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The potential role of biomethane for the decarbonization of transport: An analysis of 2030 scenarios in Italy

Michel Noussan [a,b], Viviana Negro [a,*], Matteo Prussi [a], David Chiaramonti [a]

[a] Department of Energy, Politecnico di Torino, Corso Duca degli Abruzzi 24, Torino, 10129, Italy
[b] Paris School of International Affairs, SciencesPo, 13 rue de l'Université, Paris, 75007, France

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ABSTRACT

This paper aims at evaluating the best allocation of potential biomethane generation for the decarbonization of the transport system, presenting a case study in Italy. The country has some peculiar features, such as several operating biogas plants, additional potential feedstock for biogas/biomethane generation, a well-developed natural gas network and established relevant natural gas uses in different final sectors, including transport. Based on current estimates for sustainable biomethane potential by 2030, ranging from 2.3 to 7.6 billion cubic meters depending on the scenario, the analysis compares technologies for the generation, distribution and final use of biomethane. The results of the analysis confirm the potential interesting contribution of biomethane in decarbonizing the Italian transport system: a billion cubic meters of biomethane can lead to 2.33–4.37 Mt_{CO_2e} savings, depending on the feedstock mix and the application. On a national basis, annual climate emission savings in 2030 range from 10.0 to 26.7 Mt_{CO_2e}, depending on the scenario. Additional 3.1–8.1 Mt_{CO_2} of emissions can be avoided if the CO_2 captured during the biomethane upgrading can be stored or reused. The proposed methodology could be used to extend the analysis to other countries, and to the European context.

1. Introduction

The concentration of CO_2 in the atmosphere has reached 410 ppm in 2019, the highest level in the last 2 million years [1], and climate change requires a radical evolution of current energy systems. This huge challenge will entail the deployment of a set of technologies across end-use sectors, given the different requirements in terms of technical, economic and social impact of each application.

The European Union is setting a series of targets to support the development of low-carbon technologies, both at a general level and for specific final sectors. Examples include the policies related to the Fit-for-55 package, such as the ReFuel EU Aviation and Maritime, the forthcoming revision of the Renewable Energy Directive (REDIII), the revised EU ETS system, the Carbon Border Adjustment Measure, the Effort Sharing Regulation, the Energy Taxation Directive, in addition to specific industrial policies that aim at developing the potential of the available resources.

Reaching these challenging targets also requires an effective and sustainable exploitation of bioenergy, to maximize its potential and allocate available resources in the appropriate sectors. There is currently an important amount of feedstock that can be further exploited, especially from waste streams in the agriculture and forestry sector, in addition to feedstock that can be grown on marginal land or during periods in which the land is not used for other crops [2,3].

1.1. State of the art and scope of the work

The biomethane application in transport is an important element of the decarbonization strategy, and it has been addressed in the recent literature, by comparing environmental and economic performance with conventional solutions in different transport segments [4], including public transport [5], trucks [6] and shipping [7]. However, available literature works are mostly focused on single transport segments, comparing biomethane to traditional oil-based transport vehicles or to other low-carbon alternatives. Research studies remark that road transport is likely to absorb a large share of the foreseen EU biomethane production by 2030 [2], while maritime applications are more likely to gain momentum on the long term. A review by Bidart et al. [8] focuses specifically on freight transportation, evaluating different biomethane production technologies and confirming the important emissions reduction compared to traditional applications based on fossil gas or diesel.

Emissions savings related to biomethane depend on the performance on the entire production pathway. Different research studies

* Corresponding author.
E-mail address: viviana.negro@polito.it (V. Negro).

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have addressed the potential benefits of biomethane production from different feedstocks, including maize [9], animal residues [10] municipal solid wastes [11] or energy crops [12,13]. In addition to the feedstock type, cultivation and management techniques have an impact on the energy consumption and productivity, thus leading to variable specific emissions. Other important aspects to be accounted for are the carbon intensity of the electricity mix [14], the fertilizer use and the fugitive methane emissions [9]. In some cases, seasonal variability of feedstock availability should be properly taken into account to estimate biomethane potential [15].

Some researchers also addressed the potential production of biomethane through thermochemical methanation of green hydrogen [16], although their findings suggest that its economic viability is guaranteed only in some specific conditions, due to the multiple steps involved in the supply chain. This process requires also a carbon source, which in some cases could be obtained from the carbon dioxide content of biogas, through an integrated process [17].

From an economic perspective, different research studies remark that in the current situation incentives and support systems are still necessary to ensure the profitability of biomethane plants [14,18–20]. On the other hand, the monetization of carbon emission savings of biomethane could help in filling the gap with fossil fuel prices. Moreover, the profitability of biogas upgrading plants could be enhanced by integrating the coprocessing of other commodities, such as urea [18], micro-algal products [21] or high-purity carbon dioxide.

Therefore, an effective biomethane deployment in transport would need a coherent and coordinated set of supporting strategies targeting the entire supply chain: production facilities, biomethane distribution, refueling infrastructures and final uses [20]. The lack of infrastructure could represent an important barrier to the development of biomethane in some applications, at least in the short-to medium-term [22].

This research work focuses on the potential exploitation of biomethane in Italy, with a specific focus on transport applications, which can be produced from a set of different feedstocks through anaerobic digestion, followed by the upgrading stage to biomethane. Among the advantages of biomethane stands the possibility of its direct injection in the existing natural gas infrastructure enabling a rapid decarbonization of existing applications based on fossil gas. Depending on the type of feedstock and the value chain (agricultural residues, intermediate crops, agro- and municipal organic wastes, etc.), biomethane can achieve different levels of carbon savings, even larger than 100%, especially when obtained from feedstock whose non-appropriate disposal would have otherwise generated GHG emissions. The possibility to store or re-use the concentrated CO_2 stemming from the upgrading stage is another technological option to further strengthen the environmental and economic balances of the pathway. The complexity of its supply chain can in some cases need to face trade-offs in terms of energy efficiency and investment (CAPEX) and operational (OPEX) costs, which require a careful evaluation of the best technologies and solutions for the exploitation of the available resources.

Literature analyses are mostly focused either on biomethane production pathways or on final applications. Moreover, when dealing with the transport sector, research papers are generally considering a single segment, comparing biomethane solutions to other powertrains. A combined analysis of the supply side and the demand side, including the contribution of transmission and distribution, is seldom addressed in the recent literature.

For this reason, the research objective of this work is to provide a comprehensive framework that analyses the entire supply chain of biomethane production, distribution and final use in transport. For this reason, we evaluate different pathways and uses of biomethane in terms of energy consumption and carbon emissions savings, by comparing biomethane applications across transport segments with the alternative technologies that are currently available and expected to be deployed in future decarbonization scenarios. These quantitative results are also complemented by a qualitative discussion about other important aspects related to a successful development of biomethane.

The paper focuses on Italy as a notable case study, with some peculiar features: (1) the availability of a significant potential of biomethane production from sustainable feedstocks, today only partially exploited by biogas power plants, (2) an extensive natural gas network and infrastructure, and (3) a large penetration of natural gas in different final sectors, including transportation, which is among the most hard-to-abate applications, especially for freight. The choice of focusing on a single country also allows for a better detail in evaluating the actual conditions, by considering the specific regulatory context and the incentives that are currently in place. Nevertheless, the results and conclusions can be further extended to similar countries, and to regional analyses such as for the EU27 case. Our results are also evaluated against some key parameters, such as the feedstock mix, the carbon intensity of the electricity consumed along the supply chain, and the type of final application. Thus, the results of the sensitivity analysis that complements the main findings allow to adapt this method to other contexts with different characteristics.

1.2. European regulatory context

As of 2021, around 70% of the total energy consumed in the EU-27 was produced from fossil fuels (35% from oil products, 24% from natural gas and 10% from coal) [23]. The transport sector remains the one with the lowest penetration of renewable energy and the highest reliance on oil products.

The Clean Energy for All Europeans package, adopted with the latest adjustments in 2019, aims at decarbonizing the EU's energy system, in line with the objectives of the European Green Deal. In this context, the revision of the Renewable Energy Directive (also referred as REDII [24]) came into force in 2018 as a pillar of the energy transition. More specifically, biofuels are crucial to meet EU greenhouse gas reduction targets, and the share of renewable energy used in transport was increased to 14% by 2030, including a minimum share of 3.5% of advanced biofuels. The REDII contains also the sustainability criteria for such alternative fuels.

Given the urgency of limiting the effects of the climate crisis, in 2021, the European Commission proposed the revision of RED II as part of the package of legislative proposals "Fit for 55", targeting a new goal of at least a 55% reduction in GHG emissions by 2030, compared to 1990 levels, resulting in a pathway towards climate neutrality in the EU by 2050. The Council and Parliament have recently reached a provisional deal on the Renewable Energy Directive [25]. The provisional agreement gives the possibility for each Member State to choose between two alternative targets for 2030: a binding target of 14.5% GHG emissions reductions in transport, or a binding share of at least 29% of RES in the final energy consumption in transport. Moreover, the provisional agreement includes a combined sub-target of 5.5% for advanced biofuels and renewable fuels of non-biological origin in transport energy uses. One of the pillars of the package is reviewing the Emissions Trading System (ETS) sectors: emissions from these sectors will have to decrease by 62% by 2030 (compared to 2005), representing a substantial evolution from the previous objective of 43% emissions reductions. The approved legislation [26] includes an extension of the ETS to the maritime sector for the first time, and the creation of a new separate ETS for buildings and road transport starting in 2025. In this context, the overall 2030 European renewable energy target has been continuously increased over the years, from 32% set in RED II, to 40% in "Fit for 55" package, and finally to 42.5% in 2023.

Within this recent EU policy framework, a greater attention is deserved to the biomethane sector, which is expected to contribute with 35 billion of cubic meters of biomethane by 2030 to the urgent EU need to diversify supply and reduce gas imports [27]. This volume is approximately twice the one produced during 2020, considering biogas and biomethane together; to reach such an ambitious increase it will

Table 1
Biogas power plants per type of feedstock, 2021–2022.
Source: Data from [28,29].

Main feedstock	Plants		Capacity (MW)		Generation (GWh)	
	2021	2022	2021	2022	2021	2022
MSW	386	380	382.9	372.1	1059	989
sewage sludge	82	86	46.7	50.2	124	116
Manure	688	719	249.4	254.2	1297	1277
Agri-forest	1105	1131	776.1	783.1	5645	5463
Total	2261	2316	1455.1	1459.6	8124	7845

be necessary to both upgrade the existing biogas plants and extend the current infrastructure. These upgrades are estimated to require a total investment in the EU-27 of 48 billion € to build 4000 medium-size units and 35 billion € for 1000 large-scale plants, without considering the additional investment in infrastructure, which is however expected to remain limited [27].

Also, biomethane offers the possibility of exploiting critical streams, such as industrial and agricultural waste feedstocks, municipal solid wastes, sewage sludge and others – whose disposal may be critical –, and the production of a low-GHG emission energy carrier, which can be destinated to the transport sector. In this perspective, the biomethane value-chain plays a crucial role for both the implementation of circular use of resources and the production of an alternative fuel. It worth stressing that under specific conditions, such value-chains may generate a negative GHG net balance.

1.3. Biomethane production and future scenarios in italy

The production of biogas in Italy has been significantly developed in the last two decades, especially thanks to incentives for power generation from renewables that included biogas. As of 2022, there are more than 2000 biogas power plants in operation in Italy, for a total gross capacity of 1.46 GW and a gross annual generation of 7.85 TWh [28,29]. As summarized in Table 1, around 70% of the electricity generated by biogas plants derives from agricultural and forestry products and residues, while 16% from manure, 13% from MSW and the remaining share from sewage sludge. Moreover, 69% of the electricity is generated in plants that are operating in CHP mode, for a total heat production of around 3.4 TWh. It is also important to remark that due to the former rules of the Italian incentives, around 33% of the total number of plants and 50% of the total capacity is related to systems that have between 900 kW and 1000 kW of nominal output power.

Over the last years these plants have become an interesting option for the upgrade of the available biogas to biomethane, to provide an alternative to the fossil natural gas in final uses, especially in transport. There are currently 33 plants in Italy equipped to upgrade biogas to biomethane, either connected to the natural gas grid or producing liquid biomethane [30]. The use of biomethane in transport is of particular interest due to the challenging 2030 decarbonization targets, especially considering the share of advanced biofuels to be used. This is also a relevant option given the existing natural gas-powered fleet in Italy, including 0.97 million passenger cars (2.4% of the total) and 5400 buses (5.4% of the total) as of 2022 [31]. Also, LNG use in trucks is gradually gaining interest, although high gas prices in 2022 and 2023 have limited their deployment. In Italy, the current use of natural gas in transport is supported by around 1450 refueling stations for CNG, and 140 for LNG, compared to around 14,500 for gasoline and diesel [32].

The existing incentives for biomethane upgrading (Min. Decr. 15 September 2022) provide a CAPEX financing of up to 40% of the costs and a support mechanism based on actual biomethane production. These incentives will be awarded through a series of competitive auctions in the years 2023–2025, with a total capacity of 257,000 Sm^3/h to enter in operation before 2026. The first auction has recently awarded around 30,000 Sm^3/h of installed capacity, less that the total maximum auctioned capacity. Some of the reasons include narrow timeline, bureaucracy requirements and the low incentive value for the organic fraction of municipal solid wastes (MSW) compared to other feedstocks. Nevertheless, the expected total capacity should deliver around 2.3 billion cubic meters of biomethane annually, which is more than twice the current natural gas consumption in the transport sector (mostly for private cars and buses).

Different estimates are available for the biomethane penetration in Italy in the next decade. A recent report from Gas for Climate [3] estimates a total biomethane potential of 5.5 billion cubic meters by 2030 in Italy, mainly from sequential cropping (3.2 bcm) and animal manure (1.0 bcm). National estimates from the Consorzio Italiano Biogas reach a total potential of 8–8.5 bcm, of which 6–6.5 relates to agricultural and agro-industrial biomass and 1–1.5 bcm from organic waste by the same year. Another report from the Italian National Agency for New Technologies, Energy and Sustainable Economic Development [33] estimates a technical potential of 6.2 bcm of advanced biomethane, based on 2016 feedstock data.

2. Materials and methods

This section presents the objective and the focus of the analysis, by discussing the feedstocks, processes and final uses that are evaluated in the study. The main parameters and assumptions are also reported in detail.

The different pathways considered for biomethane in this analysis are given in Fig. 1. Technologies required in the supply, distribution and final uses are described by considering their energy and GHG emissions balances, to analyze the different pathways compared to the alternative technologies that are available for each application. The main GHG emissions drivers are discussed below, with particular attention to those related to the electricity consumption. The components in gray color are not directly considered in the analysis, but they represent potential additional biomethane uses.

The aim of the analysis is to compare different allocation scenarios based on alternative biomethane potential estimates, to illustrate the expected benefits in terms of GHG emission savings.

2.1. Biomethane production stage

The biomethane production stage has been considered by evaluating the cultivation step (where relevant), the fermentation phase and the upgrading process. In the following paragraphs the main assumptions and data are presented and discussed.

2.1.1. Cultivation and fermentation

Biomethane produced from biogas upgrading after anaerobic digestion can be obtained from multiple organic feedstocks. Average emission levels in the cultivation and fermentation phases depend on the type of feedstock that is used (due to different yields, fertilizers use, treatments, etc.), as well as on other specific choices, such as open or closed digestate and the combustion of off-gas (some of these choices are no longer accepted by the existing National regulations for new plants). In this analysis, the feedstocks that are evaluated are the organic fraction of MSW, wet manure, sewage sludge, corn and double crop. This choice is related to the range of feedstocks that are currently in use, and the potential ones that are expected to play an important role in the future. Some plants also use a mix of different feedstocks.

The cultivation phase is responsible for the lion's share of emissions in the supply phase of biomethane (considering cultivation, digestion and upgrading) for the relevant feedstocks. Official reference values for the different phases are given in the RED II EU Directive, based on average EU figures. However, since an important part of GHG emissions during the fermentation is due to electricity consumption (from 47% to 88%, depending on the feedstock), in this work the figures provided

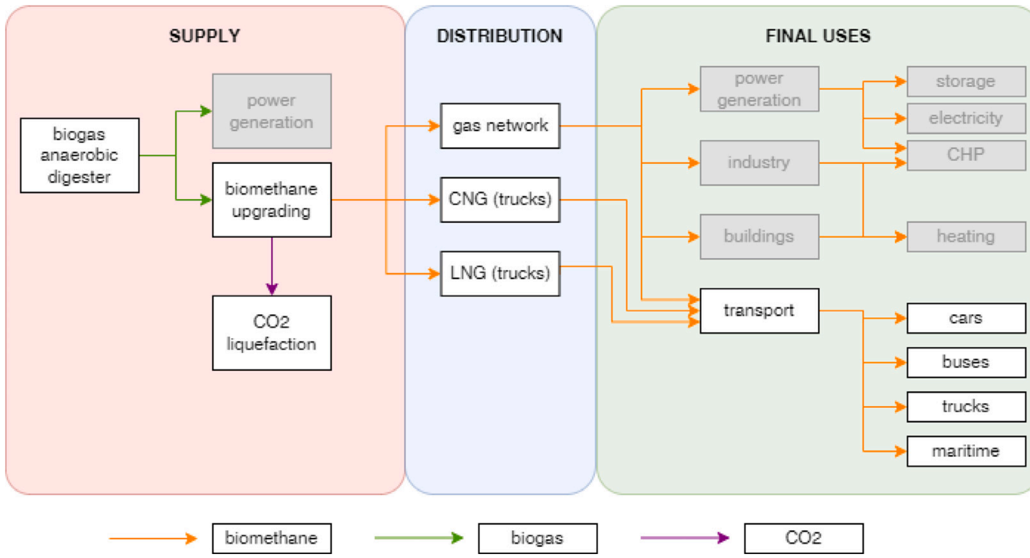

Fig. 1. Biomethane pathways considered in this study (components represented in gray are not part of the analysis).

by [34] have been used. This allows for the possibility of separating the emissions related to electricity consumption and thus accounting for the specific electricity mix of the Italian context (and its expected future evolution). The figures provided by this report are compliant with the official RED II values. These values also include the collection and transport of the feedstock to the anaerobic digestion site.

Thus, the emissions considered in this study for the fermentation phase are adapted to account for the electricity emission factor in Italy, estimated based on the 2030 electricity mix defined in National strategies (based on a 64% power generation from RES, and estimated to be equal to 101 g_{CO2e}/kWh, including the contribution of imported electricity).

2.1.2. Upgrading

Biogas produced from anaerobic digestion is a mix of CH_4 and CO_2 (at variable shares), with some additional marginal shares of steam and other gases. Different authors addressed the available technologies to upgrade biogas to biomethane, a process that is fully industrialized and commercial. A comparison of alternative options in the Italian context was provided by [35], with detailed information on biomethane yields, electricity consumption and investment and operational costs for each considered technology. Their results are well aligned with the figures provided by [34], which are used as input values to consider the upgrading process in this analysis. The average electricity consumption for the upgrading process is 0.40 kWh per kg of biomethane.

2.2. Transmission and distribution

Biomethane can be distributed to final users in different forms. In this work three alternatives are compared: direct injection into the natural gas network, distribution of high-pressure compressed biomethane with trucks and distribution of liquefied biomethane with trucks.

2.2.1. Direct injection into the natural gas network

Most of the current biomethane plants located in Italy are directly connected to the natural gas transmission network, typically at a pressure level above 5 barg, while some plants are connected to the distribution network. However, the latter possibility may not be always a viable option, due to regulatory and operational limitations [36], and for this reason the direct supply to the transmission network is considered in this work. However, many biogas plants are far from the natural gas grid, thus leading to very high connection costs that make unprofitable to inject biomethane into the grid.

Pasini et al. [37] presented a techno-economic comparison of biomethane injection in the natural gas grid and biomethane liquefaction. In the first option, they estimate an average electricity consumption of 0.07 kWh/kg to supply biomethane to the grid at 1.2 MPa (based on a mass flow rate of 10 t/d of biomethane from the upgrading system). This figure has been used in the present study to account for the electricity consumption for biomethane grid injection.

2.2.2. High-pressure compression

The high-pressure compression of biomethane can represent a viable solution for production sites located in rural areas that are not reached by the natural gas network. Biomethane is usually compressed to 20–25 MPa, with an average electricity consumption of around 0.3 kWh/kg [34]. The compressed biomethane can then be transported through trucks to end users that are not connected to the network or that need methane at high pressure (often for transport applications). In some specific cases an additional compression stage may be needed.

2.2.3. Liquefaction

The interest in biomethane liquefaction is quickly growing, linked to the cryogenig separation techniques, especially for plants that are far from the natural gas network, and when biomethane is supplied to final users that can use it directly in its liquid form (such as trucks and ships).

Electricity consumption for biomethane liquefaction in small-scale applications is estimated in the range 0.75–0.78 kWh/kg [37,38]. An alternative commercial option is represented by the integrated liquefaction of biomethane and carbon dioxide, performed in a single unit that includes the upgrading process. The total electricity consumption of that unit, expressed in relation to the liquefied biomethane, is in the range of 1.57–1.83 kWh/kg (depending on the temperature and pressure of the bio-LNG) [39]. This figure is used to account for the additional potential of recovering liquid CO_2 during biomethane liquefaction.

2.3. Final uses

This analysis focuses on the potential application of biomethane in different transport segments: cars and light commercial vehicles, buses, trucks, shipping. The main assumptions considered in the various final uses are discussed below. One of the main parameters to estimate the effectiveness of biomethane in final uses is its specific consumption compared to current alternative solutions. In the transport sector, the demand indicators that are generally used are the following: the passenger-km (pkm), the vehicle-km (vkm) and the tonne-km (tkm) for freight applications. The following sub-sections will address the main figures related to methane consumption in different segments as well as the emissions of the main alternative options.

Fossil natural gas is currently being used in different road transport segments in Italy, including in passenger cars and buses as CNG and is gaining momentum in trucks as LNG. In this work, literature values for natural gas consumption have been used to estimate biomethane use for each transport mode, and tank-to-wheels (TTW) and well-to-wheels (WTW) emission factors related to the alternative technologies are used for the comparison.

2.3.1. Passenger cars

TTW emission factors and energy consumption have been evaluated for a range of fuels by the JEC (composed by the Joint Research Centre of the European Commission, EUCAR and Concawe) in two recent reports, for both passenger cars [40] and heavy duty vehicles [41]. Passenger cars running on (fossil) CNG are estimated to consume 176 MJ of fuel per 100 km with the current fleet, while the technology improvement will lead to a decreased consumption of 139 MJ/100 km for vehicles sold after 2025. These figures correspond to TTW average emissions of 80 g_{CO2e}/km after 2025, of which around 2 g_{CO2e}/km are due to fugitive or unburnt methane (this last value is thus considered as the only TTW emission level when using biomethane). As a comparison, TTW emissions of other powertrains are 104 g_{CO2e}/km for gasoline cars, 96 g_{CO2e}/km for diesel cars and 76 g_{CO2e}/km for hybrid gasoline cars (data are referred to 2025 technologies).

Our calculations are based on an average biomethane consumption of 1.4 MJ/vkm and a methane slip of 2.0 gCO_{2e}/vkm, and on an average WTW emission factor of 106.8 gCO_{2e}/vkm for the estimated car fleet in 2030.

However, it is important to remark that the EU has recently approved legislation to ban the sales of new internal combustion engine cars and light vans by 2035 [42]. In this perspective, the allocation of biomethane to light-duty transport may remain a viable option only during this transition towards zero-emission vehicles.

2.3.2. Trucks

Regarding heavy-duty transport, fossil LNG is gradually being used in trucks in some European countries, thanks to the increasing availability of refueling stations and the potential savings on costs (before the 2021–2022 increase of natural gas prices all over the continent). Long-haul trucks running on fossil LNG, considering the future scenario (after 2025) are estimated to consume 0.685 MJ/tkm (for high pressure direct injection engines), leading to climate emissions of 42.2 g_{CO2e}/tkm (of which 2.6 g_{CO2e}/tkm due to methane emissions). As a comparison, TTW emissions for diesel trucks are 50.4 g_{CO2e}/tkm [41], and WTW emissions reach 62.9 gCO_{2e}/tkm.

2.3.3. Urban buses

As regards urban buses, different research works present a comparison of alternative powertrains focusing on climate and local pollutants emissions. Prati et al. [43] estimated the fuel consumption and emissions of natural gas buses in operation on actual routes in three different Italian cities. Guo et al. [44] also estimated emission factors from on-road operation measurements of commercial buses (also by including the additional weight due to 20–40 passengers onboard). The authors compare different buses operated on natural gas and diesel, although different average speeds makes the comparison of emission factors tricky. Another study on natural gas and diesel buses is provided by Rosero et al. [45], evaluating the performance of buses in real-traffic operation. Finally, a study by ICCT researchers discuss climate emissions for different HDVs, mostly focusing on trucks, but also including urban buses [46].

However, the most comprehensive comparison of different powertrains for urban buses is provided by Muñoz et al. [47], where CNG buses are evaluated against diesel, hydrogen and electric options. Differently from the previous cases, authors here provide a detailed evaluation of WTW emissions for both climate and local pollutants, in addition to information on fuel consumption and economics. For this reason, our analysis on urban buses has been based on the results from [47].

We assume a biomethane consumption of 20.9 MJ/vkm and a methane slip of 95.7 gCO_{2e}/vkm for urban buses, compared to an average WTW emission factor of 1369 gCO_{2e}/vkm for diesel buses.

Intercity buses have not been taken into account in this analysis, since they represent a less mature technology compared to the other applications. Some cities are starting to invest in LNG coaches, but they remain much less common compared to urban CNG buses (that are almost 5000 across the country [31]).

2.3.4. Shipping

A final potential application of biomethane in transport is the marine sector. The use of LNG is being widely evaluated as a potential solution to decrease carbon emissions of shipping, and liquefied biomethane (BioLNG) could be used in the same infrastructure. Some authors analyzed the potential of specific applications, such as a study in Cornwall for biogas upgrading to biomethane for applications in light maritime [7]. A detailed working paper from ICCT researchers [48] presents a comparison of different LNG technologies with traditional heavy fuel oil (HFO) and very low sulfur fuel oil (VLSFO) engines. Results of hull-to-wake emissions for LNG ships show CO_{2e} savings in the range 26%–31% compared to VLSFO. However, when accounting for methane slip, the benefits decrease, and in the worst-case LNG shows a 4% increase of climate emissions compared to VLSFO (although in other cases the savings remain in the range 16%–24%).

Indicators are expressed with respect to the kWh of delivered energy in the ship engine. In our calculations, we consider a bio-LNG consumption of 7.12 MJ/kWh and a methane slip of 123 gCO_{2e}/kWh, compared to an average WTW emission factor of 710 gCO_{2e}/kWh for VLSFO ships.

2.3.5. Other applications

The focus of this work is on the transport sector, but it is important to highlight that biomethane could potentially substitute fossil gas in other sectors. Natural gas is currently representing an important share in power generation in Italy. Although fossil gas consumption is likely to decrease in a decarbonization perspective, biomethane could still represent an effective solution to exploit the existing infrastructure and provide dispatchable renewable electricity. Still, the use of biomethane in power generation deployed through the natural gas Italian transmission network should be compared with the current electricity production from biogas in distributed power plants, to assess the expected benefits. Such a comparison should be also consider another important benefit, which is increasingly valuable in a decarbonized power system with a high level of variable generation from renewables, that is the possibility of exploiting existing natural gas storage systems to use biomethane for long-term storage, and in general to provide a resource for grid balance in addition to the other options that are available for short-term balancing services (such as batteries and demand response).

Biomethane can also be used as a substitute of the current fossil gas in industrial applications or for buildings heating, domestic hot water production and cooking. Biomethane could represent a low-carbon alternative where direct electrification is not a viable option, due to a number of reasons, including technical and regulatory issues (e.g. historical buildings with lack of space for heat pumps, areas where the electricity grid is overloaded, industry applications where methane is used as feedstock). However, these cases include a wide range of different applications, each having peculiar conditions, and it is hard to group them through a limited number of parameters. In these cases electrification is generally seen as a better option. For these reasons, other applications have not been considered in this study.

2.4. Analysis of emissions and scenarios

The final goal of this analysis is to compare the potential contribution of biomethane in alternative transport segments, by evaluating the emission savings compared to other available technologies.

Considering passenger cars, the comparison has been carried out based on the average estimated fleet in 2030, based on future scenarios of the different powertrains [49], already weighted by vkm, and the average estimation of future fuel consumption and WTW impacts [50]. As for buses and trucks, the comparison has been considered versus the diesel-powered solutions, since these remain the default option in both sectors (although in some cities natural gas and electric buses are gradually increasing their penetration). The same hypothesis has been done for shipping, where heavy fuel oil and very-low sulfur fuel oil (VLSFO) represents today the largest share of shipping energy consumption.

A final evaluation that is presented in this work is the potential contribution of liquid CO_2 sequestration, only when considering liquefied biomethane applications. As already discussed above, a new technology could allow for the recovery of a high-purity liquid CO_2 stream during biomethane liquefaction. The main barrier is related to the potential uses of this commodity, which remain currently limited to the food sector and few other industrial applications.

Emission savings, after having been evaluated per unit of consumed biomethane, are also estimated on a National basis, considering future scenarios of estimated biomethane supply and allocation to different applications. We compare three different scenarios based on the following hypotheses:

- Low Scenario: We assume that all the current biogas-based power plants will switch towards biomethane production, in accordance with the targets of the current Italian incentive framework, for a total of 2.3 bcm of annual biomethane production;
- Medium Scenario: the benefits of biomethane push new operators to develop additional plants, for a total of 5.5 bcm of annual supply, which is comparable to the values proposed by the Gas for Climate Report [3];
- High Scenario: we evaluate the maximum theoretical potential, considering national estimates of 7.6 bcm of annual biomethane production (average range from [3] data), with the aim of proposing a potential scenario that is more difficult to be reached in the due timeframe.

The levels of biomethane production of these three scenarios is compliant with the referred studies, which have also discussed the availability of feedstock to produce this level of biomethane.

These three scenarios also differ for the kind of feedstock that is used for the generation of biomethane, since the feedstock mix has been set in accordance to the assumptions of the three external sources mentioned above. Wet manure accounts for around half of the feedstock mix in the Low Scenario, decreasing to 18% in the Medium Scenario and 29% in the High Scenario. This decrease is balanced by an important increase in the contribution of double crop, rising from 7% in the Low Scenario to 69% in the Medium Scenario and 57% in the High Scenario. Maize contributes to 19% in the Low Scenario, although it disappears in the others. MSW accounts for 22%, 11% and 13% in the three scenarios respectively, while sewage sludge remains always between 1% and 2% of the total feedstock. As a result, the Medium Scenario includes a lower share of manure, and for this reason its emission savings will be lower compared to the other two scenarios, as will be further discussed in the next sections.

The allocation of the available biomethane is based on the potential emission savings compared to the alternative options in each application, from the highest to the lowest. The biomethane is allocated to each segment up to a maximum amount, which is equal to the estimated consumption of fossil natural gas in 2030 for that segment. This assumption is done to account for the limitation of infrastructure expansion on the short term. Biomethane is not seen as a simple substitution of fossil gas, but it is actually competing with the average technology mix of each transport segment. The potential natural gas demand in each segment is based on the estimates of two recent studies [51,52], by considering the higher penetration level for each sector.

The focus given to transport is in line with the current national strategies and the lack of effective alternatives for the decarbonization of some transport segments.

2.5. Sensitivity analysis

The analysis of emission savings relies on some parameters that show an important range of variability, requiring a sensitivity analysis to guarantee the robustness of the results. In particular, an evaluation of the effect of the electricity carbon intensity can allow for a comparison with other countries that have different electricity generation mixes. For this reason, we investigate how the emission savings change when considering different levels of carbon intensities, in a range that varies from 0 to 400 g_{CO2e}/kWh (from a current value of 256 g_{CO2e}/kWh in Italy and 238 g_{CO2e}/kWh in the EU-27 [53]). This evaluation is also performed considering the different transport segments: an additional focus was given to the main powertrain types that are considered for private cars, due to their variability in the Italian vehicle fleet.

Another important aspect to be considered is the possible risk of methane emissions in the final use of the different transport modes. Our results incorporate unburnt methane emissions in transport for each transport segment, since they are included in the emission factors discussed above. We address the potential variability of this parameter in the sensitivity analysis by modeling a potential reduction of methane emissions — up to 100% (i.e. no methane slip in the vehicles) to highlight the maximum potential benefit that could be obtained. Research is being conducted on the solutions to reduce methane slip in engines, including by evaluating possible catalysts for its full oxidation after the combustion process [54]. The methane leakages in the other parts of the supply chain have not been investigated in the sensitivity analysis, and their value is assumed to remain constant.

3. Results

3.1. Biomethane emissions

Climate emissions estimated over the supply chain for the different feedstocks here considered are given in Fig. 2, taking into account the biomethane injected into the national gas grid and the estimated 2030 electricity generation mix at National level. Depending on the feedstock, the total emissions fall between 4.7 and 22.0 g_{CO2e}/MJ. Considering the feedstock compositions of the scenarios, figures vary from 9.2 g/MJ for the Low scenario to 13.2 g/MJ for the Medium scenario, while the High scenario stays in between with 11.7 g/MJ. As already explained in the Methodology, the Medium Scenario has on average higher emissions compared to the others due to the assumptions on the mix of feedstocks (retrieved from the above-mentioned references).

These emissions are calculated considering the biomethane injected into the national grid. The figures for compressed biomethane are 0.5 g/MJ higher, while liquefying biomethane would add 1.4 g/MJ of emissions. These figures consider the expected electricity mix of 2030, based on the national decarbonization targets. Compared to the current power generation, the future mix leads to lower biomethane emissions over the supply chain, thanks to the significant part of emissions that is related to electricity consumption in the different phases.

The effect of the different feedstock compositions across the scenarios is shown in Table 2, also comparing the distribution strategies for biomethane. A cleaner electricity generation mix, in line with the current Italian targets for 2030, allows for specific emissions savings in

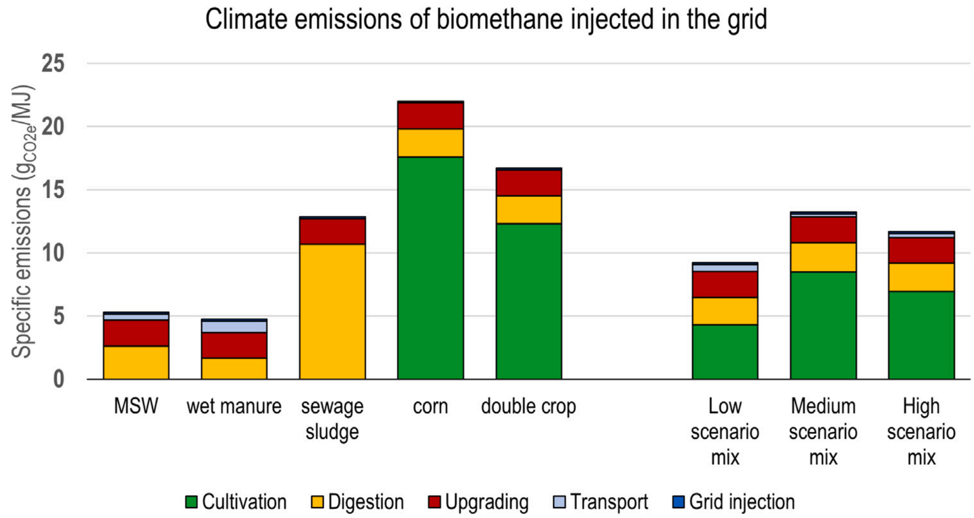

Fig. 2. Climate emissions related to the different steps of biomethane injected in the grid (considering 2030 electricity mix).

Table 2
Effect of different electricity mixes, 2021 vs. 2030, and distribution options on biomethane emissions over the supply chain. Values expressed in g_{CO2e}/MJ.

Biomethane distribution	Gas Grid		Compressed		Liquefied	
Electricity mix	2021	2030	2021	2030	2021	2030
Low scenario mix	11.76	9.21	12.96	9.69	15.40	10.65
Medium scenario mix	15.83	13.22	17.04	13.70	19.47	14.66
High scenario mix	14.27	11.70	15.48	12.17	17.91	13.13

the range 16%–31% compared to the 2021 electricity mix, depending on the case.

In particular, the decreasing carbon intensity of the electricity compensates the higher emissions related to the expected evolution of the feedstock mix. Figures show that the feedstock mix remains an important parameter in the estimation of the supply chain emissions of biomethane.

The values reported in Fig. 2 and Table 2 refer to the emissions over the different steps of the supply chain, which are sometimes referred to as well-to-tank (WTT) when discussing transport emissions. However, there are two additional aspects that should be accounted for, which are the emission credits related to the manure-based pathway, and the effect of land use change (LUC) related to the corn-based pathway.

The production of biogas from manure via anaerobic digestion is generally representing a better alternative when considering climate impacts. The avoided emissions related to this shift are estimated to be 111.9 g_{CO2e}/MJ by the RED II Directive and by the JEC study [34], when considering closed digestate storage. Thus, this value can be seen as a "credit" that can be applied to the biomethane produced from manure.

On the other hand, the production of biomethane from corn has also additional impacts related to the direct land use change, which are not accounted for in the RED II Directive, nor in the JEC study. A reference value of 21 g_{CO2e}/MJ can be added to the other emissions to account for the effect of land use changes for the corn pathway [55]. Corn is expected to gradually disappear in future feedstock mixes, given its higher impacts compared with other sustainable alternatives and its competition with food and feed. However, we decided to include it in our analysis due to its current relevance in biogas applications. The pathway related to double-crop feedstock is assumed to have no additional effect on land use changes, since it exploits land that is already used for other crops during the year.

The effects of considering or neglecting emission credits and LUC is reported in Table 3, where emission factors for the different pathways

Table 3
Emission factors for biomethane, CO_{2e}/MJ, by feedstock type, with and without emission credits for manure and LUC for corn (considering the 2030 electricity mix).

Feedstock type	w/o credits & LUC			with credits & LUC		
	Grid	CNG	LNG	Grid	CNG	LNG
Wet manure	4.7	5.2	6.2	−107.2	−106.7	−105.7
Corn	22.0	22.5	23.4	43.0	43.5	44.4
Low scenario mix	9.2	9.7	10.6	−41.8	−41.3	−40.4
Medium scenario mix	13.2	13.7	14.7	−7.1	−6.6	−5.7
High scenario mix	11.7	12.2	13.1	−20.7	−20.2	−19.3

Table 4
Emissions savings of biomethane compared to fossil natural gas, with and without emission credits for manure and LUC for corn (considering the 2030 electricity mix).

Feedstock type	w/o credits & LUC			with credits & LUC		
	Grid	CNG	LNG	Grid	CNG	LNG
Wet manure	93%	93%	91%	256%	250%	246%
Corn	68%	68%	68%	37%	39%	39%
Low scenario mix	87%	86%	85%	161%	158%	156%
Medium scenario mix	81%	81%	80%	110%	109%	108%
High scenario mix	83%	83%	82%	130%	128%	127%

and biomethane distribution solutions are compared. When considering these effects, the use of biomethane leads to negative net emissions for the three scenarios that we have considered, thanks to the beneficial effect of using a share of manure. This means that substituting existing fossil-based technologies with biomethane would lead to emission savings higher than 100%, in accordance with other studies in the literature [14,50,56].

3.2. Potential GHG emission savings

These emission factors can also be analyzed by comparing the average emissions of fossil gas, considering both its supply chain and its final combustion. Results are given in Table 4. The comparison is based on emission factors for fossil natural gas, considering 68.8 g_{CO2e}/MJ, 71.2 g_{CO2e}/MJ and 72.6 g_{CO2e}/MJ for grid natural gas, CNG and LNG respectively. These values have been obtained from median figures for different pathways presented in the JEC study [34].

However, while these figures provide a comparison with the use of fossil natural gas, the estimation of actual emission savings for the different applications should be assessed by considering the alternative technologies that are in use (as explained in Section 2.4).

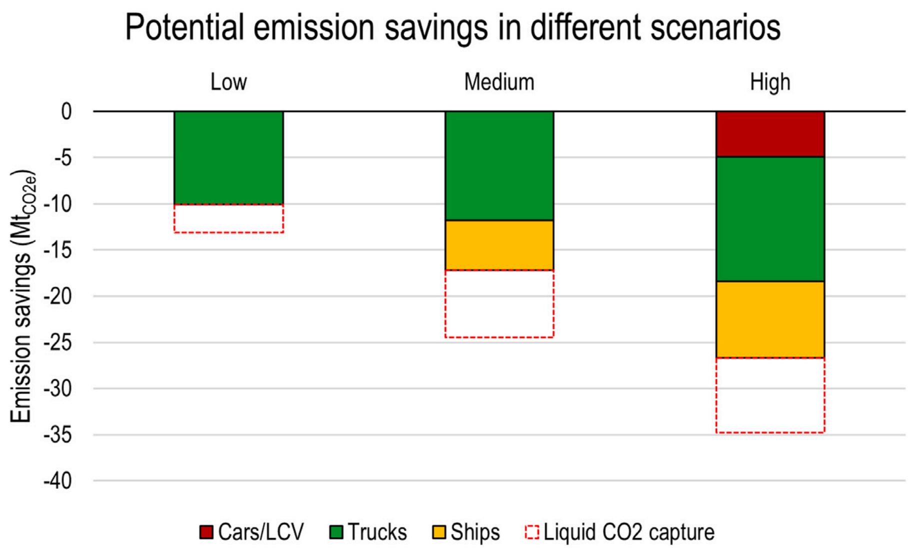

Fig. 3. Total potential emission savings by scenario and application (Mt$_{CO2e}$).

Table 5
Average emission savings per application and scenario, expressed in Mt$_{CO2e}$ per bcm of biomethane.

Mt$_{CO2e}$/bcm	Cars	Buses	Trucks	Ships
Low scenario	3.98	3.51	4.37	4.18
Medium scenario	2.80	2.33	3.19	3.00
High scenario	3.26	2.79	3.65	3.46
Additional CO_2 liquefaction	–	–	1.33	1.33

The emission savings are compared across the different applications by expressing them per unit of biomethane consumption, to evaluate the best allocation of the available resources. The specific emission savings reported in Table 5 are presented per scenario and per application. The variability across scenarios is caused by the different feedstock mixes that are used, while the emission savings for each application are calculated compared with the reference alternative technologies.

The results across scenarios show that the allocation of the available biomethane to long-haul road transport and to the maritime sector provides the highest benefits in terms of climate emissions savings per unit of biomethane consumed. These two applications are currently dominated by oil-based solutions, and they also have few alternative options for their decarbonization on the short and medium term.

Both these sectors have been analyzed considering the use of liquefied biomethane. Thus, the additional electricity consumption needed for biomethane liquefaction process compared to the other distribution strategies does not appear to have a significant impact on emission savings. Furthermore, the potential savings related to the use or storage of the liquefied CO_2 that could be recovered represent an additional aspect to be further investigated.

The emission benefits of using biomethane for private cars remain of interest, but they are lower compared to road freight and maritime applications. Also, biomethane use for urban buses appears to be the least interesting option, although these results are based on a limited number of literature references, and so they may rely on data that are less representative compared to the other applications considered in this work.

Although these results suggest prioritizing some applications over others due to higher emission savings, it is important to remember that there are also other aspects to be considered, including the availability of infrastructure, investment and operation costs, technological and economic maturity of each technology as well as regulatory issues. In particular, the economic dimension is strongly related to biomethane production costs against traditional options, that are generally higher based on recent studies in the literature [14,35,57]. However, in a decarbonization perspective, an economic comparison against fossil fuels should also include the contribution of CO_2 emissions savings by considering a relevant carbon price that is in line with the policies and programs in place in different countries around the world. When considering a high carbon price, the solutions with higher emission savings may also result in a better economic competitiveness.

The allocation logic chosen for the scenarios, whose results are presented in the next section, is based on the merit order of emission savings that emerges from these results, limited to a maximum level that corresponds to the estimated demand of natural gas in each application (to account for the infrastructure expansion limitations in the short-medium term). This choice is related to the 2030 time frame considered in the analysis, and for long-term scenarios the distribution of available resources across sectors may significantly differ. A multi-objective optimization accounting for the implementation costs of the different applications is beyond the scope of this work.

3.3. *Comparison of scenarios*

The specific emission savings presented in Table 5 can be used to allocate biomethane use to the most promising sectors, and to estimate the total potential emission savings at a national level, based on the scenario assumptions discussed in Section 2.4. A comparison of the potential savings is reported in Fig. 3.

The analysis shows that total emission savings associated to biomethane use in Italy could range from 10.0 to 26.7 Mt$_{CO2e}$, depending on the scenario. In the Medium and High scenarios, the largest benefits come from biomethane uses for road freight transport (11.8 Mt and 13.5 Mt respectively), which is also the segment with the highest biomethane consumption. In the Low Scenario, which assumes a lower development of biomethane supply chain, all the savings come from the bioLNG use in trucks, since it represents the best application and the total available biomethane is lower than the estimated potential use in trucks.

These results show that biomethane could play an important role in the decarbonization of the Italian energy system, although with some differences across scenarios. These emission savings should be evaluated taking into account that in 2019 total transport emissions in Italy reached 105 Mt$_{CO2e}$, and expected total emission savings in Italy by 2030 sum up to 128 Mt$_{CO2e}$ (compared to 2019 levels, data from [52]). In this perspective, biomethane can complement the direct electrification of some transport segments, such as light passenger

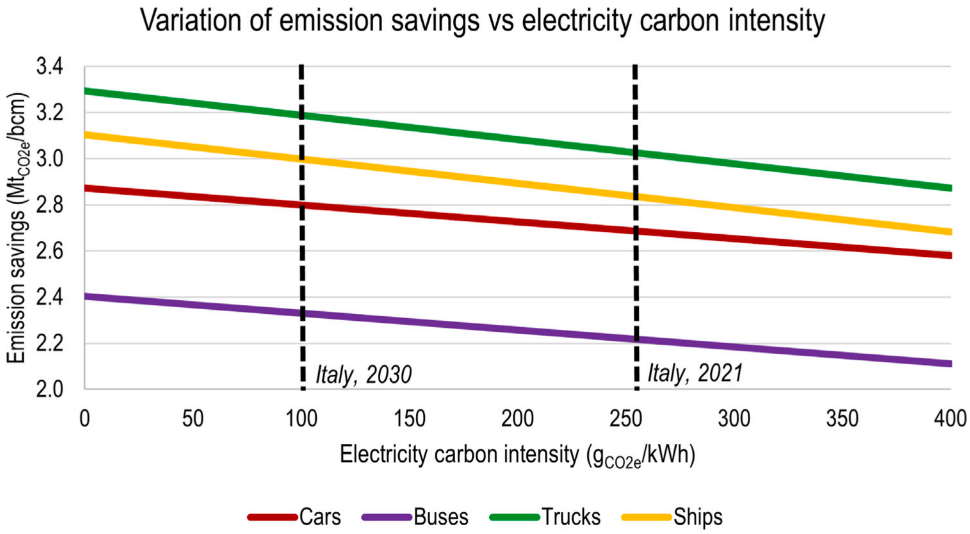

Fig. 4. Variation of emission savings vs. electricity carbon intensity for different transport modes, Medium Scenario.

transport and rail, as our results confirmed its beneficial potential in some hard-to-abate applications such as long-distance road freight and shipping.

An additional 3.1–8.1 Mt_{CO2} could be recovered by integrating liquefied biomethane production and CO_2 liquefaction, although this carbon dioxide stream should find a suitable application or storage, in addition to the required collection and distribution systems. Existing literature [58] confirms that this option is cost-effective compared to other upgrading techniques, thanks to a very competitive investment cost against other options. The selling price of the recovered liquid CO_2, either for industrial applications or for transport to permanent storage sites, is an important factor in evaluating the economic competitiveness.

3.4. Sensitivity analysis

In the sensitivity analysis, we evaluated the effects of the variation of electricity carbon intensity, the private cars powertrains and the methane emissions in different transport segments. The sensitivity analysis is carried out by considering the assumptions adopted for the Medium Scenario. Similar findings apply to the other scenarios.

Fig. 4 shows the variation of the emission savings we estimated for each billion of cubic meters of biomethane used in different transport segments, compared to the variation of the electricity carbon intensity. The lower the electricity carbon intensity, the higher the savings, due to the fact that the supply chain of biomethane decreases the share of upstream emissions that are associated with electricity use in the different processes. All the trends showed in the plot are linear, with slightly different slopes due to the various contribution of electricity emissions across the transport segments.

The importance of the electricity mix in the emission savings of biomethane is in accordance with other studies in the literature. Gustafsson and Svensson [14] evaluated the climate impacts of different biomethane pathways by accounting for the variable electricity mix across four European countries (Italy, Sweden, Germany and the UK). Their results highlight how the electricity mix is crucial in the assessment of biomethane emission savings, as electricity consumption in biomethane pathways is higher compared to other fuels.

In our comparison, we assumed that the emissions of the alternative options remain constant, since these are mostly associated to TTW emissions. The weight of WTT fossil fuels emissions is limited, and since electricity consumption emissions account for a limited share, this effect has been neglected. The only exception is represented by cars, since the biomethane emission savings compared to electric vehicles decrease for lower electricity carbon intensity. However, since electric vehicles in Italy still represent a limited share of the total expected vehicle stock in 2030 (around 7% of total vkms for BEVs and 4% for PHEVs), this effect is hardly noticeable in this chart.

However, this effect can be analyzed by a specific sensitivity simulation based on the different powertrains for private cars. In our analysis we evaluate the savings of biomethane application in private cars against the average fleet, but a comparison can be also assessed considering the single alternative technologies. The variation of emission savings of biomethane against each powertain is reported in Fig. 5. This chart clearly shows the positive slopes of battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs) compared to the negative slopes for cars using fossil fuels. The lower the electricity carbon intensity, the lower the advantages of biomethane compared to electric alternatives (although they remain positive in each situation). These figures are only considering WTW emissions, which means that no emissions related to manufacturing and disposal phases are estimated by means of a Life Cycle Assessment approach.

The results from this analysis show that biomethane remains competitive with electric cars also with very low electricity carbon intensities, mostly thanks to the benefits related to the valorization of manure compared to alternative disposal practices, leading to negative net emissions for the reasons discussed above (these figures are related to the Medium Scenario). However, as already discussed, although these benefits remain positive they are clearly much lower compared to other transport segments. Thus, biomethane is not seen as an alternative to electrification but rather as a complement for the applications that are not technically or economically easy to electrify. In addition to the environmental benefits, other factors may prove crucial in determining the success of a solution over another, and in particular the total cost of ownership that is in part related to the price of electricity and biomethane for the users.

A final sensitivity analysis was carried out as regards the methane fugitive losses due the combustion process taking place in the engine, which represent an issue due to the high global warming potential of methane. The analysis is limited to the methane leakage in transport vehicles, with the aim of comparing this specific effect. Thus, the leakage rates in the other parts of the supply chain remain constant at their estimated level.

Fig. 6 shows the effect of a reduction of methane leakage rates compared to the standard value assumed for each transport mode, up to a virtually maximum level of 100% reduction (which will be hardly

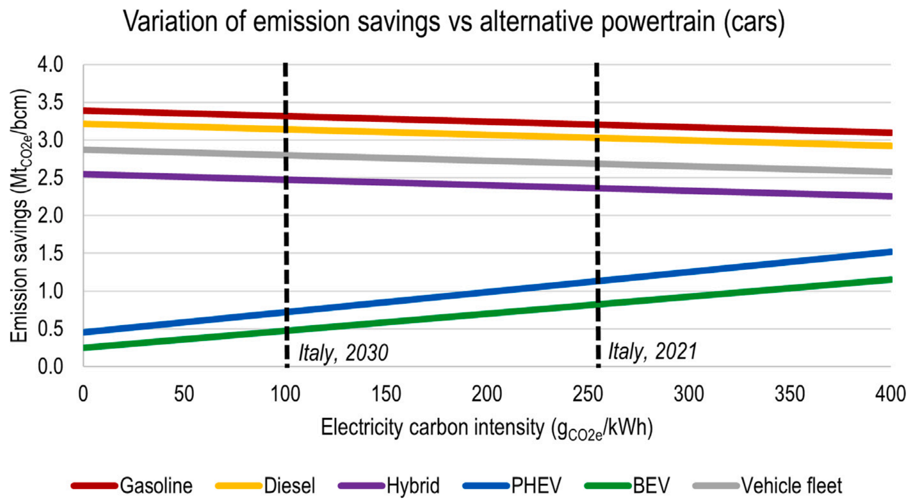

Fig. 5. Variation of emission savings vs. electricity carbon intensity for different private cars technologies, Medium Scenario.

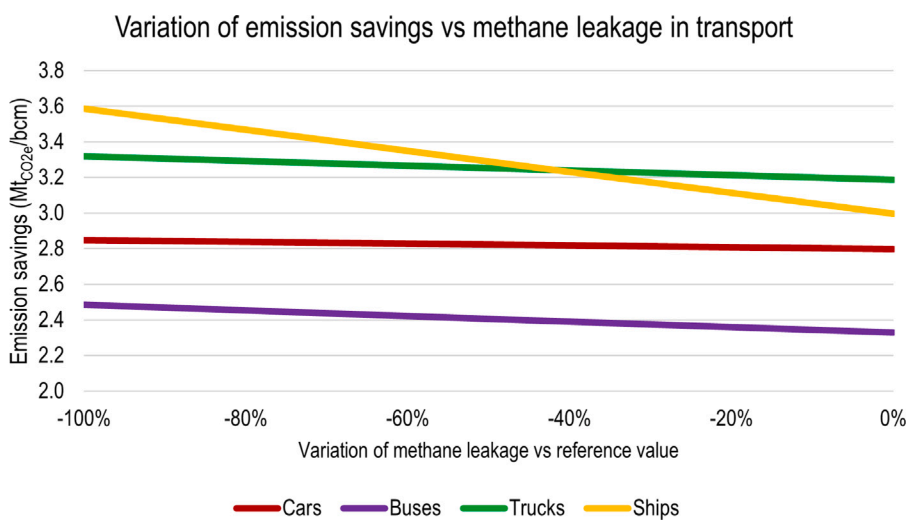

Fig. 6. Variation of emission savings vs. methane leakage rates compared to the reference value in different transport modes, Medium Scenario.

reached, but represents the optimal level). The results of the sensitivity analysis show a limited effect on the total savings but for shipping, where methane losses currently represent a possible potential limitation to emission savings from liquefied biomethane.

While a total abatement of methane losses in shipping appears rather difficult with the current technology, the analysis shows that efforts in limiting leakage rates would bring important gains to the performance of biomethane. Researchers have recently found a promising catalyst that would allow for an important reduction of methane slip in natural gas powered engines through its post-combustion oxidation [54].

4. Discussion and policy recommendations

The results of this research work highlight the potential contribution of biomethane in decreasing climate emissions in Italy by exploiting available local renewable resources. The allocation of biomethane to the transportation sector is in line with the current National and European strategies, representing one of the most sustainable alternatives in the short term, especially in hard-to-electrify segments.

Nevertheless, as regards transportation, internal combustion engines in passenger cars are expected to gradually disappear on the long-term, as the European legislation towards net-zero emission currently aims at banning the sale of new ICE cars by 2035. However, given the average replacement rate of the vehicle fleet in Italy, this would lead to a fully electrified private car fleet by 2045–2050, i.e. well beyond the 2035 timeframe. In this time horizon, which is longer than the one considered in our analysis, the available biomethane resources could be shifted towards other hard-to-abate applications, such as shipping, power-generation and possibly some long-haul freight transportation (also depending on EU rules that will be discussed for the sector).

In addition to the advantages related to climate emissions, when biomethane replaces current cars based on fossil oil products, it also brings advantages in terms of local pollutants, which are an important issue in many Italian cities, especially in urban areas of Northern Italy. The availability of cleaner vehicles, both for private cars and urban buses, contributes to the improvement of air quality in densely populated areas. Biomethane would be particularly beneficial for reducing particulate matter emissions compared to diesel vehicles, although also nitrogen oxides emissions are decreased [45].

While this work is focused on the transport sector, it is important to acknowledge that biomethane could also provide advantages in the power generation sector. The Italian power system is currently relying on natural gas for an important part of its annual generation, and although this share is expected to gradually decrease in favor of renewables, high-efficiency gas plants could be exploited to compensate for the variability of solar and wind energy and thus balancing the electrical grid, possibly exploiting biomethane instead of fossil gas.

Also, biomethane could benefit from the existing seasonal storage systems for fossil gas, which have today a capacity of almost 17 bcm [59]. On the longer term, biomethane could also contribute to other applications that cannot be electrified, such as buildings heating in some specific cases or industrial applications at high temperatures, where hydrogen may also represent an alternative. Technological and economic considerations will likely drive the choice of the best solution in these cases.

Biomethane production via anaerobic digestion is a mature technology that can exploit a local resource with limited climate emissions, which in some cases become even negative when produced from a feedstock mix including animal manure. Moreover, its production often valorize organic wastes and residues, resources that would hardly find alternative useful applications and that would generate GHG emissions if untreated. This is an additional aspect in a country that also heavily depends on energy imports today, with additional benefits in terms of energy security. A part of the resources that will be used to produce biomethane are currently in use for electricity generation from biogas (around 8 TWh in 2022, see Table 1). For this reason, it is important to ensure that other renewable sources, including solar and wind, are deployed to compensate for this shift.

As partially addressed in the study, an additional amount of carbon emission savings could derive from liquefying carbon dioxide from biomethane upgrading. This carbon stream represents an important resource, although an effective collection, distribution and use of this stream would require a specific attention and viable final uses. While liquid carbon dioxide could today be used in some applications in substitution of resources obtained from fossil fuels (e.g. food industry, refrigeration), these markets remain limited and may be easily saturated. An effective and profitable use of these resources could represent an additional important benefit of the biomethane supply chain. On the other hand, the availability of a continuous stream of concentrated CO_2 from biomethane separation from biogas could be a perfect feed for synthetic fuels (eFuels) generation all year round, given their potential interest for the aviation sector.

On the long-term, other technologies may emerge for the production or upgrade of biomethane, such as thermal gasification or biomethane pyrolysis for hydrogen production. Since these technologies are currently under development and unproved at commercial scale, they have not been considered in the time horizon of the analysis. However, on the long term they may prove to be game changers in the global supply chain of biomethane, unlocking additional potential applications.

An estimation of the costs of the different technologies considered in this study is beyond the scope of the analysis, and will be performed in a future work. However, there are already many studies in literature that confirm that biomethane applications are competitive with other low-carbon alternatives in a range of sectors [10,19,37,57]. Still, it is important to remark that economic sustainability is an essential aspect for any low-carbon alternative to succeed. At the same time, several parameters affect the economics of biomethane applications, both in the final uses and along the supply chain. In addition to CAPEX and OPEX, incentives and taxation at the national level are often crucial in supporting any new technology. Other external factors also matter, including carbon pricing, the cost of other energy sources and alternative transport technologies, and the development of the infrastructure. Thus, the policy strategies that will be implemented will be crucial in determining which of the scenarios considered in this study is more likely to happen.

Available studies for Italy provide some information on the biomethane production costs. The results presented by D'Adamo et al. [19] to a range of production cost between 0.54 and 0.78 €/m^3, depending on the size of the plant. Rotunno et al. [60] analyze a biomethane plant of 120 Sm^3/h, calculating a biomethane production cost of 0.54 €/Sm^3 when injecting biomethane into the natural gas grid, and 0.73 €/Sm^3 when compressing it for transport applications. Their sensitivity analysis also confirm a decrease of the cost with increasing capacity: raising the plant output to 250 Sm^3/h, decreases the production cost by 17% for grid injection and 23% for CNG for transport.

These figures show that production costs are higher than the average market price of natural gas in Italy in the last years (before the huge price rise following the invasion of Ukraine in 2022). Thus, without incentives biomethane was less competitive than fossil gas, as also confirmed by the analysis presented by Barbera et al. [35]. However, there are two main elements to be considered. Biomethane costs do not show the high volatility of natural gas prices, as demonstrated in 2022 in most European countries (where available biomethane was often cheaper than fossil gas). Moreover, the economic comparison with natural gas in a decarbonization perspective should also consider the carbon neutrality of biomethane: in a future energy system with carbon prices the emission savings could also impact significantly this comparison.

In addition, the selection of financing sources and investment partners is pivotal for any successful financing procedure. The biomethane plant developers must take into account also the preliminary economic feasibility analysis, the agreements regarding feedstock supply and digestate take-off with local players and permitting procedures during the development phase, as crucial steps to attract the attention of the financiers [61]. Finally, a stable legal and political framework at the country level can strongly affect the biomethane market uptake and biomethane investments. Best practices already established in countries with mature biomethane market, as the Italian case, should be spread in other countries, in terms of technological, regulatory and financing know-how. Additional efforts must be established to set a common European market to support the bio-methane cross-border trade.

Adequate supporting measures are also essential to stimulate market growth, by leveraging on the value of avoided carbon emissions. The new incentives in Italy are expected to boost biomethane production, although the recent results of the first auction are below the expectation. The limited awarded capacity may be due to a low interest from investors driven by excessive bureaucracy, potential uncertainties related to the narrow time schedule, and possibly low economic incentives for some feedstocks and applications. Thus, policy makers could take into account these outcomes and adapt the support schemes and incentives to the real conditions of the industry to ensure the desired response from investors.

With regard to methane losses, which is an important aspect of decarbonization strategies, this study considered average figures for the different stages of the supply chain, based on the best available technologies and the current approach defined in regulations. To fully guarantee the potential of biomethane in reducing climate emissions, it is of utmost importance to keep methane emissions to the lowest possible level, by ensuring the application of best practices in the different supply, distribution and use steps [62].

It is important to remark that the results of this study obviously refer to some assumptions. A limited number of feedstock groups have been considered for simplicity, and depending on the material and the size of the plant actual emissions may show a higher range of variability compared to the figures used in the analysis. The same applies to the average efficiency that has been considered for all the steps of the supply chain, which in some cases may also improve in the future for some technologies. Also, average distances have been considered to account for the impact of transporting feedstocks and biomethane, but the actual geographical distribution of production sites will be another aspect to be addressed in a specific study for a reliable account of its impact on the total emissions.

Finally, the results of this work are based on a medium-term analysis, considering a 2030 time horizon, but the best allocation of biomethane to different transport segments is likely to evolve in the future, based on the penetration of other low-carbon technologies, notably the electrification of light transport. The success of biomethane in specific applications, such as shipping, will also need to be supported by a proper distribution infrastructure, whose deployment will likely require more time. Thus, National strategies and policies may need to adapt to the context and provide adequate incentives to support the best use of biomethane depending on the quantification of actual benefits in terms of emission savings and other relevant indicators.

5. Conclusions

This study presents an analysis of the main aspects related to biomethane potential uses in Italy, with a specific focus on transport, which is the main sector currently targeted by national strategies and incentives schemes.

Our analysis demonstrated that biomethane can represent a very interesting decarbonization option to complement direct electrification in transport, especially when supported by the availability of low-carbon electricity over its supply chain. Each bcm of biomethane can lead to up to 4.37 Mt_{CO2e} of emission savings, depending on the feedstock mix and the application. On a national level, this means a total reduction of 10.0–26.7 Mt_{CO2e} by 2030 in our scenarios. The choice of the feedstock type, the agricultural model, and the control and limitation of methane emissions also represent important aspects that need to be addressed to maximize GHG emission savings. The recovery of the CO_2 stream that is captured in the upgrading process can lead to 3.1–8.1 Mt_{CO2e} of additional savings, provided that it can be stored or used as a substitute of fossil CO_2 in existing applications.

While the main reason driving the development biomethane is currently the possibility of supporting the energy system decarbonization, other benefits should also be considered. Those benefits include lower pollutant emissions in road transport compared to existing technologies, the development of a local resource that will decrease dependence on fossil fuels import (which remains a critical issue in Italy), the useful exploitation of wastes or crops that are cultivated on unused land, the valorization of the agricultural sector and its diversification by means of additional revenues from a new value chain.

The economic dimension of biomethane development remains a critical issue, and further research is needed to evaluate the main barriers and opportunities. The economic sustainability of the supply chain is a complex evaluation, which is beyond the scope of this study. However, although current biomethane applications mostly rely on support schemes, some studies highlight biomethane as a competitive technology in some sectors compared to other low-carbon options.

The results that are presented for Italy can be also extended to other countries, accounting for different feedstock mixes and electricity intensities, although the best use of biomethane may depend on the available infrastructure and the possibility of substituting existing applications that currently use fossil natural gas. International cooperation may be required for the successful implementation of biomethane use in shipping and long-haul road transport (especially in Europe, due to the large share of international road freight transport). Since some transport applications are already investing in fossil LNG as a transition solution, biomethane could complement these efforts by providing a low-carbon option to exploit existing technologies and avoid investing in potential stranded assets.

Supporting mechanisms and policies should incorporate the evaluation of emission benefits in specific transport segments, to foster the allocation of the available biomethane to the best applications in terms of climate impacts. Although existing incentives require a minimum level of emissions savings compared to fossil-based technologies, they do not encourage firms to improve this indicator. Future research is also needed to confirm the actual benefits in different applications, by means of actual monitoring data of real case studies that can provide independent evidence in support of policy decisions.

CRediT authorship contribution statement

Michel Noussan: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Viviana Negro:** Writing – review & editing, Writing – original draft, Visualization, Formal analysis, Conceptualization. **Matteo Prussi:** Writing – review & editing, Writing – original draft, Conceptualization. **David Chiaramonti:** Writing – review & editing, Writing – original draft, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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