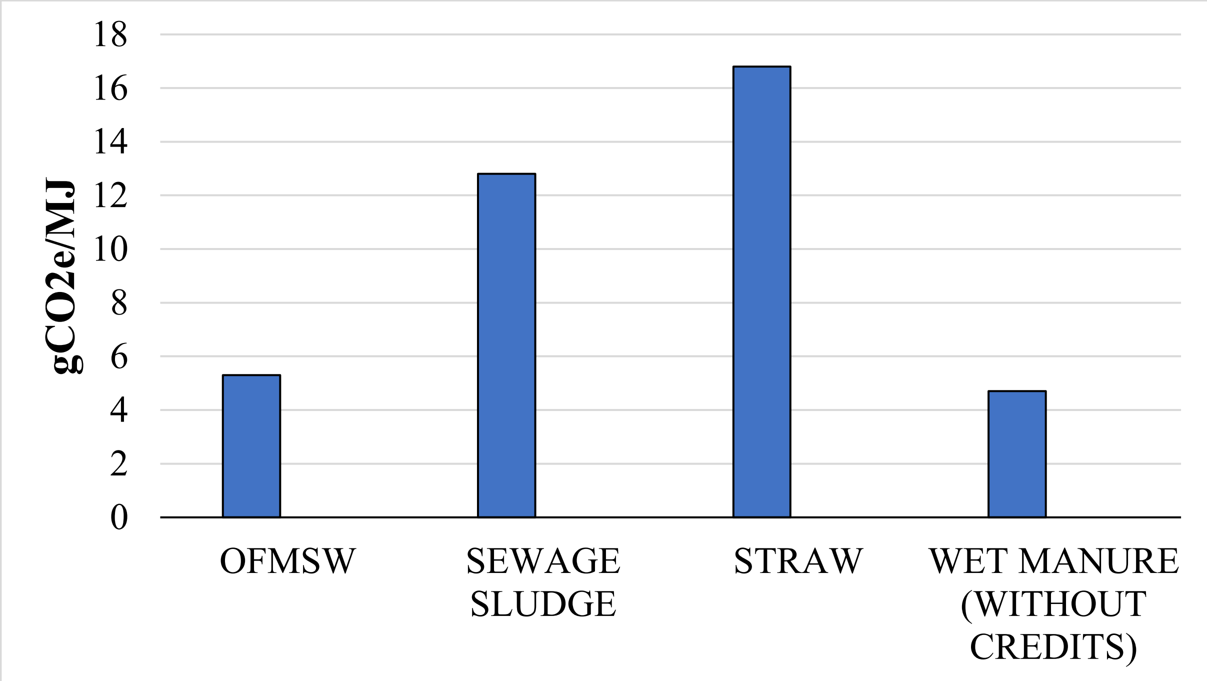

Figure 43: Total specific emissions related to the different steps of biomethane injected in the grid in WTT phase (considering 2030 electricity mix) [50]

Figure 43 shows a large total specific emission from straw through double cropping (considering the two related emissions equal as an additional hypothesis, elaboration rom [48]) because of the important environmental impact caused by its cultivation, and from sewage sludge because of the important emission contribution made by its digestion.

Following the previously cited literature and considering the previously defined feedstock mix scenario, it is found that the production of 1 MJ of biomethane emits 13.3 g_{CO2e} to the atmosphere in the case where emission credits from manure are not counted, while 6.9 g_{CO2e} per MJ of biomethane are avoided in case they are considered.

FOSSIL-DERIVED NATURAL GAS

Following the JRC study results and GMCG2a pathway [49], it is considered an EU-mix natural gas in which 90% of its volume is transported to the EU by pipeline (1900 km to the EU border, 500 km inside the EU), distributed through gas trunk lines and a low-pressure grid, and compressed to CNG at the retail point. The other 10% was delivered in LNG form (according to the GRCG1 pathway). Its extraction, transport, distribution, and compression processes resulted in CO_2 emission of 11.9 g_{CO2e}/MJ.

Considering the Tank-to-Wheel (TTW) phase, according to IPCC and the United States Environmental Protection Agency (EPA) [51], [52], CO_2 equivalent emissions are equal to 2821.32 $g_{CO2e}/kg_{methane}$ (considering a fuel having a density of 0.72 kg/m3 and Lower Heating Value of 50 MJ/kg). Apart from the post-combustion carbon dioxidewhatsa, this value takes into account the unburned CH4 (assumed to be 5 grams per kg of fuel), whose CO_{2e} emission is equal to 70 $g_{CO2e}/kg_{methane}$ methane. Dividing the value of total CO_{2e} emitted, this results in the release of about 56.4 g_{CO2e} /MJ in TTW phase in case fossil-derived natural gas is burned.

Since the emissions related to the entire methane production and consumption cycle (Well-To-Wheel, WTW) are equal to the sum of the WTT and TTW phases, a total equivalent carbon intensity of 68.3 g_{CO2e} /MJ will be considered.

FOSSIL-DERIVED DIESEL

Considering COD1Crude pathway [53], hence diesel production derived from crude oil from typical EU supply, transported by sea, refined in EU and following typical EU distribution and retail processes, the total specific emissions related to WTT phase are equal to 18.9 g_{CO2e}/MJ.

Taking into account the Tank-to-Wheel (TTW) phase, CO_{2e} emissions equal 2685.27 $g_{CO2e}/litre_{diesel}$. Unlike natural gas combustion, diesel combustion has no significant CO_{2e} level associated with CH4; however, the equivalent carbon dioxide level associated with N_2O emission are more significant and therefore counted in our calculations (about 5 $g_{CO2e}/litre_{diesel}$). Taking into account that 1 liter of diesel conventionally has a potential energy equal to 42.31 MJ [54], the total equivalent emission value corresponds to 63.5 g_{CO2e}/MJ. Hence, for the WTW phase a total equivalent carbon intensity of 82.4 g_{CO2e}/MJ will be considered.

ELECTRIC ENERGY

The total specific emission of equivalent CO_2 related to electricity is directly related to the Italian energy mix of electricity production, as shown in Figure 46. After a slight rise in the emission value due to the temporary return to coal in the period around the outbreak of the Russian-Ukrainian conflict, the trend is downward to 2023 [53]. Following the scenario described by I4C [55], owing to the disruptive increase in renewables in the Italian mix, a 62 percent reduction in emissions will be achieved in 2030 compared to the 2019 findings. Consistent with the community goal of achieving carbon neutrality in power generation in 2050, a carbon intensity (23.2 g CO_{2e}/MJe) of half the value assumed in 2030 was assumed in reference to 2040.

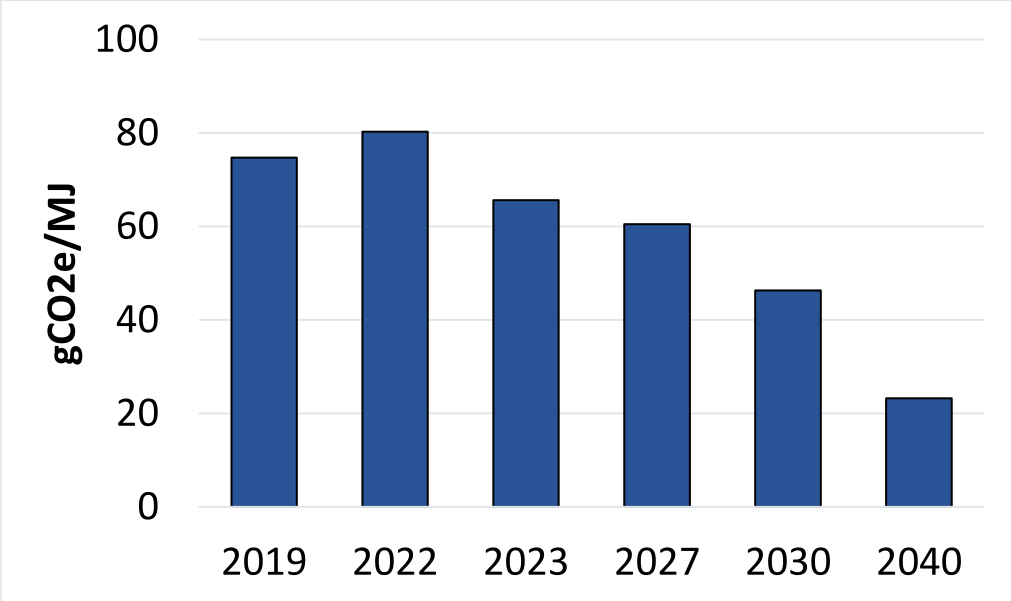

Figure 44: Trend of total specific emission related to power generation in Italy, [53] [55]

As described in Figure 44, CO_{2e} emission values provided by ISPRA and I4C) related to electricity generation were found to be strongly decreasing by 2040; nevertheless, in 2040 the CO_{2e} emission value turns out to be still higher than the emission value related to biomethane WTT phase, especially if credits from wet manure were counted.

	BIOMETHANE WITHOUT MANURE CREDITS	BIOMETHANE WITH MANURE CREDITS	FOSSIL CNG	FOSSIL DIESEL	ELECTRICITY (IN 2023)	ELECTRICITY (IN 2040)
WTT	13.3	-6.9	11.9	18.9	65.6	23.2
TTW	-	-	56.4	63.5	-	-
TOTAL (WTW)	13.3	-6.9	68.3	82.4	65.6	23.2

Table 23: Resume of CO_{2e} emission values for WTT, TTW and WTW phases (in g_{CO2e}/MJ)

3.2. TOTAL FLEET EMISSION IN DIFFERENT SCENARIOS

Having obtained the related CO_{2e} emissions for each type of energy carrier and knowing the associated city bus fleet energy consumption for each scenario (as defined in Figures 42 and 43), The following section describes the results representing the levels of total CO_{2e} emitted to the atmosphere, represented by engine type.

Methane gas appears to be associated with three different levels of CO_{2e} specific emissions, so the analysis was carried out considering the consumption and related emissions of fossil methane, biomethane with manure credits, and biomethane without manure credits.

CASE 1: FOSSIL METHANE

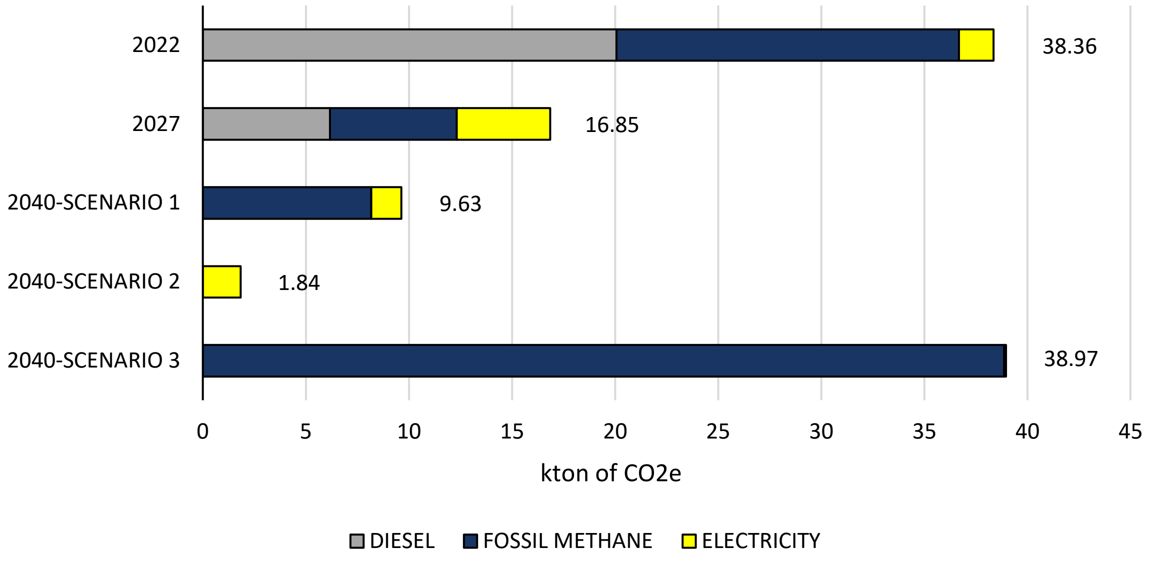

Figure 45: CO_{2e} emissions related to fuel type for each scenario, considering the use of fossil methane and "Medium scenario, GTT data elaboration

Figure 45 shows the emissions of the urban bus fleet in 2022 and 2027 for the three scenarios considering the use of only fossil methane. As of 2022, a total atmospheric emission of 38.36 kton of CO_{2e} has been found. As predicted by NTT [36], in 2027, the above value will drop dramatically owing to the gradual electrification of much of the fleet and phasing out of obsolete diesel and CNG vehicles, resulting in a reduction of 56.1%. In the Scenarios to 2040, immediately apparent to the eye is the large reduction in emissions that would be achieved as a result of the full electrification of urban vehicles (Scenario 2), falling sharply to -95.2% compared to 2022 values; in Scenario 1, CO_{2e} production would fall less substantially than today's levels (-74.9%). Finally, considering a fleet almost entirely powered by fossil methane (Scenario 3), emissions in 2040 would almost double the 2027 levels, despite the expected increase in thermal engine efficiency. From these results, it can be seen that using only conventional methane would increase GTT emissions, in contrast with 2050 and GTT's goal of achieving carbon neutrality relative to the Well-To-Wheel phase.

CASE 2: BIOMETHANE WITHOUT MANURE CREDITS

If the values depicted above are compared with those in Figure 46 the result using 100% biomethane (without considering manure credits) generally shows a greater decrease in emission values. A more pronounced reduction would occur in 2027 owing to the complete use of biomethane, with -29,5% compared to the use of fossil methane Scenario and -69,0% compared to the total emissions in 2022. CO_{2e} production in Scenario 1 would be close to the value associated with the 100% electric scenario (3,04 kton and 1,84 kton, respectively), whereas in Scenario 3, there would be a 80,1% reduction in emissions in contrast to the use of fossil methane. The result is that the use of biomethane would contribute to the decarbonization of Turin's local public transport sector, even though it does not consider the emission credits associated with the avoidance of wet manure digestion and Scenario 2 would be less impactant yet.

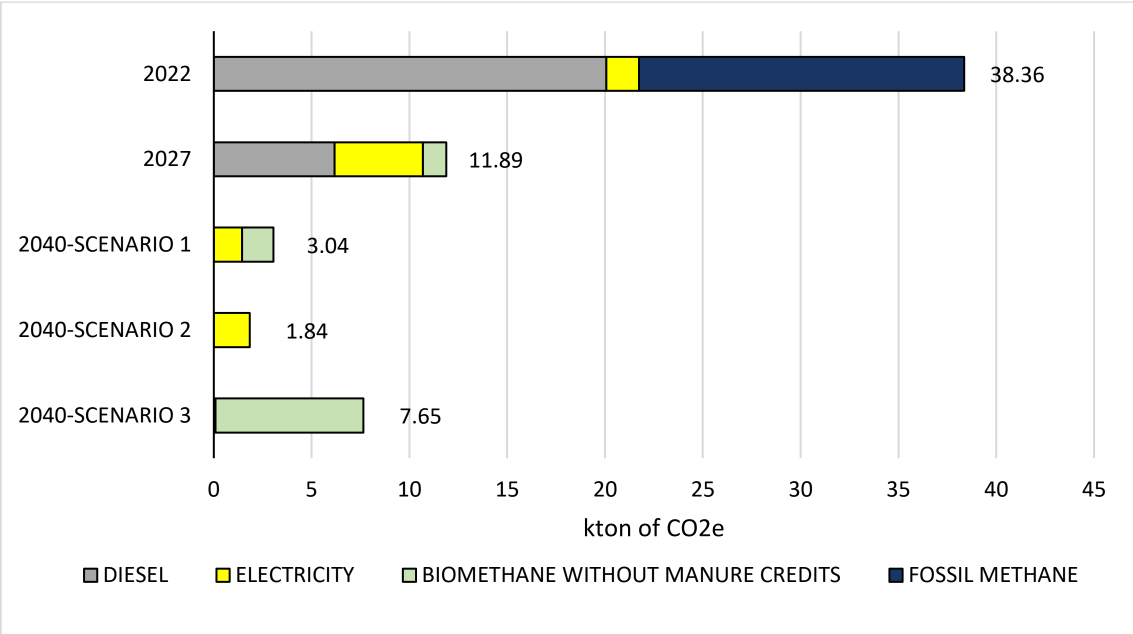

Figure 46: CO_{2e} emissions related to fuel type for each scenario, considering the use of biomethane without credits and “Medium scenario”, GTT data elaboration

CASE 3: BIOMETHANE WITH MANURE CREDITS

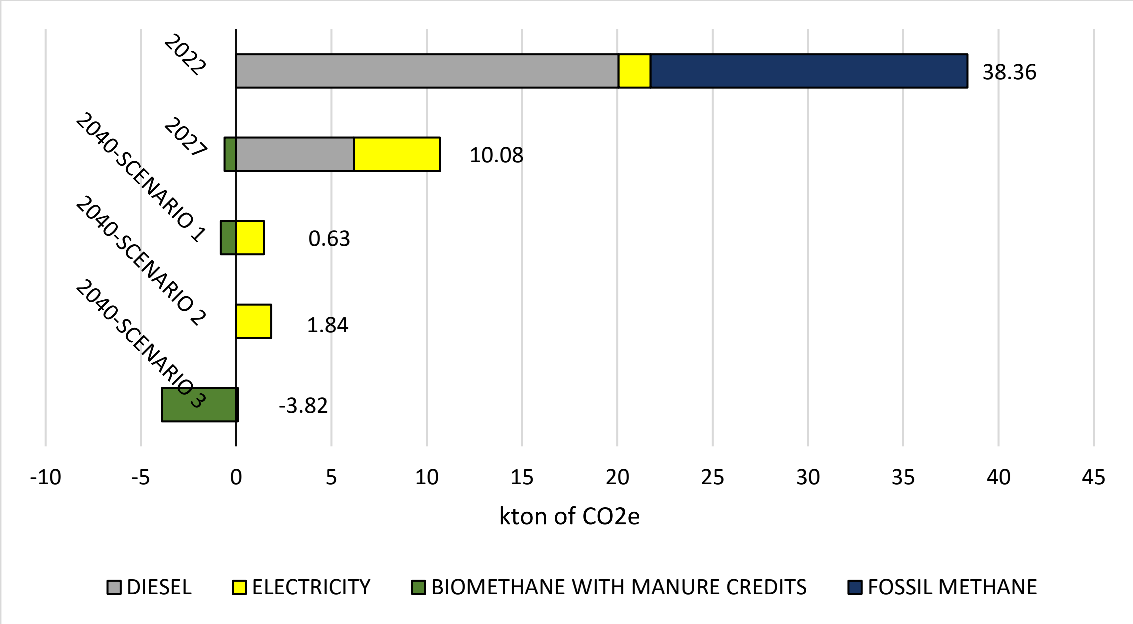

Figure 47: CO_{2e} emissions related to fuel type for each scenario, considering the use of biomethane without credits and "Medium" scenario, GTT data elaboration

A further decrease in the total emission values occurs if, along with the assumption of a 100% biomethane scenario, wet manure credits are counted. Relative to 2027, a record reduction in emissions of 73,8% will be achieved compared with 2022. Since the CO_{2e} emissions associated with the process of producing a mass equivalent of 1 MJ of biomethane were found to be -107,2 gCO2e, in Scenarios 3 the emissions from the GTT's urban fleet would be even negative; in Scenario 1, a value of 0,63 kton CO_{2e} is reached, balancing the emissions related to electric vehicles, while in Scenario 3, a record value of -3,82 kton CO_{2e} avoided would be reached. The latter analysis demonstrates how biomethane (given the credits described above) can play a key role in cancelling GTT emissions while also maintaining a share of electric vehicles in its fleet, following the assumptions related to Scenario 1. Nevertheless, although biomethane represents a promising renewable source, its potential for use is limited due to restrictions in production and distribution. Therefore, it is essential to target biomethane to sectors with the greatest environmental and socioeconomic impact, as the heavy transport.

SENSITIVITY ANALYSIS RELATED TO FOSSIL METHANE CONSUMPTION CONTRIBUTION

To study the possible moderation in the amount of biomethane required, a sensitivity analysis was performed to consider the introduction of a share of biomethane in the fuel supply of natural gas vehicles in the scenarios. The following analysis was conducted in view of the introduction and use of biomethane with lower percentage values in the coming years.

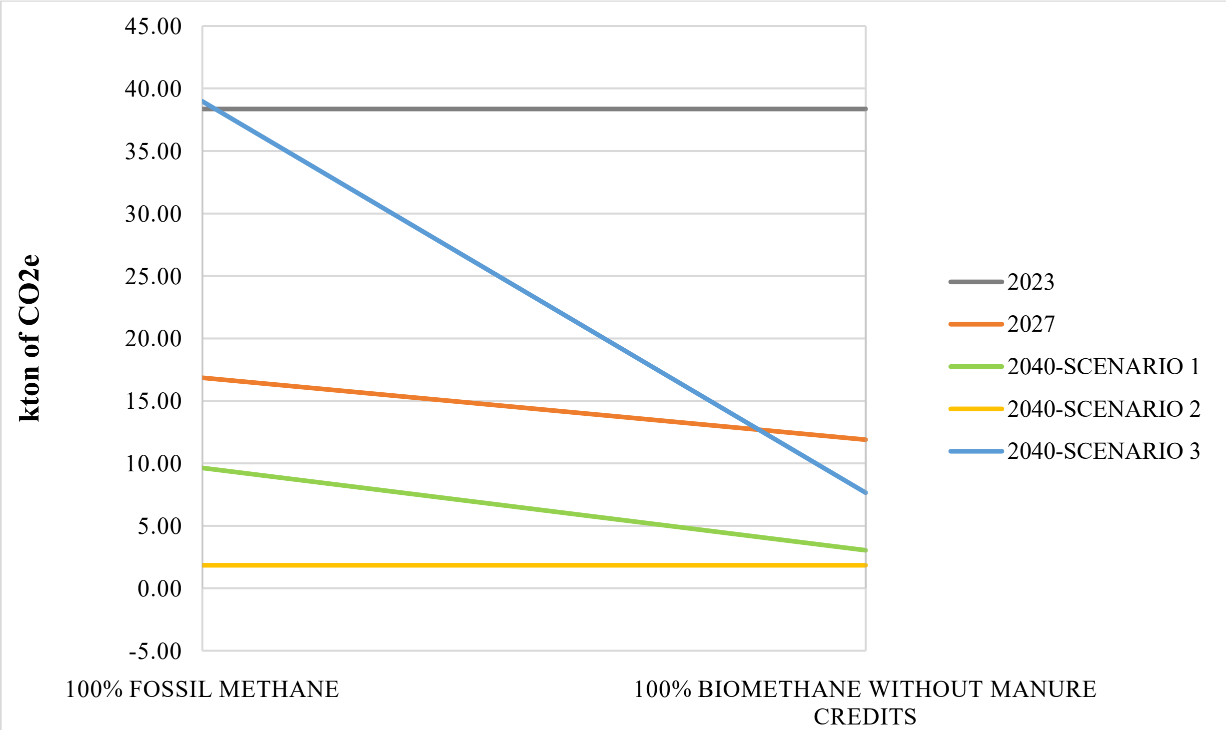

Figure 48: CO_{2e} emission trends by scenario, considering different percentage values of biomethane without credits and fossil methane, GTT data elaboration

As shown in Figure 48, Scenario 3 would have a total emission value equal to that associated with 2027 in the case where 83% of the methane demand is met by biomethane, with the feedstock mix considered in the analysis.

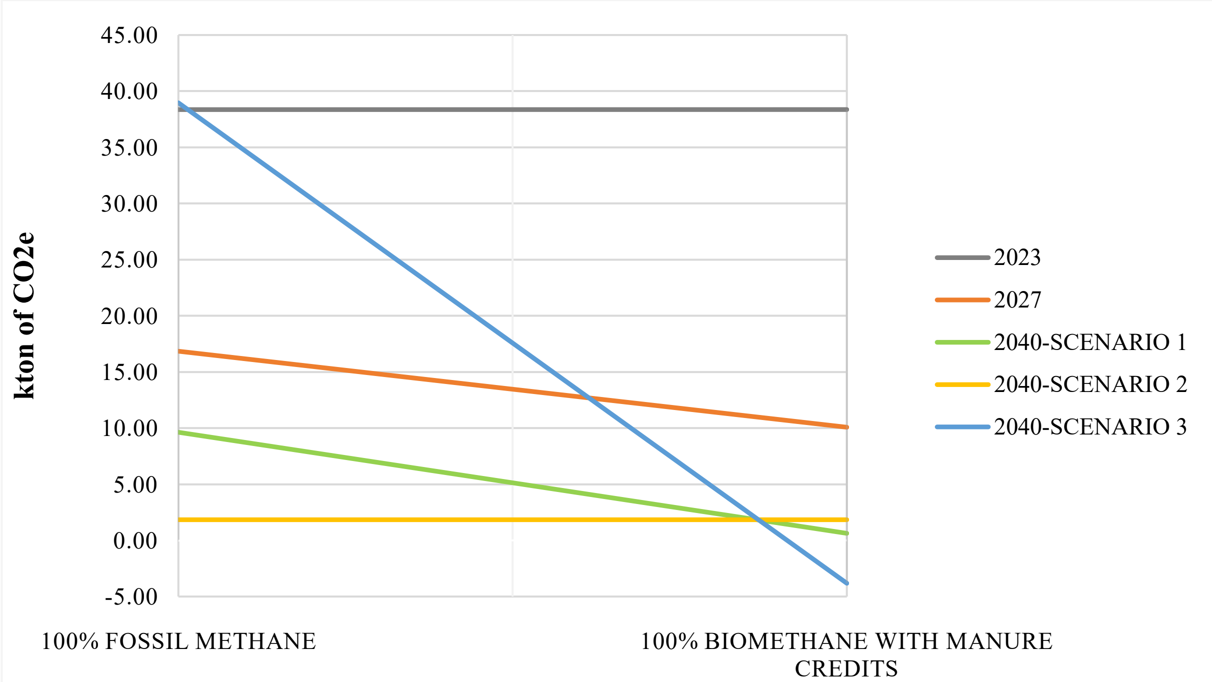

Figure 49: CO_{2e} emission trends by scenario, considering different percentage values of biomethane with credits and fossil methane, GTT data elaboration

Of greater interest is the case study in which manure-related credits are considered: to achieve carbon neutrality, approximately 9% of fossil methane could be still used in Scenario 3, whereas to achieve the total associated with the 100% electric scenario (Scenario 2), approximately 83% of biomethane should be used in Scenarios 1 and 3.

It is important to remember, however, that the results obtained are valid considering the chosen feedstock mix; should the mix vary, the computational outputs would also vary considerably, as with the results reported in Section 2 of the Appendix.

3.3. EQUIVALENT CO2 EMISSION FOR PASSENGER

A parallel analysis was conducted to calculate the emissions associated with each individual passenger; however, in this study, two different average fill rates of urban vehicles, corresponding to 100 percent and 20 percent of the declared maximum capacity for each vehicle model, were examined, in line with what was done in the analysis of per capita energy consumption. Emission levels, represented in gCO_{2e} emitted per passenger per kilometer, were obtained by multiplying the energy consumption (by fuel type and scenario, in MJ per passenger per kilometer) with the respective emission factors (in grams of CO_{2e} per MJ).

gCO_2/passenger*km	2023	2027	2040-SCENARIO 1	2040-SCENARIO 2	2040-SCENARIO 3
EV	3.02	2.23	0.74	0.77	0.74
FOSSIL METHANE	16.34	12.85	12.30	/	11.65
DIESEL	12.69	11.50	/	/	/
BIOMETHANE WITHOUT MANURE CREDITS	/	2.50	2.39	/	2.27
BIOMETHANE WITH MANURE CREDITS	/	-1.29	-1.24	/	-1.17

Table 24: Per-capita emission levels by power type and scenario considered, assuming 100% of occupancy with respect to bus capacity, GTT data elaboration

Considering the maximum occupancy of the available capacity per vehicle, fossil methane-fueled buses are found to belong to the most impactful engine category in 2027, after diesel-fueled buses; fossil-methane fueled vehicles emissions are characterized by a reduction over the period 2023-2027 that equals 21.4 percent. This is in parallel with that related to fuel consumption, which is caused by the gradual shelving of obsolete vehicles and introduction of increasingly efficient buses. As shown in Table 23, fossil-methane related emission levels would be lower in 2040 than the latest findings but still insufficient to allow every passenger to be CO_{2e} free in their urban travel. The values associated with scenarios 1 and 3 for fossil methane turned out to be very similar, but still different, because different assumptions were considered for the two scenarios regarding the introduction and provision of the means until 2040. Equivalent emissions associated with a 1 km trip in a diesel vehicle will decline by 9.4 percent over the period 2023-2027.

In contrast, when considering other non-"fossil" engines, the emission levels per passenger traveling on electric vehicles were found to be far lower than those of the two fossil fuels (-82.7 percent and -80.6 percent compared to conventional natural gas and diesel in 2027). In addition, thanks to decarbonization in power generation and the achievement of ever-higher electric bus efficiencies, only 0.77 gCO_{2e}/km*passenger will be emitted in Scenario 2 to 2040, nearly 4 times less than the 2023 level. Finally, the use of biomethane in vehicles (without manure credits) would allow the achievement of emission values comparable to those of "electric" travel in 2027, as described in Table 24. However, the drop in emissions over the 2027-2040 period appears to be less steep than that associated with EV buses. However, if credits from wet manure were factored into the calculations, each passenger would avoid the emission into the atmosphere of approximately 1.2 grams of CO_2 per kilometer.

gCO_2/passenger*km	2023	2027	2040-SCENARIO 1	2040-SCENARIO 2	2040-SCENARIO 3
EV	15.12	11.16	3.69	3.83	3.69
FOSSIL METHANE	81.70	64.25	61.50	/	58.25
DIESEL	63.45	57.50	/	/	/
BIOMETHANE WITHOUT MANURE CREDITS	/	12.49	11.96	/	11.33
BIOMETHANE WITH MANURE CREDITS	/	-6.46	-6.18	/	-5.86

Table 25: Per-capita emission levels by power type and scenario considered, assuming 20% of occupancy with respect to bus capacity, GTT data elaboration

The values described in Table 25 correspond to those found in Table 23 multiplied by a factor of five, because if an average vehicle occupancy at 20 percent of the maximum capacity is considered, each passenger would emit five times the amount of CO_{2e} compared to a trip with the vehicle full.

To make the results more concrete with respect to total vehicles and easier to interpret, a weighted average of emission values was calculated with respect to kilometers driven by fuel type (see Table 16) to obtain an average value per passenger*km of emissions for each scenario considered. Because we did not have data on the GTT's average vehicle occupancy by fuel type, graphs containing emission trends with respect to the relative percentage of maximum vehicle capacity by scenario and CNG fuel type are shown below. Tables showing the precise emissions per capita at 20% and 100% containment capacity are given in the Appendix, section 3.

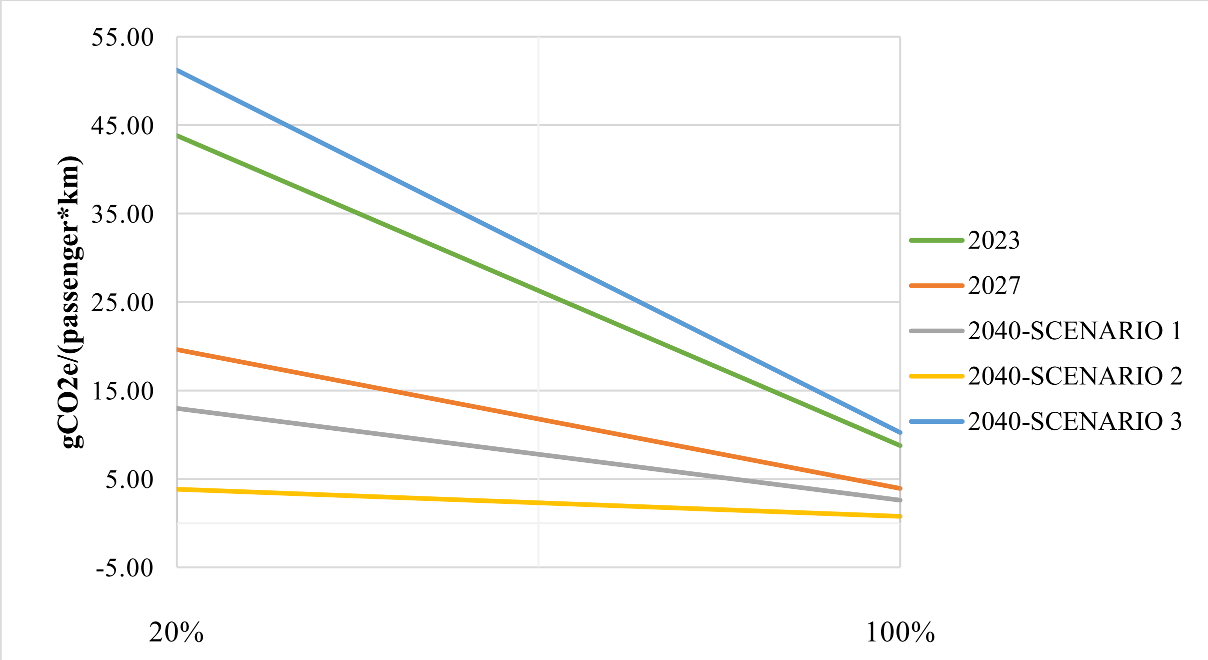

Figure 50: CO_{2e} per-capita emission trends by scenario, considering different percentage values of bus occupancy with respect to bus capacity and the use of fossil methane, GTT data elaboration

As expected, considering the use of fossil methane, scenario 2 (100% EV) has the lowest emission values per passenger on record (0.77 gCO_{2e}/passenger*km with 100% capacity), while scenario 3 (100% fossil methane) would be found to have even higher per capita emissions than those measured in 2023, with as much as 10.24 and 51.22 gCO_{2e}/passenger*km taking into account 100% and 20% vehicle occupancy, respectively.

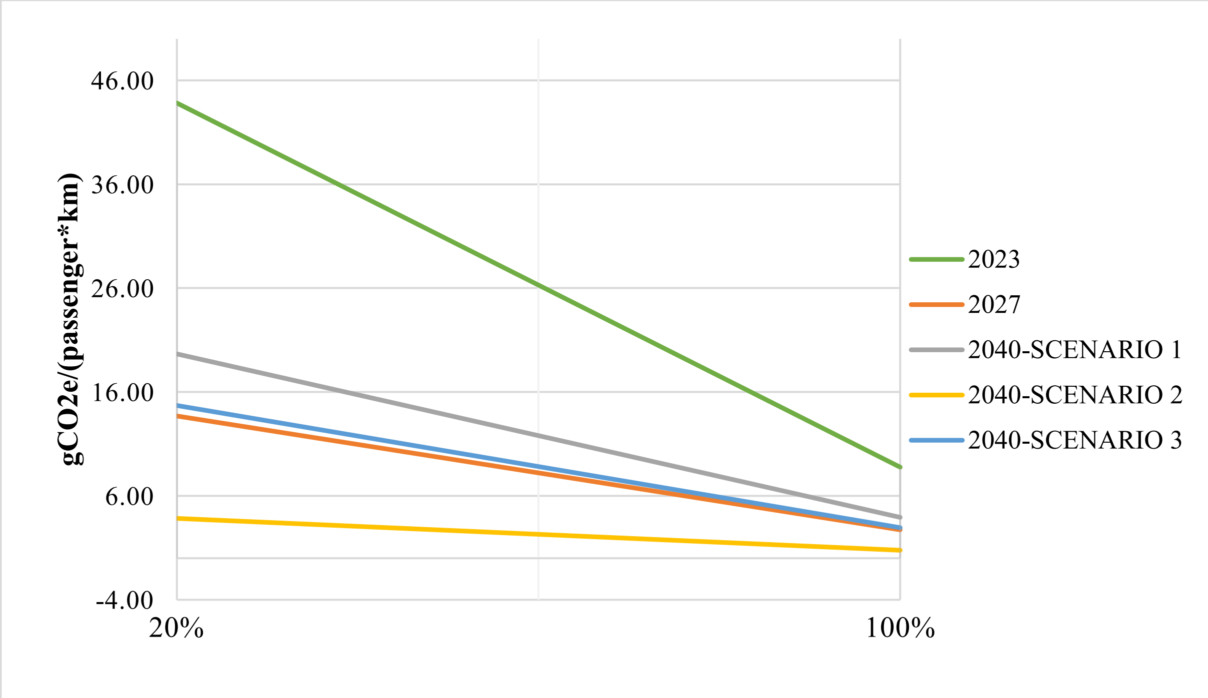

Figure 51: CO_{2e} per-capita emission trends by scenario, considering different percentage values of bus occupancy with respect to bus capacity and the use of biomethane without manure credits, GTT data elaboration

Considering the use of biomethane without manure credits, scenario 3 to 2040 are in line with 2027 emission levels but still have values approximately three times higher than those in scenario 2.

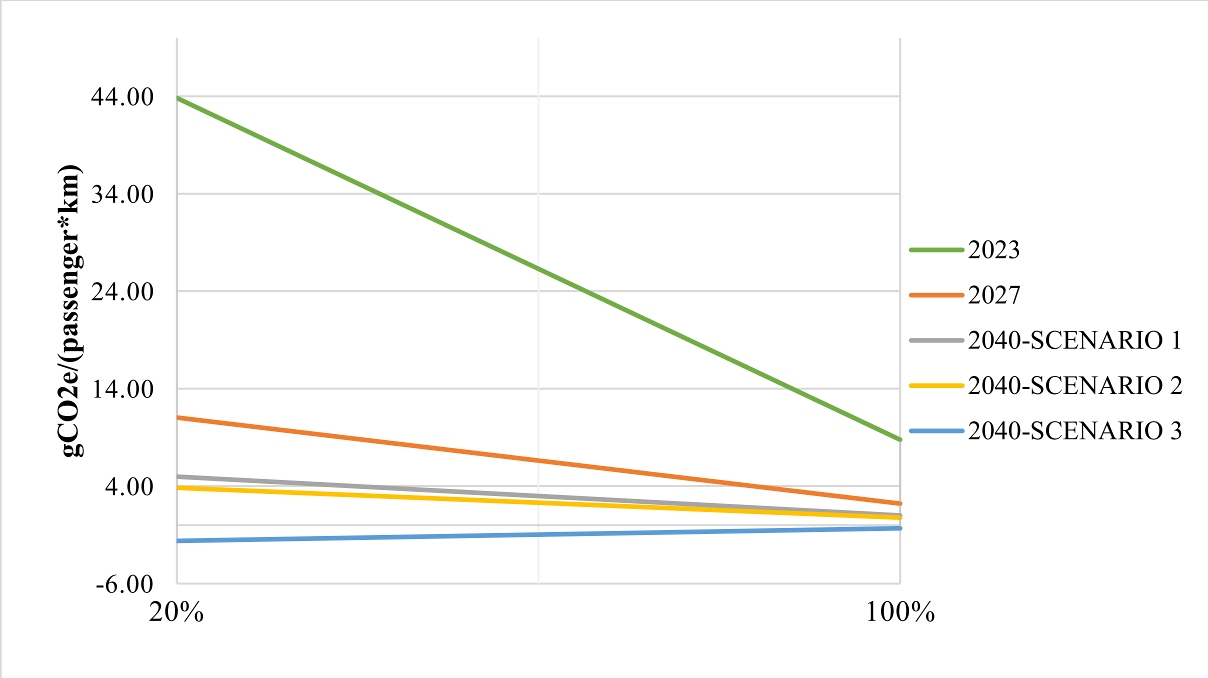

Figure 52: CO_{2e} per-capita emission trends by scenario, considering different percentage values of bus occupancy with respect to bus capacity and the use of biomethane with manure credits, GTT data elaboration

Finally, considering the credits associated with the use of biomethane, it is found that scenario 3 is characterized by negative values (-1.62 and -0.32 gCO_{2e}/passenger*km, respectively) and the emissions of scenario 1 possess the same order of magnitude as scenario 2, in line with what was seen in the analysis of total annual emissions from the urban fleet.

3.4. LIMITATIONS OF THE ANALYSYS

The analysis presented encounters some limitations that it is important to highlight in order to properly contextualize the results obtained and conclusions drawn. First, GHG emissions data were collected from different sources, each with their own methodologies and update times. This may introduce discrepancies in direct comparisons between different datasets. In addition, the analysis is based on hypothetical scenarios of biomethane production and use, which may not fully reflect actual future conditions, especially considering possible legislative, economic and technological changes. Another limitation concerns the assumption of constant efficiency in biomethane conversion and utilization technologies. Any unanticipated technological improvements or regressions could significantly alter the calculated CO_{2e} emissions results. In addition, an assumption of a 5 percent reduction in energy consumption was assumed for all city bus engines every five years, an assumption that could also be inaccurate. The availability and quality of local data specific to the metropolitan city of Turin is a further limitation, as estimates of biomethane production and demand are based on data that may not be completely up-to-date or accurate. Finally, the economic analysis assumes a stable incentive framework, but changes in government incentive programs could significantly affect the economic feasibility of biomethane. These limitations suggest that the results should be interpreted with caution and that further studies are needed to confirm the conclusions in different contexts and with more recent and complete data.

CONCLUSIONS

This study has demonstrated the significant potential of biomethane as a renewable energy source for public transportation, particularly within the context of the Metropolitan City. The integration of biomethane into Turin's urban transport system offers a promising pathway to reduce greenhouse gas emissions for GTT, aligning with both local and national environmental goals. The assessment revealed that biomethane can substantially lower CO_2 equivalent (CO_{2e}) emissions compared to fossil fuels. Under Scenario 1, a reduction of up to 92.1% in emissions from 2022 levels would be achievable by 2040, while Scenario 3 (100% biomethane) could achieve a reduction of up to 81 percentage points if manure credits are not counted. However, if these credits are included, the well-to-wheel analysis indicates that using biomethane could result in negative CO_{2e} emissions under certain scenarios (-3.82 kton of avoided CO_2 emissions per year in 2040 under Scenario 3). This underscores the environmental benefits of adopting biomethane for urban fleets.

Economically, biomethane production is feasible under current incentivization schemes, with financial analyses showing that it can compete with conventional fuels, provided that supportive policies and financial incentives continue. Although this study did not focus on economic aspects, the technical analysis confirmed that the potential supply of biomethane in the Turin metropolitan area can meet the demand of the public transport fleet operated by GTT, ensuring the practical implementation of biomethane in the urban transport sector.

Recent legislative developments, such as the Italian "Decree Biomethane," have created a favorable framework for the growth of the biomethane sector. These policies are crucial for promoting the production and use of biomethane, facilitating the transition to renewable energy sources in public transportation. The research also affirmed the technological and logistical feasibility of utilizing existing biogas facilities and potential feedstocks in Turin for biomethane production. The integration of biomethane into the public transport system is manageable given the current infrastructure and technological capabilities.

It has been demonstrated that the adoption of biomethane as an energy source for public transportation in Italy is both environmentally beneficial and technically feasible. Nonetheless, it is important to recognize that the potential of biomethane is limited compared to other conventional fuels in the transportation sector, making it appropriate to target the production of this biofuel for specific applications, such as heavy transport and public transportation.

The findings of this thesis support the transition to greener urban mobility, emphasizing the need for continued policy support, financial incentives, and infrastructure development. Policymakers, energy engineers, and stakeholders are encouraged to collaborate in fostering the growth of the biomethane sector, contributing to a sustainable and low-carbon future for urban transportation. The successful implementation of biomethane in Turin could serve as a model for other cities, demonstrating the practical benefits of renewable energy integration in public transportation systems. This thesis provides a comprehensive framework for understanding the potential of biomethane, offering valuable insights and recommendations for advancing sustainable urban mobility.

APPENDIX

SECTION 1: Analisi sullo storico dei costi delle materie prime di GTT adibite al trasporto pubblico

Given the numerous crisis events related to the global geopolitical and health scenario over the past four years, raw material costs and, consequently, the company's costs related to energy consumption have fluctuated greatly. For the purpose of illustration, the following describes and shows the costs incurred by GTT allocated to powering the urban fleet.

During the 2020s, there was a general decline in both consumption and prices of energy resources. In particular, for the first time in the past 20 years, the price per liter of diesel fuel crossed downward by the € 1/liter threshold in 2020, allowing fuel costs to be cut by 25.8 percent. Costs associated with the supply of CNG per kg destined for automotive use experienced a less steep decline during the pandemic period, reaching €0.43/kg in 2020, down 12 percent from the value recorded as of 2019. In parallel with diesel fuel, the total costs of natural gas and electricity fell sharply during the first pandemic period, as shown in the graphs below.

During the second pandemic period (2021), there was an increase in the average purchase price of the two fossil fuels, followed by an increase in total costs at the expense of a decrease from 15.5 c€/kWh to 13.2 c€/kWh in the price of electricity, followed by a slightly increasing trend in total cost (+11.3%), despite a 31.1% increase in consumption between 2020 and 2021.

Following the Russian territorial invasion of Ukraine in February 2022 and the ongoing outbreak of the conflict, there has been a major rise in the prices of commodities, especially oil and gas resources. Despite a steady downward trend in methane consumption (-11.2% between 2021 and 2022), the cost per kilogram of methane increased at an all-time high (+68% between 2021 and 2022), paralleling the total cost that GTT had to cover. The unit costs associated with diesel fuel and electricity also showed significant increases (+26.3% and +55.7%, respectively) as the price of electricity is strongly linked to markets for buying and selling methane resources. This situation has primarily contributed to rising corporate operating costs, placing the group’s balance sheet in serious difficulty and requiring extraordinary restorative intervention by government authorities.

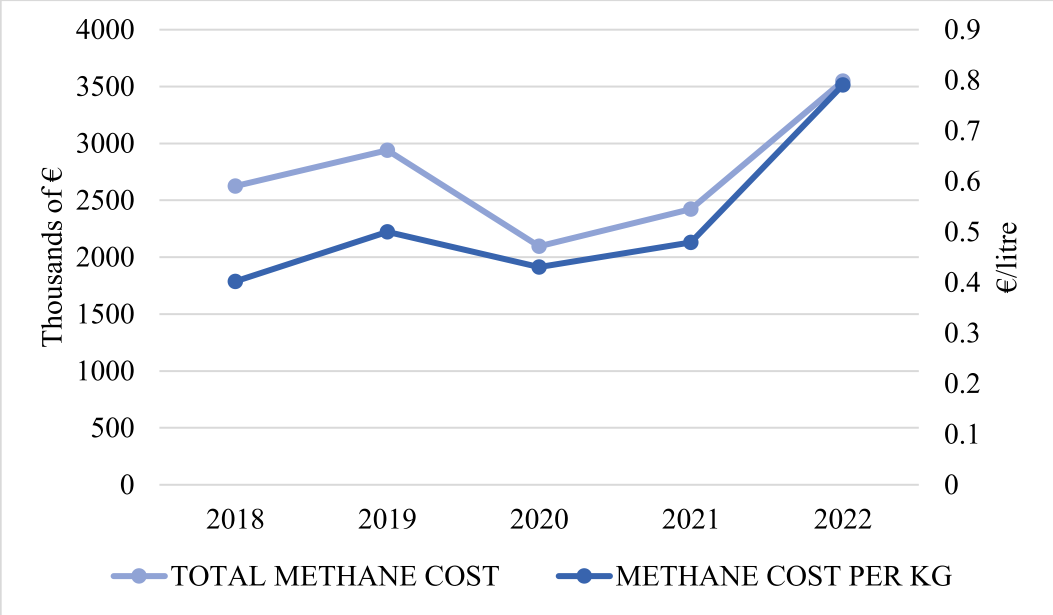

Figure 53: Total and unitary cost of methane trend (respectively in thousands of € and €/kg) [33]

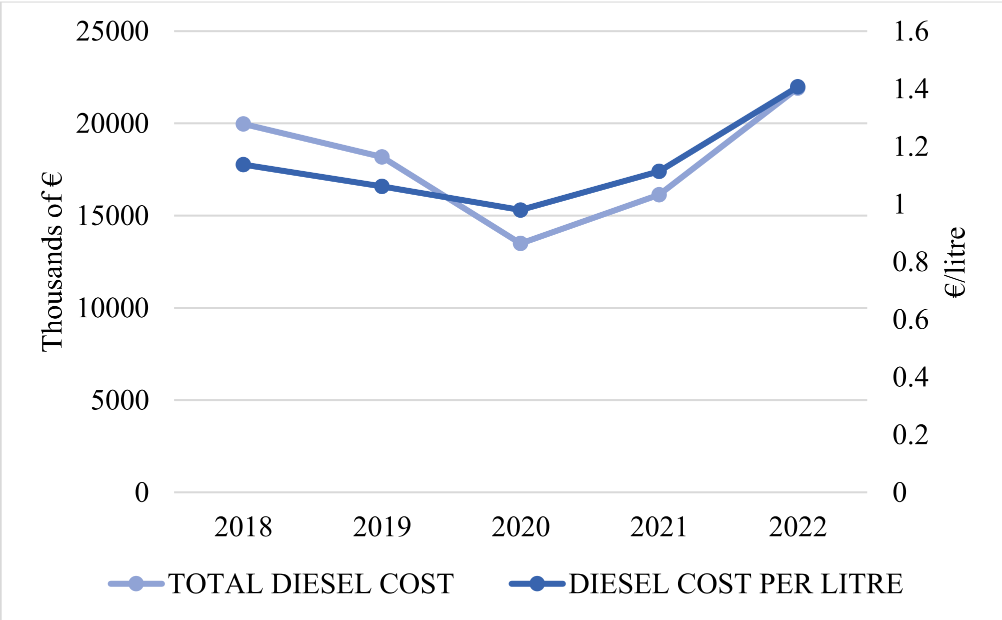

Figure 54: Total and unitary cost of diesel trend (respectively in thousands of € and €/liter) [33]

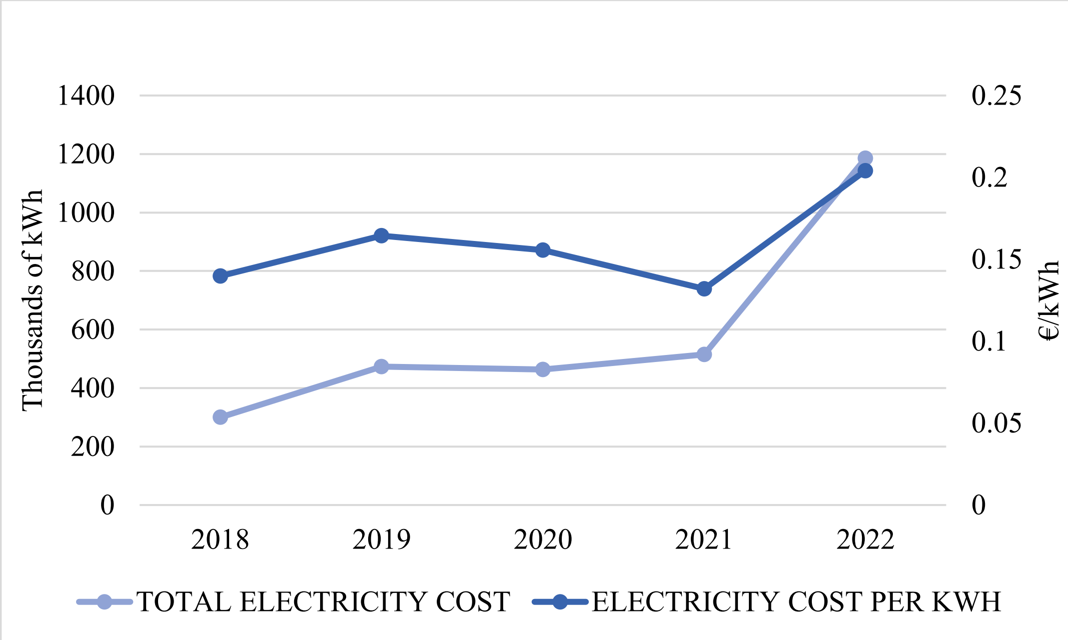

Figure 55: Total and unitary cost of electricity trend (respectively in thousands of € and €/kWh) [33]

SECTION 2: Sensitivity analysis considering biomethane feedstock in Piedmont Region

In Piedmont, the biomethane maximum production turns out to be 732.1 million Smc, equivalent to 9.1 percent of Piedmont's needs in 2020 [56]. As shown in Figure 58, the feedstock with the greatest potential was straw, with 540.3 million Smc.

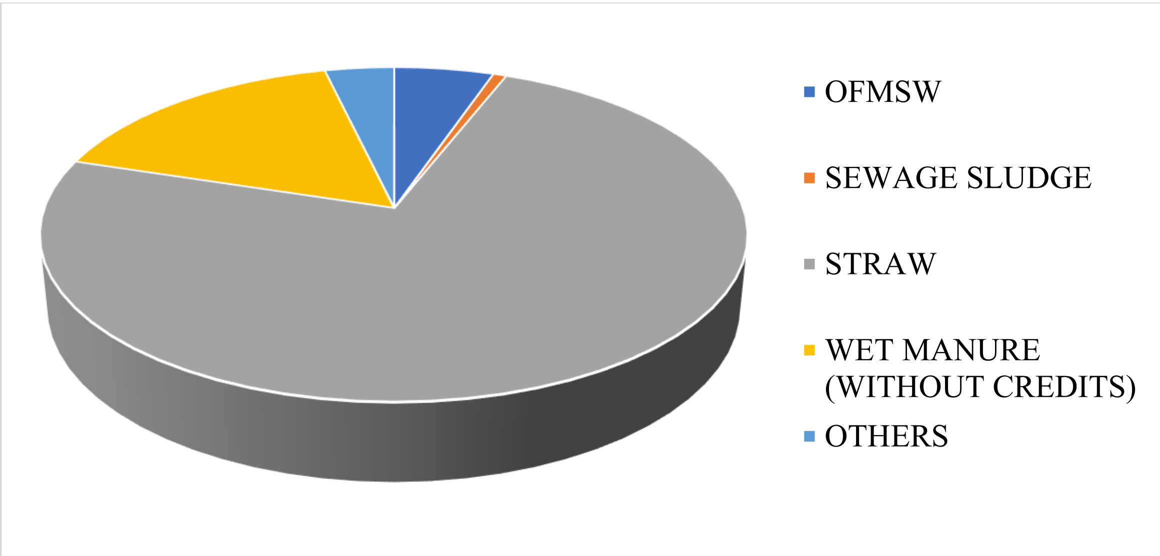

Figure 56: Breakdown of maximum potential production of advanced biomethane by feedstock type, ENEA [47]

Owing to the lack of references regarding feedstock quantities in the provincial context, the subdivision described in Figure 56 depicts the potential feedstock supply for biomethane production in the Metropolitan City of Turin. With respect to the "Medium scenario" considered in the paper, more hypotheses have been adopted in the following appendix analysis:

- The straw feedstock is a double-cropped product.
- Because of the wide spatial spread of straw production (especially among small farms) and the resulting logistical difficulties that would result from its procurement and transport, we assumed the potential for biomethane production in an annual volume equal to half of that stated by the ENEA.
- Feedstocks belonging to the "others" category in Figure 58 are not considered in the calculations in the following analysis because their order of magnitude and carbon intensity are irrelevant to our calculations.

Consequently, the biomethane feedstock mix will be characterized by a scenario including 62% volume of double crops, 28% of wet manure, 9% of OFMSW (Organic Fraction of Municipal Solid Waste), and 1% from sewage sludge.

Considering the previously defined feedstock mix scenario, it is found that the production of 1 MJ of biomethane emits 12.4 gCO_{2e} to the atmosphere in the case where emission credits from manure are not counted while, considering that 28% of biomethane is produced from wet manure (+10% with respect to the national "Medium" scenario), 18.7 gCO_{2e} per MJ of biomethane are avoided in case they are considered, with a saving of additional 11.8 gCO_{2e} per MJ compared to "Medium" scenario. This would result in a higher CO_{2e} emission saving with respect to the use of biomethane, especially if wet manure credits are considered.

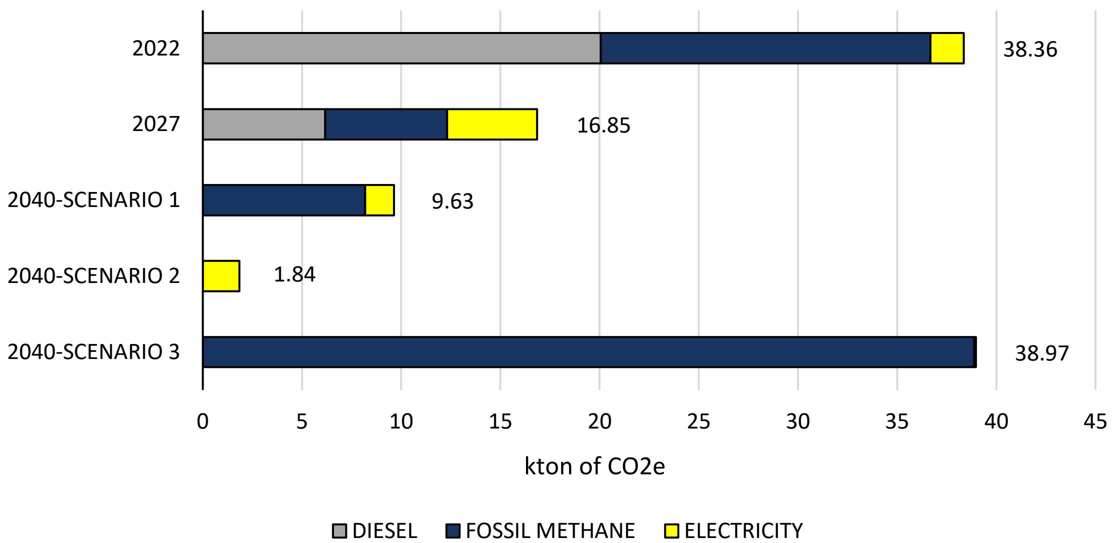

Figure 57: CO_{2e} emissions related to fuel type for each scenario, considering the use of biomethane without credits and Piedmont feedstock, GTT data elaboration

Considering this scenario, in Piedmont Region it would be possible to save a further 3,8% of CO_{2e} emissions quantity in scenario 1 and 6,8% in scenario 3, with respect to "Medium" scenario and considering the implementation of biomethane without considering the manure credits (data are shown in Figure 57).

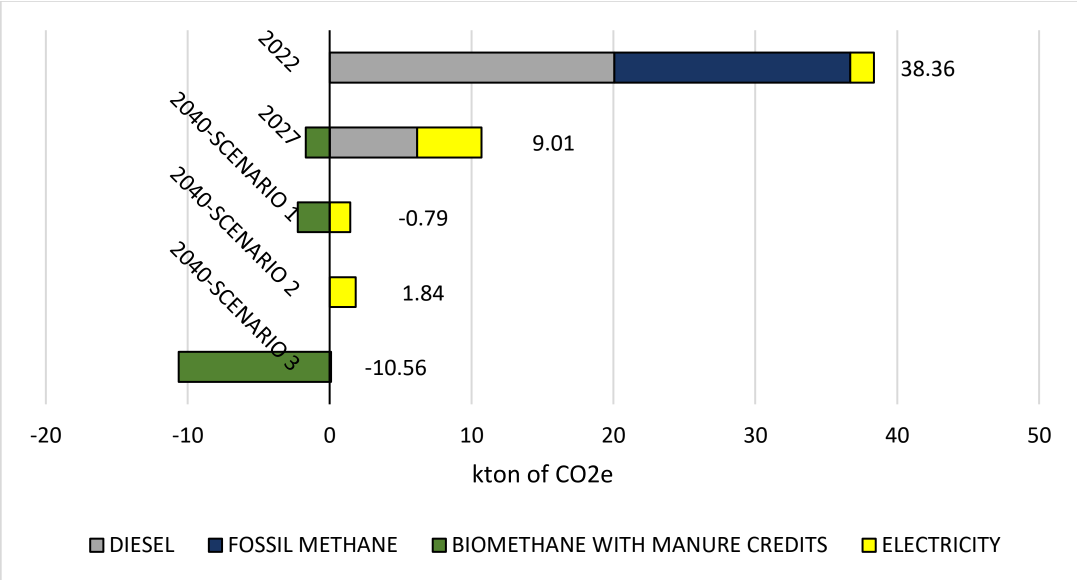

Figure 58: CO_{2e} emissions related to fuel type for each scenario, considering the use of biomethane without credits and Piedmont feedstock, GTT data elaboration

As shown in Figure 58, further quantity of CO_{2e} production would be avoided also considering the use of biomethane if wet manure credits are taken into account; the quantity of CO_{2e} avoided in 2040 in scenario 3 would be three times higher than considering "Medium scenario", and in case of scenario 1 the emissions would become negative (-0.79 kton of CO_{2e} versus +0.63 kton in "Medium scenario").

In case emission per passenger*km is considered, there would be a considerable values reduction; considering there is no vacancy in the buses seats (corresponding to the occupation of all the available places)in scenario 1 (in 2040), the emission value per capita would turn to be slightly negative (-0.04 gCO_{2e}/passenger*km) if biomethane with credits is used, meanwhile in scenario 3 the emission level would reach -3.00 gCO_{2e}/passenger*km, allowed an additional saving of 2.68 gCO_{2e}/passenger*km with respect to "Medium" scenario.

SECTION 3: Tables containing the results obtained and illustrated in Figures 50,51 and 52

"FOSSIL" SCENARIO	2023	2027	2040-SCENARIO 1	2040-SCENARIO 2	2040-SCENARIO 3
20%	43.82	19.62	12.97	3.83	51.22
100%	8.76	3.92	2.59	0.77	10.24

Table 26: Data depicted in Figure 52

"BIO WITHOUT CREDITS" SCENARIO	2023	2027	2040-SCENARIO 1	2040-SCENARIO 2	2040-SCENARIO 3
20%	43.82	13.69	19.67	3.83	14.70
100%	8.76	2.74	3.933	0.77	2.94

Table 27: Data depicted in Figure 53

"BIO WITH CREDITS" SCENARIO	2023	2027	2040-SCENARIO 1	2040-SCENARIO 2	2040-SCENARIO 3
20%	43.82	11.04	4.97	3.83	-0.06
100%	8.76	2.21	1.00	0.77	-0.32

Table 28: Data depicted in Figure 54

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