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Well-to-wheel greenhouse gas emissions comparison of electricity and biomethane urban buses

Michel Noussan [a,b], Lorenzo Laveneziana [a], Matteo Prussi [a,*], David Chiaramonti [a]

[a] Department of Energy, Politecnico di Torino, Torino, Italy
[b] Paris School of International Affairs, SciencesPo, Paris, France

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ABSTRACT

Public transport can represent an important solution to reduce the greenhouse gas emissions of the transport sector, even more when relying on low-carbon powertrains. Compared with other public transport modes that are already mostly electrified, buses still rely on oil products in many cities around the world. This work analyses two promising alternative options for urban mobility, by evaluating the greenhouse gas emissions intensity of the supply chains of battery electric buses and biomethane-powered internal combustion engines. In addition to general results, the analysis also presents a focus on each EU country, to highlight the potential variability related to different operating conditions. The outcome of the study confirms that interesting emissions savings can be achieved through the substitution of diesel buses with these low-carbon alternatives. The level of emissions savings depends on the source of electricity generation and the feedstock used to produce biomethane. A bus fleet composed by half electricity and half biomethane buses could lead to savings between 70%–125% depending on the country (figures higher than 100% can be obtained thanks to negative emissions associated to biomethane production from some feedstocks). These results can support decision makers working on strategies to reduce emissions of urban transport modes, as they confirm the interesting opportunity represented by these technologies compared to the current situation, and even more when considering them against the use of private cars in urban environments.

1. Introduction

Public transport is among the most promising solutions to decrease energy consumption and emissions for passenger mobility, especially in medium and large urban areas [1,2]. Many cities worldwide have developed plans and strategies to improve the offer of public transport solutions and infrastructure for their citizens, aiming at addressing multiple issues including local air pollution, congestion, space use in cities and impact on global warming. To further improve the positive effect on greenhouse gas (GHG) emissions, it is of paramount importance to shift towards technologies that are not relying on fossil fuels. However, although some specific public transport modes have always been electrified, including rail, subway and trolleybuses, a large number of urban and extra-urban buses are still operating on diesel, with negative impacts in terms of both climate emissions and local pollutants. Low-carbon alternatives are being increasingly considered in many cities worldwide, in accordance with national and local decarbonization targets. Different solutions exist to decarbonize urban buses, including direct electrification [3,4], liquid and gaseous biofuels [5,6], or synthetic fuels [7].

This work will analyze two promising options that are increasingly being considered in many cities worldwide: battery electric vehicles (BEVs) and biomethane buses. The second option uses traditional buses powered by internal combustion engines (ICEs), in some cases exploiting the already existing bus fleets operating on compressed natural gas (CNG). The GHG emission savings attained through the replacement of conventional diesel-fueled buses with these two alternatives are analyzed and compared. The GHG emissions that are estimated encompass both the tailpipe emissions from the fuel in use (tank-to-wheel, TTW) and the upstream emissions associated with the phases of feedstocks provision, processing, transport and conditioning (well-to-tank, WTT). As the variety of pathways for the production of biomethane and the expected decarbonization of the electricity grid induce large uncertainties in the determination of WTT emission factors, the analysis considers the conditions in each EU country to evaluate the effect of different contexts.

* Corresponding author.
E-mail address: matteo.prussi@polito.it (M. Prussi).

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Nomenclature

BEV	battery electric vehicle
CNG	compressed natural gas
EEA	European Environment Agency
EU	European Union
GHG	greenhouse gas
GWP	global worming potential
ICE	internal combustion engine
IEA	International Energy Agency
JRC	Joint Research Center
LCA	Life Cycle Assessment
LNG	liquefied natural gas
LPG	liquefied petroleum gas
PHEV	plugin hybrid electric vehicle
TTW	tank-to-wheels
WTT	well-to-tank
WTW	well-to-wheels

1.1. Literature review

Many international studies highlight the beneficial impact of public transport compared to private cars, not only in terms of carbon emissions but also on multiple aspects related to human life in urban environments. Also, in terms of climate emissions, which are the focus of this work, the specific emission factors of public transport options often outperform those of private cars. This is especially true when considering the current average utilization rates of the different vehicles, as private cars are mostly being used by lone drivers, especially during the commuting trips, that represent in many cities the lion's share of mobility demand.

The potential carbon dioxide emission savings related to electric buses have been widely addressed in the literature in recent years. Some studies have focused on their comparison with other zero-emission solutions, like hydrogen [8], highlighting the better energy efficiency of BEVs. Other authors have compared GHG emissions and operational costs of electric buses with traditional diesel buses [9]. Some authors have also broadened the comparison, including traditional buses operating on diesel and natural gas and low-carbon alternatives such as electric and hydrogen buses [10]. These comparisons are often focused on economic and environmental performance, although some research has also investigated additional social impacts, aiming at a comprehensive social cost–benefit analysis [11].

Conversely, although fossil natural gas is often used for urban buses in its compressed form (CNG), and it is starting to gain momentum as liquefied natural gas (LNG), research on the potential benefits of biomethane buses are less diffused. Biomethane has been considered in the literature as a viable option in road transport, especially when analyzing private cars [12] and heavy-duty vehicles [13,14]. Regarding buses, some works focus on specific case studies, such as an application to couple the biomethane and hydrogen production from the wine industry with urban bus fleets in Brazil [15], or the possibility of producing biomethane from food waste to substitute diesel buses in Mexico [16].

Summarizing the existing literature, recent studies focus on electric buses, while in the past decades the attention was more on biomethane as a viable alternative fuel; of these, several focus on highly specific case studies, several focus on highly specific case studies, lacking breadth in terms of the variety of feedstocks considered. Moreover, to the authors' best knowledge, none of these studies has investigated the broad impact of biomethane use in buses at the country level. This paper aims to contribute filling the research gaps detected in literature. The analysis carried out in the work considers both biomethane- and electricity-powered buses, comparing a variety of electricity production as well as feedstock mixes for biomethane generation and the related greenhouse gas performance. Moreover, the investigated fuel mixes are based on 2030 scenario projections for European countries, enabling the broad assessment of these options at state-level.

2. Materials and methods

The study aims to assess the potential CO_{2e} emission reductions achievable through the use of biomethane and electric buses, using diesel-powered buses as the reference scenario. The proposed approach is Well-to-wheel (WTW), meaning that the evaluation estimates the energy use and related greenhouse gas (GHG) emissions associated with the entire fuel pathway and vehicle operation. It integrates two main components:

- Well-To-Tank (WTT): covers the energy and emissions involved in the production and distribution of the fuel, from primary energy sources to the vehicle's tank.
- Tank-To-Wheels (TTW): accounts for the energy use and emissions during the use phase of the fuel in the vehicle.

The WTW approach cannot be defined a full Life Cycle Assessment (LCA) as it does not include emissions from the construction of vehicles or fuel infrastructure, nor from end-of-life disposal. WTW focuses specifically on energy and GHG performance, excluding broader environmental impacts such as water usage or toxic emissions. The approach ensures a balanced comparisons among alternative solutions, focusing on the aspects related to the fuel production and utilization stages.

The impact of using a broader life cycle assessment (LCA) is qualitatively discussed in the specific section of the paper, as well as the potential for a quantitative analysis in a future work.

The main research question is focused on the most significant aspects that are responsible for the resulting emissions of biomethane and electricity supply chains that support alternative low-carbon options for public transport, focusing on buses.

2.1. Calculation methods

The estimation of the emissions related to the alternative fuel production and use phases are reported in terms of CO_{2e} per unit of fuel. The CO_{2e} equivalent allow considering the effect of other GHGs, such as methane and N_2O, potentially released in the value chain. The contribution of the non-CO_{2e} gasses are weighted by their own Global Warming Potential (GWP), as per the IPCC AR6 [17].

For the WTT part, and specifically for the biomethane case, the evaluation includes both pure biomethane and its blends with fossil natural gas under various levels of integration into the existing gas network. The potential benefits in terms of emission savings, related to the use of biomethane, is dependent from the feedstock used in the anaerobic digestion process. In order to capture the variability of biomethane emission factors, an extensive collection of literature data has been performed. In line with standard conventions, emissions resulting from the combustion of the biomethane are treated as carbon-neutral, due to the biogenic origin of the Carbon atoms constituting the molecule, as amply recognized in the scientific literature and by the European regulation [18–20]. It is also important to note that methane slip occurring during vehicle operation is not considered in this analysis, due to the present scarcity of data on this subject, while upstream methane leakage is incorporated within the WTT emission calculations. Similarly, a significant variability applies to battery electric vehicles (BEVs), with respect to the electricity generation. Emissions for electrical energy may vary depending on the national generation mix, the inclusion or exclusion of imports from other countries, the hour of the day, the day

Table 1
Main parameters used in the analysis.
Sources: [21,22].

Powertrain	Energy consumption (kWh/100 pkm)	WTT emissions (g_{CO2e}/kWh)	TTW emissions (g_{CO2e}/kWh)
Diesel	4.88	68	265
CNG (fossil)	8.22	41	202
CNG (biomethane)	8.22	variable	–
Battery electric	1.43	variable	–

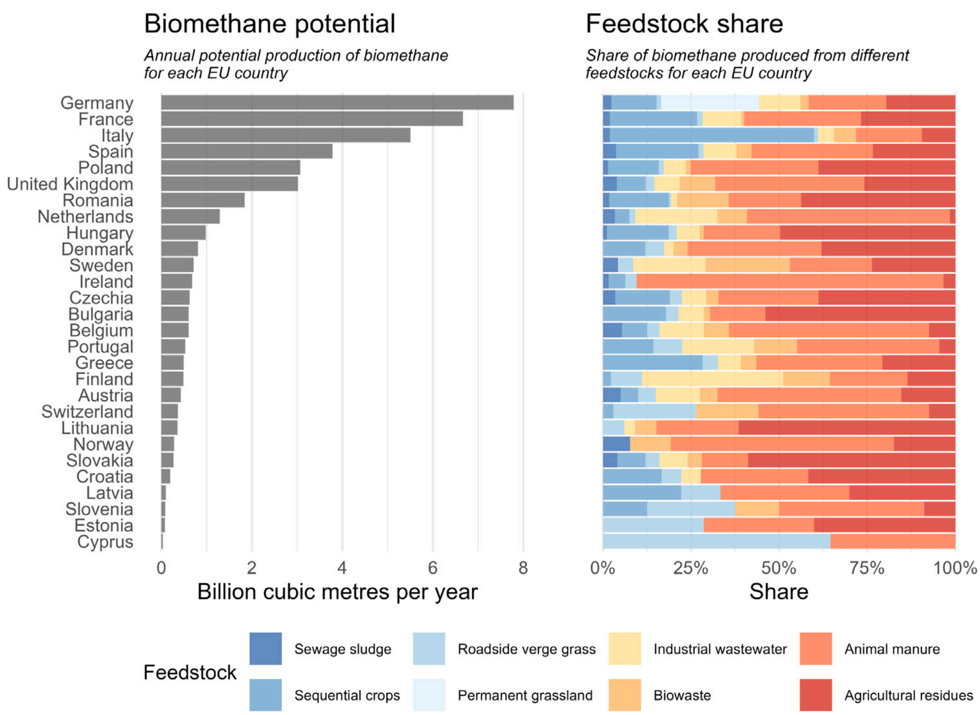


Fig. 1. Biomethane potential and feedstock mix for European countries. Source: Gas for Climate [23]. Countries ordered by biomethane potential.

of the year and the specific location. A specific sensitivity analysis is proposed, to compare the impact of different carbon intensity levels, on the environmental performances of the analyzed pathways.

In this study, in line with the vast majority of the scientific works on the topic, the comparison of the emission intensity of alternative fuels for buses is carried out on a WTW basis. Contrarily to broader LCA approaches, the scope of the WTW analysis exclude the *material* cycle involved in fuel production. In other words, it does not include the emissions contribution related to the construction of machinery, vehicles and other durable assets employed in the fuel production value chain (a category of emissions often referred as "embodied emissions" or infrastructure emissions). In agreement with this methodology, in this study the emission factors for grid electricity do not include the life cycle contributions related to the construction of power plants. Accordingly, the emission factors of biomethane exclude the life cycle contributions related to the construction of the biomethane plant. The same holds true for the emission factor of the reference fuel, diesel.

The adoption of a WTW approach rather than a full LCA study leads to the underestimation of the emission factors of fuels, as it excludes a portion of their life cycle. Nonetheless, the embodied emissions attributable to the plant construction phase are limited, for most fuel value chains, when compared to the emissions related to the consumption of energy and other non-durable materials. Moreover, the value of this study does not lie in the absolute numbers produced by the analysis but, rather, on the relative greenhouse gas performance of alternative fuel options. In this sense, the consistent adoption of a WTW approach for all fuel value chains enable a balanced comparison of the different value chains. It is however noted that some literature resources [24,25] provide estimations of upstream emissions, especially for electricity, for the current energy mix.

The emissions factors for the specific alternative fuel and energy carrier (i.e. electricity) are applied to the fuel consumption rate of the urban buses. The TTW consumption data are derived from studies using real data of current operating fleets. The approach is used to compare different powertrains, both based on fossil fuels (diesel and natural gas) and on low-carbon alternatives (biomethane and electricity).

2.2. Data sources

This assessment draws on actual fuel consumption data collected from a fleet of buses operating over a one year time-frame. It compares multiple electricity generation sources and biomethane production pathways to reflect the intrinsic variability of the problem. The data used to evaluate diesel, CNG, and electric buses originate from earlier research [21]. Table 1 provides the specific energy consumption figures and the emission factors used in the analysis, with values normalized to the buses' maximum passenger capacity (i.e., full load operation). The energy consumption is expressed per 100 passenger-km (pkm) of bus capacity. Since natural gas and biomethane have nearly identical chemical compositions, their fuel consumption rates are assumed to be equivalent. Well-to-tank (WTT) and tank-to-wheels (TTW) emission factors for diesel and fossil gas are sourced from a recent Joint Research Center (JRC) publication [22,37]. The methodologies used to determine the emission factors for biomethane and electricity are outlined in detail in subsequent sections.

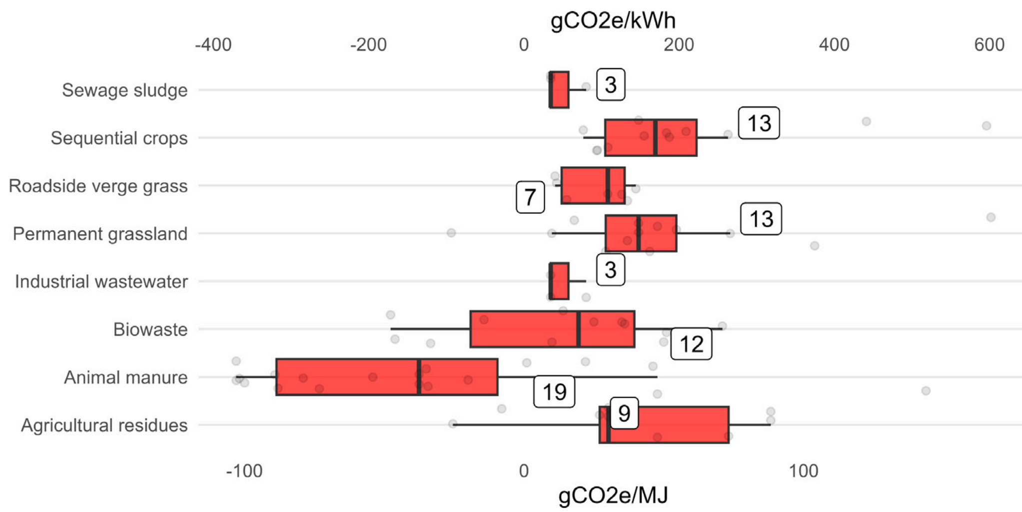


Fig. 2. Variability of biomethane WTT emission factors for each feedstock reported by the Gas for Climate report. Numbers in boxes show the number of literature sources available for each feedstock. Source: HANDY's database (main sources: [22,26–36]).

The previously described parameters serve as the basis for calculating the GHG emission intensity and associated savings of the various powertrain technologies, taking into account the variability in biomethane feedstock composition and electricity carbon intensity. Despite the analysis is tailored to reflect the specific conditions of individual EU countries, the proposed methodological approach aims to provide results that are adaptable to different contexts.

2.3. Biomethane country mix

As anticipated, European countries show substantial variation in both their biomethane production potential and the types of feedstocks used. To accurately reflect these differences in the calculation of country-specific average emission factors for biomethane, this study draws on the comprehensive 2022 report by Gas for Climate [23]. The feedstock composition and the related biomethane potential, as estimated in the report for 2030, are shown in Fig. 1.

Biomethane production potential varies significantly across countries, largely influenced by their geographical size. While there are commonalities in the feedstocks used — such as the widespread use of agricultural residues, manure, and sequential crops — distinct national characteristics and strategic choices lead to notable differences. For example, Germany exhibits extensive use of permanent grassland, Italy emphasizes sequential cropping, and Ireland relies heavily on manure as a primary feedstock.

2.4. Biomethane WTT emission factors

The biomethane WTT values were sourced from the in-house designed HANDY database, a tool for WTT assessment of biofuels value chains, introduced in [38]. The biomethane WTT emission factors are determined by the feedstock production pathway. Each entry in the database represents a fuel production pathway with an associated WTT and TTW emission factor. The production pathway is defined by the type of feedstock, the conversion process, the type of fuel produced and the underlying LCA assumptions. The HANDY database is sourced by the main lifecycle studies available in literature (i.e. [22,26–36], etc.). At present, the database accounts for more than 600 production pathways, with more than 50 related to biomethane. HANDY is a proprietary product of Politecnico di Torino; data are made available on request.

For each specific pathway, several Carbon Intesity (CI) values may be available: the distribution of available emission factors for each value-chain are shown in Fig. 2, purposely mapped to Gas for Climate's nomenclature. This variation is largely due to differing assumptions about production processes and methodological approaches used across literature sources. Excluding a few outliers, most reported emission values fall below 50 gCO_{2e}/MJ. When residual feedstocks like manure, agricultural residues and biowaste are used, negative emissions may be obtained. These negative emissions result from credits granted by several methodologies (e.g. REDII annex VI [35]) for avoided emissions associated with the untreated manures, etc. By contrast, the highest emissions are generally associated with cultivated feedstocks such as energy crops and grassland.

To support the analysis, an average emission factor for biomethane is proposed for each country, using the feedstock distribution detailed in the previous section. It should be noted that, in this calculation, all available data points for each feedstock category were treated with equal weight. This because the feedstock mixes scenarios developed by Gas For Climate do not provide detailed-enough information to differentiate alternative production pathways for the same feedstock. Future research is encouraged to explore the implications of feedstock-specific variability in greater detail.

2.5. Country gas grid emission factors

Emission factors for national gas grids in 2030 were estimated by considering the share of biomethane in the total gross available energy from gaseous fuels. Biomethane shares were calculated as the ratio between biomethane potential and the sum of biomethane potential and natural gas available energy. Country-level data on gross available energy from natural gas were derived from the MIX policy scenario, which underpins the European Commission's impact assessment in support of the European Green Deal [39]. The resulting gas grid-mix emission factor are the average of biomethane and natural gas, on the relative weighted shares. For fossil natural gas, a WTT emission factor of 41 gCO_{2e}/kWh (11.4 gCO_{2e}/MJ) is considered [22], in addition to the combustion emissions of 202 gCO_{2e}/kWh (56.1 gCO_{2e}/MJ).

2.6. Country electricity grid emission factors

The analysis incorporates projections for the carbon intensity of grid electricity in European countries by 2030.

For nations representing 97% of total electricity consumption, emission factors were obtained from EMBER's recent study [40], which evaluates the evolution of the European power sector based on National Energy and Climate Plans (NECPs). For the remaining countries not covered in EMBER's dataset, grid carbon intensity was estimated using

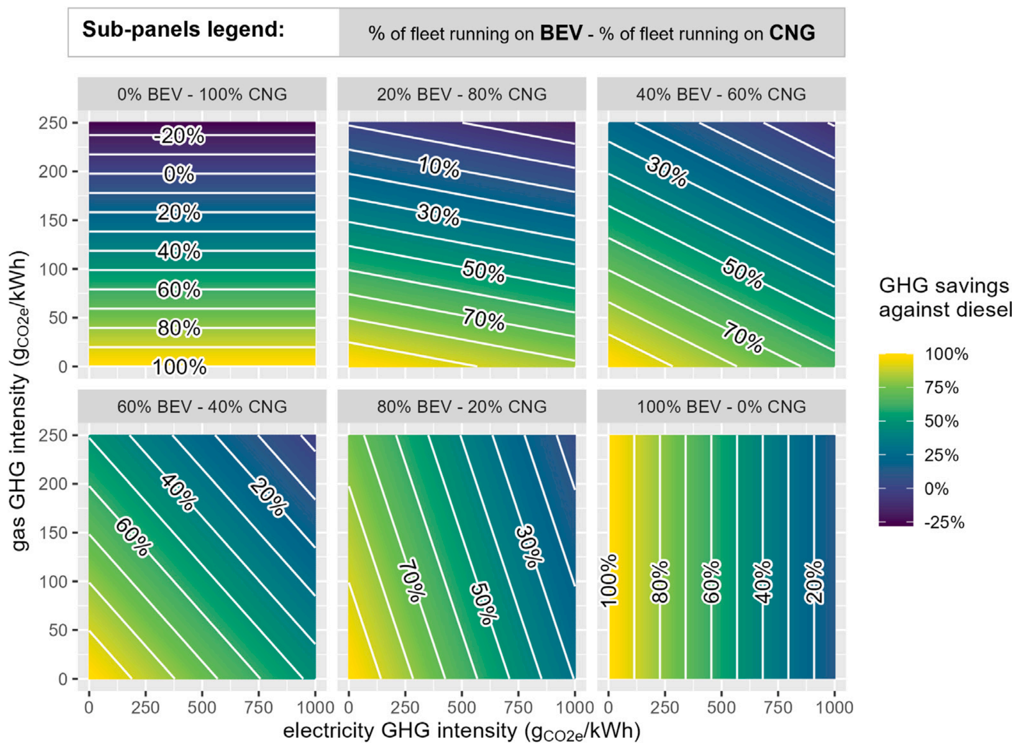


Fig. 3. Specific CO_{2e} emissions savings of electric and CNG buses against diesel buses, based on the fleet composition, and the GHG intensities of electricity and gas.

current emission levels, adjusted according to the EU-wide emissions reduction target for 2030, as outlined by the European Environment Agency (EEA) [41].

The country-level carbon intensity has been calculated in the cited study [40] by using standard emission factors for lignite (1000 g_{CO2}/kWh), hard coal (850 g_{CO2}/kWh), fossil gas (380 g_{CO2}/kWh) and other fossil fuels (650 g_{CO2}/kWh). It is important to remark that these standard values do not capture the full nuance of the range of power plant efficiencies at a country level, which is difficult to predict for 2030. Also, the authors point out that these emission levels do not include the upstream emissions released during the extraction and transportation of the fossil fuels before delivery to the power station. However, these contributions are strongly dependent on the country from which these fuels are imported and the distance and mode, which are hard to predict given the important variability seen in the last years.

Based on the results of the study [40], four countries (Germany, Poland, Italy and Czechia) will be responsible for around 70% of all the emissions from electricity generation in the EU. In relative terms, eight countries will still have more than 30% of electricity produced from fossil fuels, with Poland and Belgium having more than 50%. Most of the countries will have an important share of fossil gas power plants, but five of them will still have in 2030 more than 10% of their power generation relying on coal. The authors point out that these estimates are generally higher than the official EU projections, thus they may incorporate to a certain level an overestimation by national authorities.

3. Results

Based on the methodology described in the previous section, the following charts report the main quantitative results that can be used to compare the alternative powertrains that are considered in the analysis. The results are presented both in terms of general indications and with country-specific focus, that illustrates the potential variability related to different national contexts.

3.1. General results

A comparison of the CO_{2e} emission savings of low-carbon alternatives to diesel are represented in Fig. 3, where different fleets composed by CNG and electric buses are evaluated against diesel buses, considering various GHG intensity levels for electricity and gas supplied to the buses.

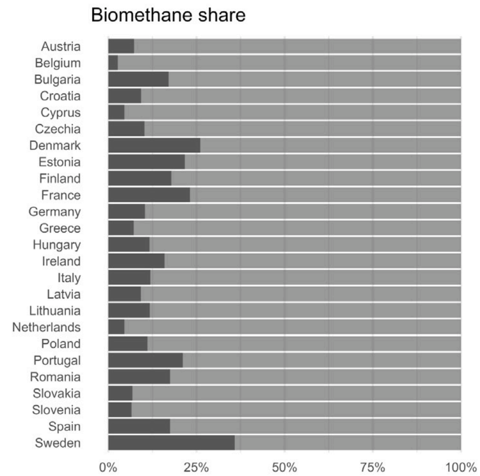
The results show the importance of the pathways used for the production of biomethane and the sources used for electricity generation, which are among the main aspects in driving the achievable emission savings compared to the traditional diesel solution. Both solutions show emissions that are on the WTT part, as TTW emissions are null for both technologies (as already mentioned in the methodology, biomethane TTW emissions are considered to be carbon neutral, and methane leakage in the vehicles are currently neglected).

It is important to remark that the figures illustrated in the previous charts have been limited to GHG intensity levels from 0 to 250 g_{CO2e}/kWh for gas and from 0 to 1000 g_{CO2e}/kWh for electricity. These ranges have been chosen based on the characteristics of the current and future scenarios in most of the cases considered, thus presenting charts that are relevant but also easily readable. However, it is important to remember that some specific feedstocks can allow for negative emission factors for biomethane, and the same could also be reached for electricity generation (e.g. using bioenergy with carbon capture and storage). Some of the following analyses will indeed present negative emission factors for biomethane, leading in some cases to emission savings larger than 100% compared to diesel buses.

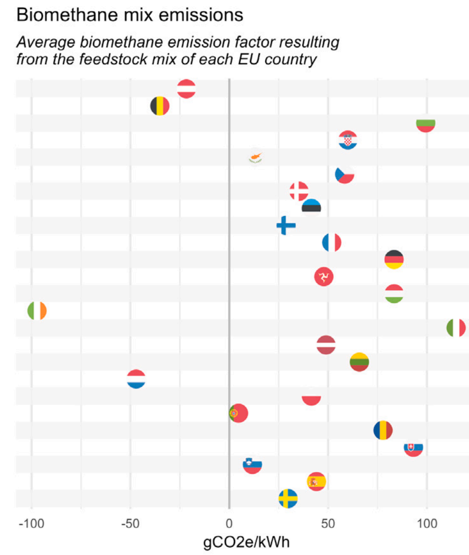
The following section presents an application of emission savings evaluation to the context of EU countries, to highlight the effect of variable local conditions.

3.2. Country-specific results

This section presents the results of the analysis conducted on specific country-mix emission factors of biomethane and grid electricity,



(a)



(b)

Fig. 4. Estimated biomethane share in gas demand (a) and average emission factor of biomethane mix (b) in 2030 for European countries. Biomethane share was calculated from Gas For Climates potential [23] and projected European gas demand [39]. Emission factors were derived from HANDY database.

as well as the positioning of countries with respect to the emissions savings maps introduced above, using 2030 as the year of analysis.

Fig. 4 characterizes the biomethane value chain for different countries. Sub- Fig. 4(a) shows the share of biomethane in countries' gas supply. Also exploiting the full biomethane potential reported by the Gas for Climate report, biomethane shares are around 10%, on average, and, with the exception of Sweden, never go above 25%.

Fig. 4(b) reports the emission factor of countries' biomethane mix. This demonstrates a high variability, heavily dependent on the different composition of feedstocks for biomethane production. Countries with high proportions of manure-based biomethane, like Ireland and Netherlands, achieve negative emission values (thanks to the additional effect of reducing methane emissions that would have happened in the disposal of manure). On the other side of the chart, countries relying more on cultivated feedstocks, among which Italy, Germany and Romania, show the highest emission factors, exceeding 75 gCO_{2e}/kWh. Most of the countries are found within the 25–75 gCO_{2e}/kWh band.

Figs. 5(a) and 5(b) respectively report on the estimated emissions intensity of the gas and electricity grid of European countries in 2030. Gas grid emissions in Fig. 5(a) were derived building on the biomethane shares and carbon intensity previously reported in Fig. 4. Due to the relatively limited proportion of biomethane, the emission factor of the gas mix is only slightly inferior to that of pure natural gas. Most of the countries present emission factors higher than 200 gCO_{2e}/kWh, although for some of them characterized by high biomethane penetration (Sweden) or particularly low biomethane emission factors (Ireland), the carbon intensity of the gas mix is found below this threshold.

Finally, Fig. 5(b) shows the projected carbon intensity of the electricity grid. This is quite variable, depending on the country mix, ranging from nearly 0 to around 600 gCO_{2e}/kWh. However, the majority of the countries it lays below 200 gCO_{2e}/kWh, with several of them reaching under 100 gCO_{2e}/kWh.

All these data are reported in detail in the supplementary materials of this paper.

The different levels of GHG intensity reported in the previous charts are associated to variable levels of emissions savings compared to diesel buses. Fig. 6 shows the achievable emission savings of different low-carbon bus fleets, with variable levels of BEV and CNG powertrains, across EU countries when using gas and electricity from the grid. These figures are representing the 2030 situation, based on the assumptions explained above.

The chart clearly illustrates that electric buses are on average able to provide higher emission savings compared to CNG buses. In fact, for the majority of countries a fleet that is only composed by CNG buses would lead to even higher emissions compared to diesel (due to the very low share of biomethane in the grid and the contribution of methane leakages in the upstream processes). On the other hand, for the majority of countries, a fleet that is composed of electric buses only can reach emission savings higher than 75% compared to diesel buses.

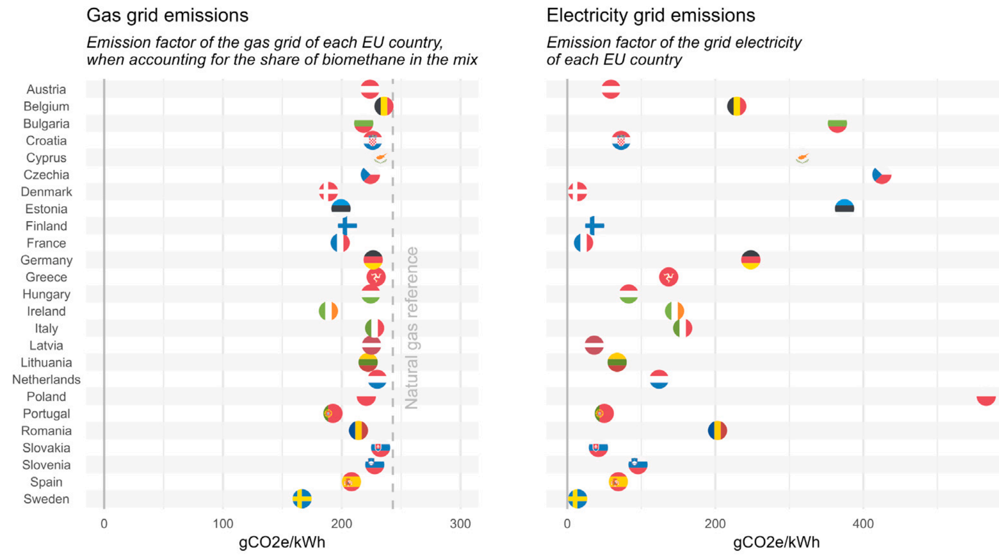
However, this analysis is only considering energy and emissions performance of the powertrains, without considering other technical and economic considerations. Due to the range limitations of the batteries and their charging times, not all the current diesel buses may be substituted by BEVs, unless schedules are modified or additional buses are added to the fleet. Also, economic considerations should be considered to evaluate the optimal fleet composition.

Different figures emerge when considering alternative powertrains coupled to biomethane or renewable electricity, as Fig. 7 clearly illustrate much higher emission savings. WTW emissions of BEVs that are fully supplied by renewable electricity are zero, thus leading to a 100% decrease of emissions compared to diesel buses for all the countries. Conversely, CNG buses supplied by biomethane lead to variable emission savings based on the feedstock mix of each country. For some countries with negative emission factors, emission savings can significantly exceed 100%, making it more convenient than BEVs coupled to renewable electricity. Still, median and EU-27 levels of emission savings for CNG bus fleets running on biomethane are around 80% and 70% respectively.

While this analysis provide some indication at the country level, it is important to remark that both electricity mixes and biomethane feedstock mixes have an additional variability at the local level, as each city can have peculiar conditions. Thus, the general results presented in Section 3.1 could be used to evaluate local conditions that differ from national levels.

4. Discussion

The main results of this paper highlight the average situation at the EU level, as well as for each country. However, it is important to note that these benefits may vary quite significantly from a city to another, as well as the crucial effect of the load factor of buses. A further aspect



(a) (b)

Fig. 5. Estimated emission factors of gas (a) and electricity (b) grid in 2030 for European countries. Gas grid emissions were calculated from biomethane-natural gas mix. Electricity emissions comes from EMBER's data [40].

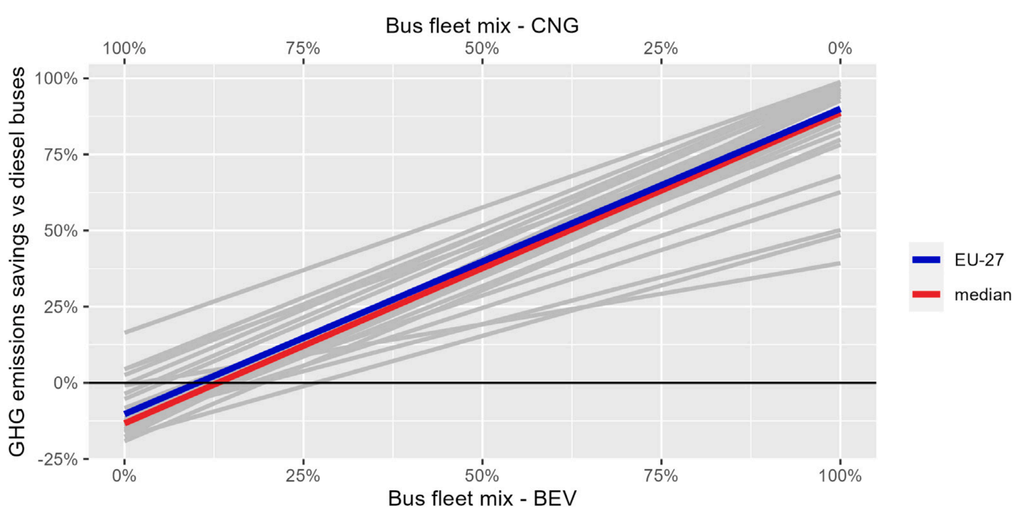


Fig. 6. Estimated GHG emissions savings of the bus fleet - average intensity levels of gas grid and electricity grid, results for single EU countries and EU-27 average level, 2030.

that is not accounted for in this paper is the comparison with private mobility, which is the main alternative to public transport and remains the preferred transport mode in many cities. Any policy that could shift trips from private cars towards public transport would further increase emissions savings.

When considering available resources, an important aspect that should be evaluated is also the interaction with other applications, given the limited availability of biomethane production feedstocks. A national analysis of the available potential and the possible applications in transport and other sectors, such as the one presented in [42], should be used to compare the potential benefits of different applications to allocate the available resources to the most appropriate solution for the reduction of GHG emissions. For this reason, future research needs to assess an integrated analysis of different sectors based on real performance data and a standardized comparison of achievable emission savings.

An additional point to be taken into account is the local availability of resources for biomethane production. An effective use of biomethane rely on minimizing the need for transporting it, or the feedstocks, over long distances. For this reason, trying to match the production and consumption by considering neighboring areas would decrease the need for additional energy consumption for its transportation. This would also offer the opportunity to exploit local synergies between the urban and suburban transport in the cities and the agricultural activities in the countryside, fostering the relationship between the city and the surrounding communities.

A similar aspect should also be considered for electricity, although in this case the geographical proximity is less critical. Conversely, the electricity charging profiles over time should be matched as closely as possible with the electricity generation from renewable sources, as this would ensure that electricity supply for electric buses would not lead to additional CO_2 emissions. This aspect promises to be of major importance and will be addressed in future studies, considering the operation of a real fleet of urban buses and alternative charging strategies.

This analysis is currently addressing urban buses, where these two low-carbon alternatives can compete with diesel buses. For intercity bus travel, the current fleet is totally dependent on diesel powertrains,

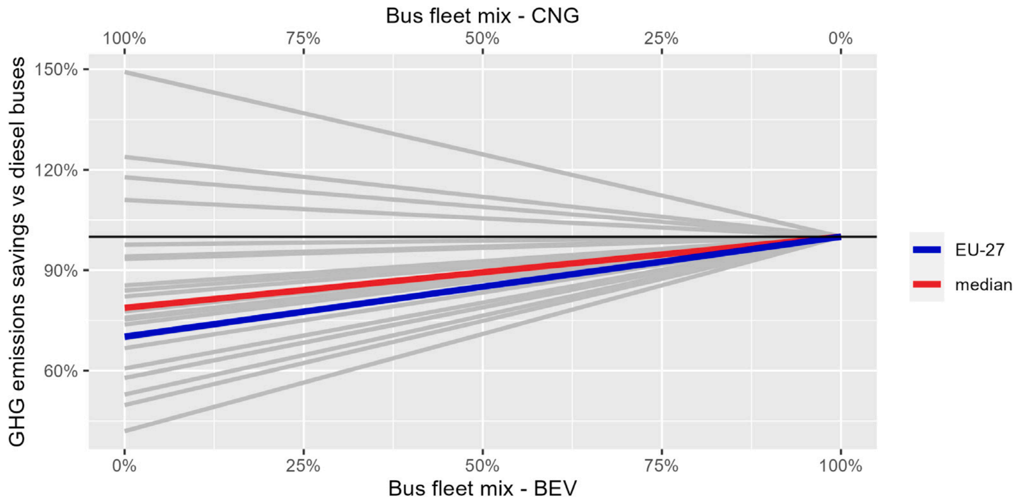


Fig. 7. Estimated GHG emissions savings of the bus fleet - renewable (or low-carbon) electricity and biomethane, results for single EU countries and EU-27 average level, 2030.

as BEVs are not yet providing suitable ranges and LNG buses for long distances are still at early stage. Nevertheless, some companies are already working on these options for the future, and the technology development may allow for a penetration of low-emission alternatives also for long-distance trips in the future.

This work has considered WTT and TTW emissions, thus reaching a WTW approach. A further step would be to incorporate the contribution of bus manufacturing and decommissioning, reaching a comprehensive LCA comparison. Nevertheless, such an analysis requires several assumptions and additional data on the actual use of the vehicles, their production, their average age and the estimated years of operation. However, electric bus manufacturing may be associated with non-negligible additional emissions, mainly related to the production and end-of-life treatment of the battery pack. Some recent studies report that the emissions related to battery manufacturing could represent between 10% and 20% of the lifetime emissions of electric bus operations [43,44], but these levels are strongly dependent on the electricity mixes of bus manufacturing and operation. In order to evaluate the impact of this aspect on the overall emission savings, a future improvement of this work will address this specific topic by adding the additional emissions related to electric bus manufacturing. This is expected to slightly decrease the emissions savings of electric buses compared to diesel buses, as is the case for passenger cars, while the relative comparison of biomethane and diesel powertrains and pathways should not be affected significantly.

5. Conclusions

This work presents an analysis of the potential CO_{2e} emission savings that can be obtained by shifting the current public transport based on diesel buses towards low-carbon alternatives such as biomethane or battery electric buses.

The results of this study, based on the real fuel consumption for a large bus fleet of diesel, CNG and electric vehicles, show that emission savings could reach significant levels compared to the diesel benchmark. The actual level of savings depend on the share of BEV and CNG buses in the fleet, but even more on the GHG intensity of the electricity and gas that are used to supply the buses, which depends on the mix of sources and feedstocks used for their production.

The analysis has also considered the expected figures of GHG intensity for EU-27 countries in 2030, based on the current strategies for the deployment of biomethane and renewable electricity in each country. A bus fleet composed by half BEV and half CNG buses could lead to savings between 13% and 55% compared to diesel buses, depending on the country. The very same fleet, when supplied with biomethane and renewable electricity, could lead to 70%–125% of savings. Figures higher than 100% can be obtained thanks to negative emissions associated to biomethane production from some feedstocks, whose use lead to additional upstream GHG savings that are incorporated into the final results.

The results of the country-level analysis also highlight that BEVs appear to have on average better performances than biomethane buses, due to the higher contribution of low-carbon sources in the electricity grid compared to the gas grid. In fact, biomethane availability is expected to be lower than renewables for power generation, thus its use may be allocated to specific sectors based on an integrated analysis of the economic system of a country or region.

These results confirm that the development of alternative powertrains in urban buses alone is not sufficient to maximize GHG emission savings. Thus, it is of utmost importance to ensure that electricity generation is increasingly obtained from low-carbon sources, and that the use of fossil gas can be gradually shifted towards biomethane.

Emissions are evaluated on a WTW perspective, thus encompassing both the tailpipe emissions and the emissions over the fuel pathways. However, a further expansion of this analysis will also incorporate the contribution of the LCA for bus fleets, as especially for BEVs the manufacturing of the vehicle is often associated with an important amount of climate emissions, although their depend on the specific assumptions that are considered.

The analysis also shows a large sensitivity of BEV emission savings to the carbon intensity of the electricity. This hints to the need to consider not only the future penetration of renewable electricity in the grid, but also the matching of renewable generation and bus charging patterns. Future analysis should thus address this critical aspect, together with the impact of fast-charging stations for buses on the stability of the electricity distribution grid.

As concerns biomethane, the influence of the feedstock mix on the emission savings is a relevant field of research, strongly linked to local biomass availability, that can also vary significantly within a country. Specific case studies should evaluate the synergies between agricultural activities and urban public transport, stressing the effect of local biomethane uptake with respect to long transportation distances.

CRediT authorship contribution statement

Michel Noussan: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Lorenzo Laveneziana:** Writing – review

& editing, Writing – original draft, Visualization, Software, Formal analysis, Data curation, Conceptualization. **Matteo Prussi:** Writing – review & editing, Supervision, Resources, Methodology, Conceptualization. **David Chiaramonti:** Writing – review & editing, Supervision, Methodology.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Matteo Prussi reports financial support was provided by European Union. This publication is part of the project NODES which has received funding from the MUR – M4C2 1.5 of PNRR funded by the European Union – 477 NextGenerationEU (Grant agreement no. ECS00000036). The other 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.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.ecmx.2025.101232.

Data availability

Most of the data used in this research is openly available from the cited references. The data developed in the HANDY tool, a proprietary product of Politecnico di Torino, are available on request.

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