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Biomethane as alternative fuel for the EU road sector: analysis of existing and planned infrastructure

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ABSTRACT

Biogas upgrading to biomethane is a feasible option for greening the European energy sector, and specifically transport. Bio-CNG and bio-LNG fuels are considered a valid solutions for freight, and the European biomethane sector displays an interesting production potential, supported by a growing demand. A key asset for sector deployment is represented by an appropriate refuelling infrastructure.

To promote alternative fuels in the EU, Member States have been adopting national policy frameworks (NPFs), setting targets for 2020–2030. This work aims to investigate how bottlenecks, such as infrastructure fragmentation, can hamper the diffusion of alternative fuels. The NPFs analysis reveals divergent countries' expectations for natural gas in transport, leading to a possible infrastructure fragmentation.

Pushing biomethane to decarbonise transport requires a careful assessment: while it can potentially reduce GHG emissions, it can also trigger fugitive emissions, e.g. through gas transport and combustion, thus compromising the advantages. Additionally, current high costs can restrain a larger diffusion of this alternative fuel.

This study highlights the need of a policy perspective aiming to target a synchronised deployment of CNG and LNG vehicles, related refuelling infrastructure and bio-CNG/LNG production. This is paramount to prevent the infrastructure from becoming a barrier to the development of biomethane, at least as in the short-to medium-term.

1. Introduction

Europe is investing in developing a more resilient and environmentally friendly energy infrastructure to support its energy transition. Diversification in energy sources is a pillar of the European Commission (EC) energy security strategy [1], due to the current strong dependence of the European Union (EU) on imports [2]. EU Member States (MSs) have been asked to develop diversification strategies at national level. Natural gas (NG) is a key player in the current energy market, and its demand is expected to gain market share in sectors otherwise difficult to decarbonise [3]. Nevertheless, NG per se will not necessarily reduce the EU's dependence on energy imports. What can potentially ease this dependence are bio-derived alternatives to NG, which can also support greenhouse gases (GHG) reduction in many economic sectors. Biomethane obtained by biogas upgrading is a potential option in this sense, able to displace both compressed natural gas (CNG) and liquefied natural gas (LNG) [4].

Biomethane, either compressed (bio-CNG) or liquefied (bio-LNG), can be produced through biogas upgrading or via gasification followed by synthesis. Once produced, biomethane offers the advantage to be injected into the existing and widely distributed EU gas grids. As an example, Italy has a well spread gas infrastructure/grid of more than 32,000 km [5] and numerous connections to other transnational grids. This kind of assets can clearly support biomethane penetration in several sectors. Social and social implications of these alternatives are reported in several studies (e.g. Refs. [6,7], representing foundamental elements to foster the development of this sector.

In order to be used for grid application or for transport [6], biomethane needs to meet quality specifications:

- the European standard EN 16723-1 for injection into the gas grid;
- EN 16723-2 listing the quality specifications for use in road transport.

Current production technologies allow for meeting these standards.

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List of abbreviations

AD	Anaerobic Digestion
AF	Alternative Fuels
AFI	Alternative Fuels Infrastructure
AFID	Alternative Fuels Infrastructure Directive
bcm	Billion Nm^3
CIC	Italian certificates used for biomethane incentive (*Certificati di Immissione in Consumo)*
CNG	Compressed Natural Gas
EC	European Commission
EU	European Union
GHG	Greenhouse Gases
HDV	Heavy-Duty Vehicles
HFO	Heavy Fuel Oil
HHV	Higher Heating Value
IMO	International Maritime Organization
JRC	Joint Research Centre
LNG	Liquefied Natural Gas
MSW	Municipal Solid Waste
NECP	National Energy and Climate Plans
NG	Natural Gas
NGVA	Natural and bio Gas Vehicle Association
NPF	National Policy Framework
PM	Particulate Matter
REDII	Renewable Energy Directive Recast
SNG TEN-T	Synthetic Natural Gas Trans-European Transport Network

Using biomethane in transport today is considered a mean to contribute to the target of reducing GHG emissions: for instance 6% reduction compared to a 2010 baseline, as set in the Fuel Quality Directive (2009/30/EC) [8]. Biogas, and biomethane in particular, represents an effective strategy to move towards the targets set in the renewable energy directive 2018/844/EC (REDII) [9]. As of July 2021, biogas will count towards the 32% renewable energy share from EU energy consumption and biomethane in transport fuels towards a sub-target of minimum 14% of the energy consumed in the transport sector, by 2030. Within the transport sub-target, 3.5% must in fact come from advanced biofuels produced from feedstocks listed in Part A of Annex IX from REDII that includes manure and sewage sludge, biowaste from households and industry, agriculture and forestry residues, algae and energy crops among others. Clearly, biogas technologies (with biomethane upgrade) are able to produce advance gaseous fuels from these feedstocks. Advanced biofuels will be double-counted towards both the 3.5% and the 14% sub-targets. Sustainability criteria for biofuels used in transport are defined by REDII - as well as for solid and gaseous biomass fuels used for power, heating and cooling sectors - and they must be fulfilled in order for biofuels and bioenergy to account for the above-mentioned targets.

In the road sector, CNG and LNG are the two technical solutions already in use, as they allow for a significant increase of vehicles operational ranges (Pääkkönen et al., 2019). It has to be noted that natural gas vehicles, as well as the refuelling infrastructure technologies, are compatible with renewable gas and therefore have the capability to accelerate the reduction of GHG emissions [10], with limited additional costs to the system.

The use of biomethane in the transport sector is not necessarily limited to the road segment: it is worth considering that natural gas use in the maritime and inland waterways sectors is rapidly gaining momentum [11]. According to EU statistics [12], European domestic shipping in 2017 accounted for 2% of the final energy consumption of the whole EU transport sector. Today this sector is supplied with heavy fuel oil (HFO): a fuel characterised by very high viscosity, high sulphur levels and extremely high GHG emissions. In addition to GHG emissions from navigation, the transport sector also contributes to local air pollution. The adoption of new regulations for fuel quality aim at reducing the sector's environmental impact: the United Nations' International Maritime Organization (IMO) stated that from 2020 the 0.50% m/m global sulphur limit [13] is expected to result in large changes in marine fuel markets. At the present stage, there are different options available that could be implemented to comply with new regulations. On the GHG side, a key challenge for shipping will be to decarbonise its activities: in 2018, IMO released its initial vision and strategy to reduce GHG emissions aiming to at least halve total GHG emissions from shipping by 2050, when compared to levels in 2008, while - at the same time - pursuing efforts towards phasing them out entirely [14] in the long term.

Despite the interest shown by several industrial key players and MSs, a shift towards a higher share of biomethane in transport is strongly affected by the real viability of being distributed, up to the final users. Infrastructure therefore appears to be a key asset to achieve a tangible penetration for any alternative fuel in transport. Several articles have addressed the relation between alternative fuels and infrastructure, an overview being provided in Ref. [15]. Different US alternative fuel vehicle programmes and corresponding legislative policies were investigated in Ref. [16] with the conclusion that for a fruitful development of alternative fuels in transport it is crucial to coordinate the deployment of vehicles and refuelling infrastructure. An interesting example was reported for California about policy interaction with the expanding natural gas infrastructure to promote renewable natural gas [17]. In Europe, Germany was selected as a case study for CNG to highlight how the lack of coordination between fleet and infrastructure development may lead to a poor penetration of alternative fuels [18]. Similar observations about vehicles and their related infrastructure can be found in the literature for other alternative fuels. In the case of electro-mobility, several studies assessed the optimal electric vehicles per publicly accessible recharging point ratio [19]. A study on the deployment strategies of EU Member States for recharging infrastructure was performed in Ref. [20].

In 2014, the Alternative Fuels Infrastructure Directive (AFID) (2014/94/EU) was adopted with the main goal to facilitate the transition to alternative fuels in the transport sector across the EU, and reduce the region's dependency on oil. AFID requires Member States to present strategies for market development of alternative fuels and their infrastructure, including common technical specification for recharging and refuelling stations and relevant consumer information on alternative fuels, such as a clear and sound price comparison methodology. More precisely, Member States had to develop and adopt National Policy Frameworks (NPFs), providing for minimum infrastructure coverage by 2020, 2025 and 2030, depending on fuel types, and to notify them to the EC by November 18, 2016. The AFID targeted alternative fuels requiring specific infrastructure, including recharging points for electric vehicles and refuelling points for natural gas (LNG and CNG) and hydrogen. The NPFs had to set clear long-term national targets and objectives for the deployment of the necessary infrastructure as well as stipulate adequate support measures for providing long-term policy certainty for market operators. The EC Joint Research Centre (JRC) has performed the assessment of the NPFs, and their coherence at Union level, as required by AFID itself [21]. Table 1 presents the requirements and the mandatory timeframe set by AFID that MSs had to consider in their NPF for the natural gas refuelling infrastructure.

The research question the paper aims to address is how bottlenecks, such as infrastructure fragmentation, could hamper the uptake of alternative fuels, in the EU transport sector. In this context, this paper

Table 1
Natural gas refuelling Infrastructure sufficiency requirements for road transport.

Year (mandatory)	Alternative Fuels	Objectives/Distance requirements
2020 2025 (TEN-T Core)	CNG for vehicles	At least every 150 km on TEN-T Core Network 1 CNG refuelling point per estimated 600 CNG vehicles
2025 (TEN-T Core)	LNG for vehicles	At least every 400 km on TEN-T Core Network

investigates the impacts of EU Member States' national plans for infrastructure deployment, focusing on CNG and LNG. By analysing and comparing targets set by the EU MSs, it has been possible to draw a realistic scenario for the uptake of natural gas in the European transport sector by 2030. Once a scenario is defined, it is fundamental that alternative fuels infrastructure is able to deliver low GHG solutions, to achieve the goal of transport decarbonisation: the work shows the potential for substituting fossil natural gas with bio-derived alternatives, in the EU transport sector.

2. Methodology and data sources

In order to draw a reliable picture of the current state of play for biomethane in Europe, it is fundamental to assess the production potential, the expected demand and possible missing links related to refuelling infrastructure (Fig. 1). To define the current production potential and estimate a figure for 2030, other technologies, besides biogas upgrading, can be taken into consideration. A recent review on the technology status [22] has been used as the main source of information.

The JRC developed a database of the most relevant biomethane initiatives in Europe, as presented in Prussi et al., [23]. This database comprises information obtained from various sources, such as project websites, datasets provided by associations, literature sources, etc. [24–29]. The database was created by harmonising information from various and heterogeneous sources, allowing to obtain an organic set of data. The selection of plants to include in the database was based on a basic criterion set in the JRC study, where a threshold of min. 10 m^3/h of nominal biomethane production capacity was used as filter. The threshold was chosen considering as a faction of the average size of plant in Europe: 1MW_{el} output plant. Although smaller, pilot initiatives were also scientifically interesting, they would not contribute to the real technical production potential. The production potential (in Nm^3/h) excluded by this filter was estimated to be below 1% of the total. In the database, besides nominal productivity, each plant is classified by its location, the feedstock(s) used and technology adopted for biomethane separation. Data are organised in a pivot structure in Excel in order to extract datasets segmented per technology, country, feedstock type, etc. Since the JRC database was used as a reference for the considerations presented in this paper, it was complemented by information on natural gas infrastructure and vehicles per EU Member State. Supporting measures, currently present at MS level are expected to promote the installation of new biomethane plants, mainly fed by organic fraction of municipal solid waste (MSW). At the same time, incentives for electricity produced from biogas conversions are expiring progressively in many MSs. These two factors suggest an increase in net available biomethane production, together with a shift towards more sustainable feedstocks.

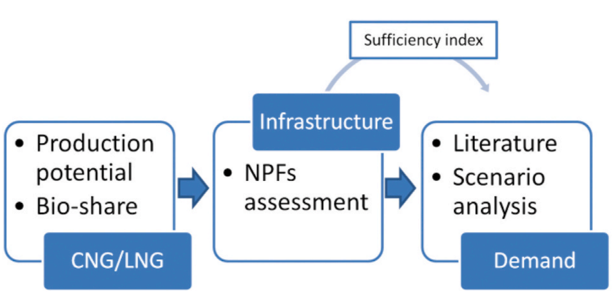

Fig. 1. Scheme used for answering the research question.

Introduced in the framework of the Regulation on the governance of the energy union and climate action ([9]/1999), as part of the Clean energy for all Europeans package in 2019, the National Energy and Climate Plans ([30] provide further relevant information. These 10-years integrated national plans aim to meet the EU's energy and climate targets for 2030 and were used to derive considerations about the expected production and consumption of alternative to natural gas. In fact, to meet the EU's energy and climate targets for 2030, MSs have established a 10-year integrated NECP, covering the period from 2021 to 2030.

Moreover, data were enhanced by additional information, such as the elaboration of future targets, estimates and timelines as contained in the NPFs. In addition to provide AFI targets in their NPFs, MSs were also requested to specify alternative fuels vehicle estimates for the future, in order to ensure coherence between expected fleet penetration and refuelling points deployment. Many of the data used for setting the current baseline are elaborated by the European Alternative Fuels Observatory (EAFO) online portal [31]. To perform scenarios for 2020, 2025 and 2030, the CNG and LNG infrastructure and vehicle data provided by the MSs in their NPFs [21] were further elaborated.

Since not all MSs provided infrastructure targets or vehicle estimates, assumptions had to be made to cover the entire period of the analysis performed in this paper. If a MS had not provided any future infrastructure target, the value at the end of 2018 was kept as constant, while in the case of partial future infrastructure targets or vehicle estimates, the values for the missing years were defined by linear interpolation. If a MS had not provided any future vehicle estimates but provided infrastructure targets, the ratio vehicles/infrastructure was kept constant, and the corresponding vehicle estimates were computed by assuming a synchronised evolution of alternative fuels fleet and infrastructure.

In order to define whether the planned infrastructure could properly support the expected vehicle CNG stock increment, a sufficiency index was defined. The sufficiency index is defined as the ratio of CNG vehicles per refuelling points: this index is relevant to evaluate the potential availability and proximity of refuelling points for a vehicle user. According to current values for fossil standard fuels, in assessing the NPFs [21] a ratio of less than 600 CNG vehicles per one publicly accessible CNG refuelling point was considered sufficient.

3. Results and discussion

3.1. Biomethane EU production potential

Whereas the demand for gaseous fuels seems to be clearly assessed in several studies, the question about the realistic potential for renewable sources to satisfy a significant share of it remains unanswered. A recent review on the technology status update [22] identified that EU biomethane production relies on biogas upgrading. Unlike other estimations [32,33], according to Ref. [22] power-to-gas and SNG technologies are expected to have a limited impact in the next 10-years horizon. With the exception of the Ambigo (AMBIGO, 2018) project, no other relevant initiatives are currently ongoing: lack of investors' confidence, regarding SNG profitably, appeared evident with the cancellation of the EU largest project (GoBiGas) [34], which unfortunately can be considered as paradigmatic of the current state of play of this technology.

According to Ref. [35], the JRC database reports a total number of 465 operative plants in EU-28 in 2018; other authors showed similar figures [33,36]. Focusing on biomethane production from biogas upgrade, the JRC database shows a nominal capacity, currently installed in EU-28, accounting for 236,000 m^3/h, potentially equivalent - considering a 96% technical availability [37] – to 1.98 bcm/y (equivalent to 71.7 PJ - calculated on the basis of the Higher Heating Value (HHV)). A recently published report from the European Biogas Association confirmed these values [38], reporting a stable growth, which accounted for +14% in 2018.

Investigating the potential contribution of this alternative fuel for transport, it is worth remarking that today biogas production is almost entirely devoted to electricity production, with low heat recovery rate. This is mainly due to the intrinsic characteristics of the biogas plants, which are typically located in the countryside, thus far from industrial clusters where heat could have been valorised. At the same time, the presence of relevant incentives for electricity production allowed plants to become economically viable [39], even without heat integration. This situation is expected to change in next years with the shift towards biomethane separation. This energy carrier can be easily delivered through existing grid, or stored for other applications. Its use in road and maritime sectors is expected to be relevant, due to the high economic value, and because many existing plants might not be economically connected to grid. Additionally, several MSs (i.e. Italy) specifically support the use for road applications.

Studies about production, and future projections, were integrated with the data reported by MSs. This allows to create a scenario for biomethane production over the period 2020–2030. Results are shown in Table 2. By 2030, a total potential of 20 bcm/y is expected to be available. This represents a 10-fold increase, which could be challenging over a period of 10 years but achievable, considering the existing installed capacity in terms of biogas combined with the ambitions of several MSs.

Figures estimated by the JRC are moderate when compared to those of other studies: TU-Delft [40] reported a 2030 potential ranging from 33.6 to 46.9 bcm/y, and NGVA [41] one ranging from 36 to 51 bcm/y. However, it is worth noting that the JRC acted on the data collected on the base of the existing plants and initiatives.

It is also worth remaking that even with the assumption that not all of the biomethane produced in the EU will be destined to the transport sector, this estimate clearly shows the potential for substituting a relevant share of fossil natural gas.

3.2. Estimation of CNG and LNG demand at 2030

3.2.1. Road sector

Based on several techno-economic considerations, the road sector is expected to increase its demand for gaseous fuels, especially for freight. According to the outcome of the REGATRACE project [42], and a yet-to-be-published NGVA report, in 2019 the consumption of CNG and LNG was close to 2.5 bcm, with a percentage of bio-CNG and bio-LNG around 15%. The JRC-EUCAR and CONCAWE, JEC Alternative Fuels study [7] reported a consumption for CNG and LNG fleets of about 112 PJ in 2020, equivalent to 3.0 bcm.

With regards to the existing vehicles fleet, the Natural and bio Gas Vehicle Association (NGVA) reported for 2017 a total of more than 1.3 million vehicles [43]. There were more than 20,000 natural gas buses and coaches in 2017 [31] corresponding to 15 different models [43] (the numbers of models on the market increased continuously from 10 in 2015 [44] to 21 in 2019 [45]). NGVA estimates that one out of three new urban buses and coaches is expected to be fuelled by gas, in 2030 [32]. Despite these studies, the interest for CNG passenger car segment seems to be stationary or even reducing with an almost unchanged number of models on the market since 2015. Conversely, freight sector is showing a different trend, with an increasing interest in LNG as alternative fuel. Specifically for freight, promising vehicle initiatives are already ongoing [46], while the number of LNG truck models on the market increased from one in 2015 [44] to eight in 2019 [45]. NGVA foresees that the natural gas (CNG and LNG) trucks will reach 25% of the new registrations in 2030 [10].

Table 2
Moderate scenario for biomethane (*bcm/y*).

	2017	2025	2030
Biomethane	1.9	15.5	18.0
Power-to-Gas	8.0E-03	1.2	1.9
SNG	3.0E-06	0.2	0.3
TOTAL	**1.9**	**16.9**	**20.2**

3.2.2. Maritime sector

Total energy demand for shipping is expected to grow by mid-century [47], the baseline of the EU long-term strategy [48] sets the total demand for 2030 around 60 Mtoe, with an increment of about 8%, compared to 2015. According to Ref. [49], alternative fuels for maritime transport can play a crucial role in decarbonising the shipping sector and ultimately contribute towards climate change goals.

Among the various technical options available today, LNG is considered an interesting solution, with regards to the sector's ambitions for GHG reduction. As presented in the JEC WTW study [7], bio-LNG produced from the organic fraction of MSW offers significant savings, in terms of GHG emissions. In terms of fleet, according to Refs. [11,45], globally the LNG-fuelled maritime fleet already accounts for more than 100 vessels in operation, further 101 confirmed new builds and an additional 72 LNG-ready ships, running on other fuels.

3.3. Deployment of alternative fuels infrastructure

The link between the technical production potential and the expected demand is represented by refuelling infrastructure. According to NGVA [50], in May 2019 there were 457 stations delivering biomethane in Europe, of which 44 were in Germany. As infrastructure is a key part of the EU alternative fuels strategy, EU Member States' NPFs were used to identify any need for additional actions. Based on the strategies communicated by the MSs to the EC, Table 3 presents the situation at EU level for CNG and LNG for road refuelling infrastructure targets, and vehicle estimates for the mandatory years required by the AFID.

The analysis performed is focused on road transport, and is based on the information provided by the MSs in their national strategies. This information has been complemented by the methodology described in Section 2, to deal with the missing values of infrastructure targets or vehicle estimates. Fig. 2 and Fig. 3 provide an overview of the 2030 targeted CNG publicly accessible refuelling points, and CNG vehicles according to the NPFs, as well as the target achievements at the beginning of 2019. In both figures, the MSs are presented in decreasing order, with respect to their foreseen CNG infrastructure targets for 2030. In Fig. 2, the light shade green indicates the four MSs that have not provided any future CNG infrastructure targets, for which the values from the end of 2018 have been kept constant (Bulgaria, Cyprus, Malta and Sweden). The lighter shade colours in Fig. 3 indicate the MSs that did not provide any future CNG vehicle estimates, for which the assumptions presented in Section 2 were made to derive the future fleet (out of these 15 MSs, eight MSs providing infrastructure targets).

According to the NPFs analysis, some MSs, namely Czechia, Hungary, and Italy, consider natural gas as a relevant element of their future mobility, and they foresee significant fleet and infrastructure deployment. Conversely, other NPFs (i.e. Austria, Germany, Luxembourg, and the Netherlands) provided data that report a stable or no relevant increments in CNG refuelling infrastructure. As to be noted that a stable or not relevant increment in planned infrastructure does not necessarily represent a negative vision, or a turning point with respect to this fuel option, as some of the above mentioned MSs already have significantly invested in the sector. In terms of future CNG vehicle perspectives, results for 2030 show that the EU average fleet share of CNG cars would be around 1.5% with two Member States having shares superior to 5% (Italy and Hungary). At the end of 2018, the EU overall attainment level was 44.4% with respect to the considered CNG infrastructure targets for 2030 and 27.4% with respect to the considered CNG vehicle estimates for 2030.

Table 3
Overview of NPFs for CNG and LNG in road transport.

AF	Year	Number of MS providing NG infrastructure targets	Number of NG infra. targets	Number of NG infra. existing at December 2018	Target attainment level [%]	Number of MS providing NG vehicles estimates	NG vehicles future share [%]
CNG	2020	24	3996	3225	80.71%	12	0.04–3.27[a]
LNG	2025	21	396	146	36.87%	8	0.01–4.38[b]

[a] Light-duty vehicles (passenger cars and light commercial vehicles).
[b] Heavy-duty vehicles (HDV) (heavy goods vehicles, buses and coaches).

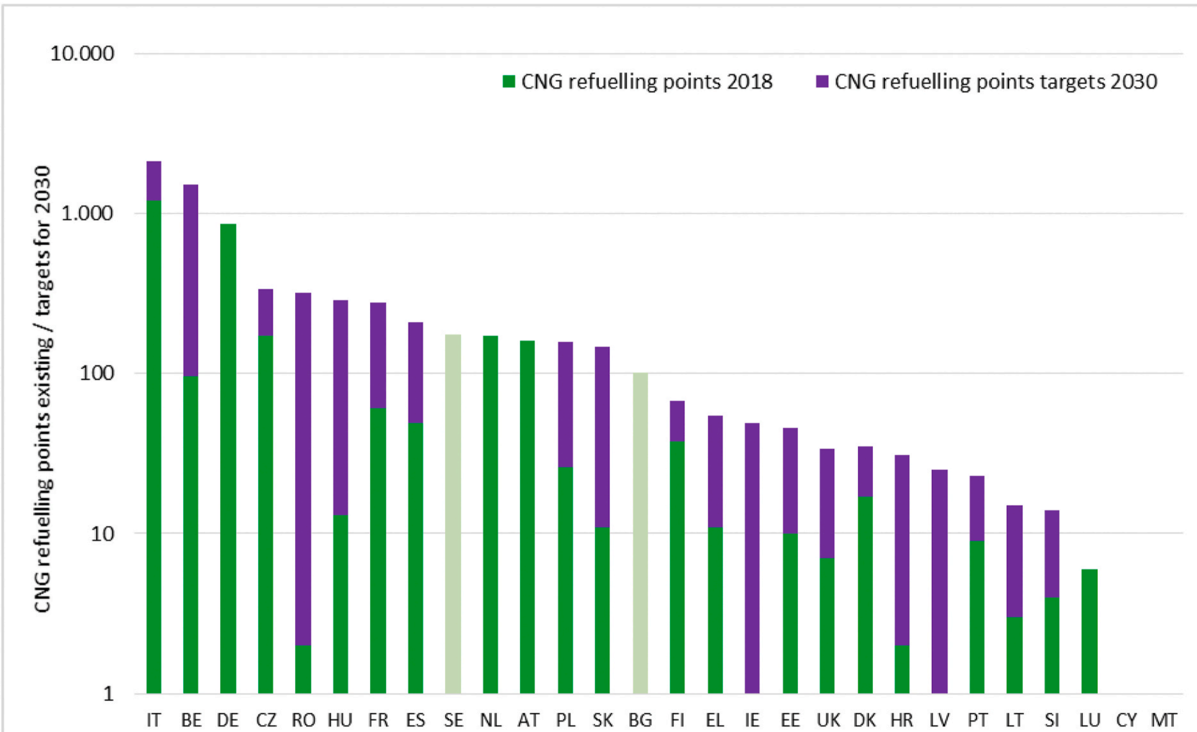

Fig. 2. CNG refuelling point targets for 2030. (Logarithmic scale. Data based on NPFs [21,31] and JRC elaborations).

Fig. 4 shows the CNG sufficiency index for 2018 and 2030, defined as the ratio of CNG vehicles per refuelling points. The sufficiency index can help assessing how the envisaged development of CNG vehicle fleet is supported by planned refuelling infrastructure. Since the CNG vehicle values are foreseen to increase more significantly than the CNG refuelling points values, the situation of the CNG sufficiency index deteriorates in 2030 compared to 2018. All the MSs with a ratio lower than 600 (which is considered sufficient on the base of the ratio values for regular fuels) are displayed in the maps in different shades of green. In Fig. 4, it can be observed that the CNG sufficiency index value increases in 11 MSs, with eight MSs displaying values superior to 600 in 2030, compared to three MSs in 2018. In these MSs, with high foreseen ratios of vehicles per infrastructure, it would be advisable to monitor closely the CNG vehicle market development and utilisation of the infrastructure, in order to try to steer the deployment of CNG refuelling points in line with the vehicle fleet change.

LNG has been considered by many studies as a suitable fuel for the freight sector. LNG refuelling infrastructure targets for heavy-duty vehicles are provided by 21 NPFs, and initial steps to ensure adequate Trans-European Transport Network (TEN-T) coverage have been taken. Several Member States mentioned in their NPFs their intention to review LNG refuelling infrastructure targets, following further market and cost-benefit analyses. Eight NPFs contain vehicle estimates and in these cases, the expected shares of LNG heavy-duty vehicles vary between 0.01% and 4.38% in 2025. The most ambitious MSs are Hungary (expecting 6300 LNG HDV corresponding to 4.38% of the national HDV fleet) and Slovenia (expecting 1900 LNG HDV corresponding to 4.14% of the national HDV fleet).

The resulting overall situation for CNG and LNG infrastructure until 2030 can be observed in Table 4. By comparing the 2018/2030 expected increments for the infrastructure network, the difference in commercial maturity level of the two fuels becomes clear.

These values resulted aligned, although more conservative than some estimations presented by other sector associations [43].

3.4. Case studies and support schemes

3.4.1. Biomethane – support measures for infrastructure/fuel mentioned in the NPFs

At national level, several MSs have already introduced support measures for stimulating the use of natural gas (CNG and LNG) in the transport sector. In addition to these, MSs included a series of measures specifically dedicated to biomethane in their NPFs, and their overview is provided in Fig. 5.

In general, the support measures can be financial incentives (e.g. feed-in tariffs, premium feed-in tariffs and fiscal incentives), non-financial incentives (e.g. preferential access to restricted areas like low emission zones, parking policies like preferential parking for CNG vehicles and dedicated/preferential lanes like the allowance to use bus lanes) or education/information related activities. Feed-in tariffs are the minimum prices guaranteed, over a defined period, by the national governments for each kWh generated, either injected into the gas grid or

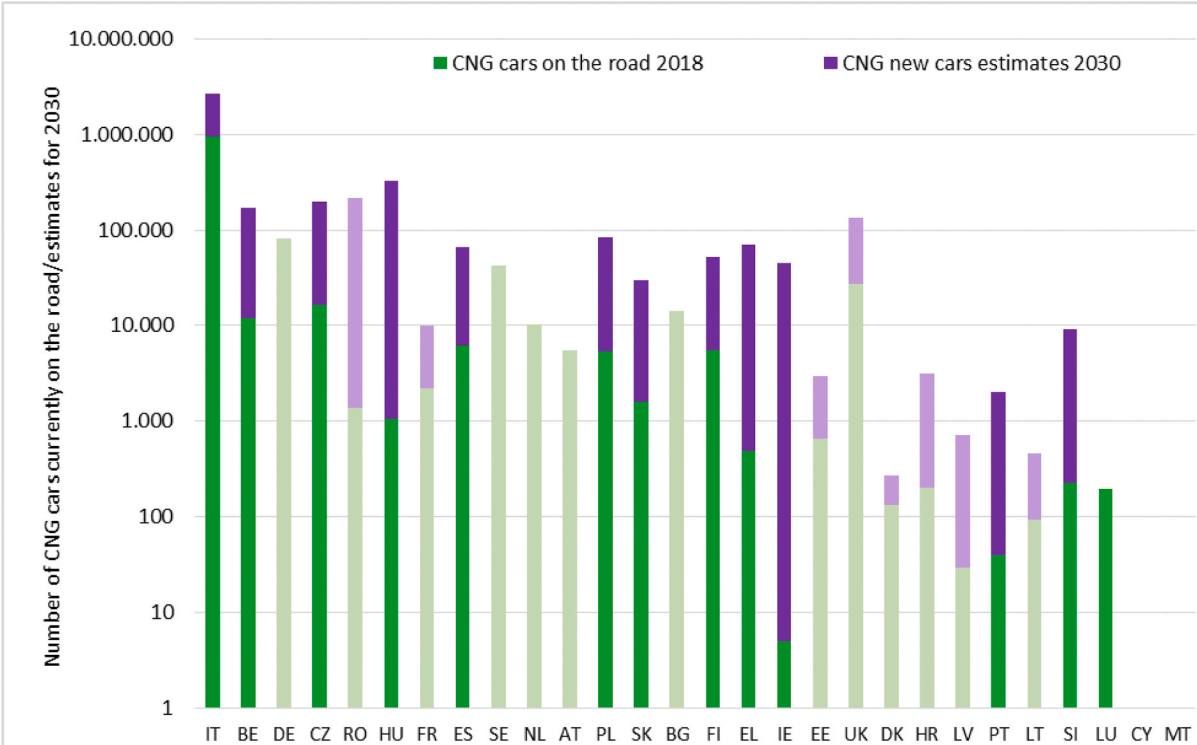

Fig. 3. CNG vehicle estimates for 2030. (Logarithmic scale. Data based on NPFs [21,31] and JRC elaborations).

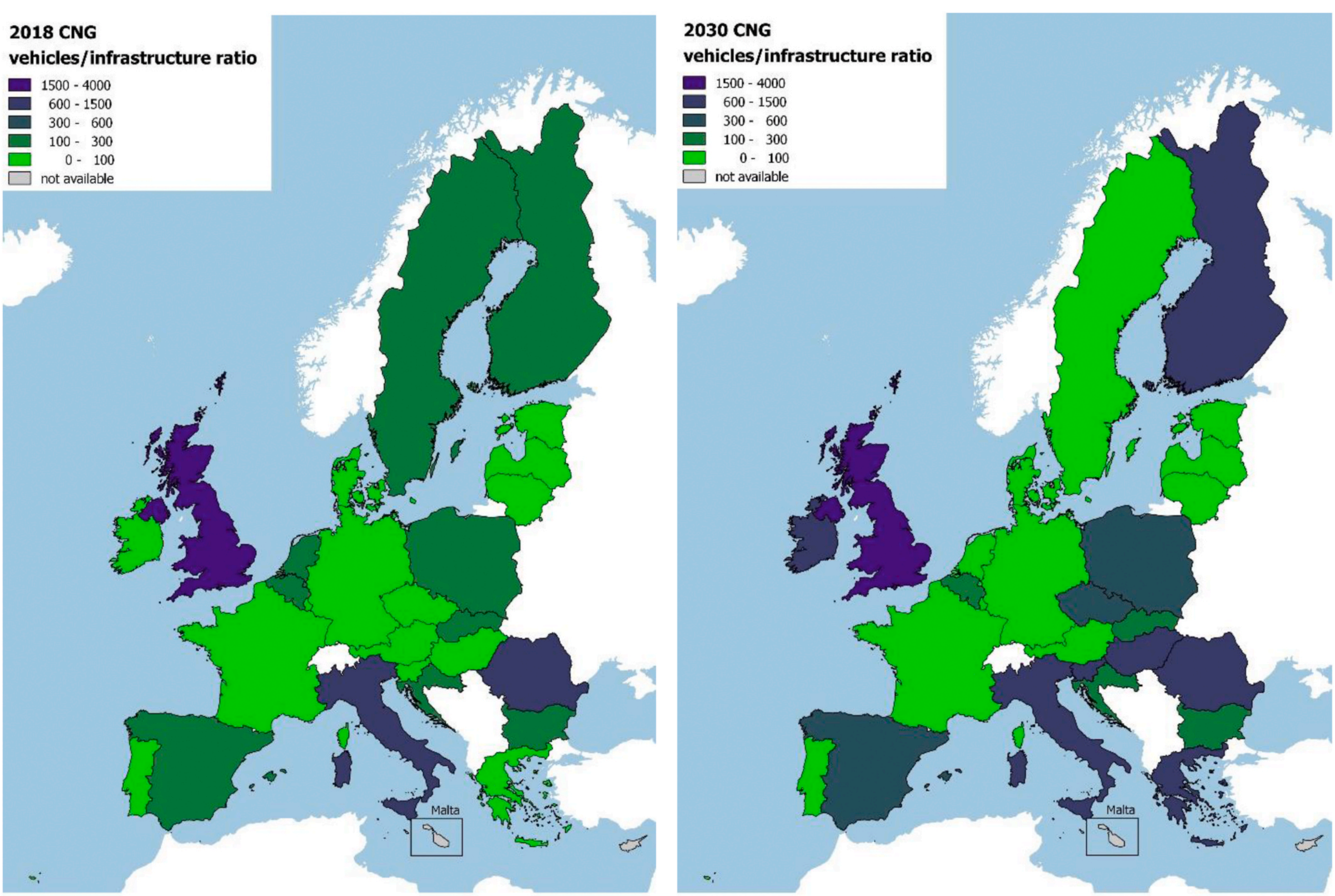

Fig. 4. Overview of CNG refuelling point sufficiency index per Member State at the end of 2018 (left) and at 2030 (right).

Table 4
CNG and LNG refuelling points for road transport (2018–2030).

AF	NG infrastructure existent at December 2018	AFI targets			Increment
		2020	2025	2030	2018/2030
CNG	3225	3996	5579	7257	125.0%
LNG	146	204	396	1335	814.4%

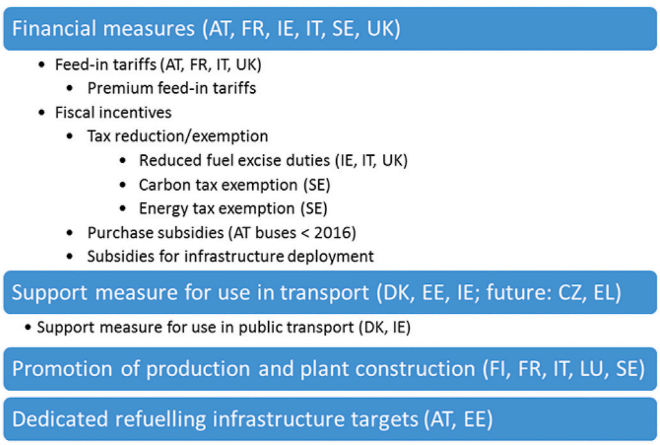

Fig. 5. Overview of biomethane support measures based on the NPFs of the EU Member States (for the used country codes see Ref. [26]).

directly used. This incentive is currently applied in Italy, Austria, France and the United Kingdom. Premium tariffs set a premium on the existing electric power price; the producers obtain a revenue from the sale of energy in the electrical market and an additional one related to the premium tariff [51]; this is a technology-specific subsidy level per unit of renewable energy at a pre-set, fixed or floating rate. As a relevant case study, Italy issued in March 2018 the 'Biomethane Decree' [52], with specific targets for the transport sector. If biomethane is to be used in transport, the incentive is a Certificate (CIC) – equivalent to 10 Gcal of fuel, corresponding approximately to 1000 Nm3 - with an average value of 375 €/CIC. Additional premiums are foreseen in case of installation of compression, liquefaction and/or distribution plants.

Among the fiscal incentives are reduced taxation schemes like lower fuel excise duties, vehicle purchase/substitution subsidies, funding/subsidies for the deployment of refuelling infrastructure, etc. According to NPFs, lower fuel excise duties for renewable natural gas have been implemented and are planned to continue in Ireland, Italy and the United Kingdom. Another example is Sweden, where biogas is not subject to carbon dioxide and energy taxes (until end 2020). In relation to purchase subsidies, Austria implemented this measure for biomethane buses until 2016. Estonia reported an existing support scheme for biomethane use in transport, while Czechia and Greece indicate that preparatory work to promote biogas will start. In addition, Denmark and Ireland mention they support the use of biomethane for public transport.

Support can also be provided as investments for building/improving biomethane plants, especially in areas with restricted access to the natural gas grid. Several MSs mention projects and future incentives to promote biomethane production and plants support (i.e. Finland, France, Italy, Luxembourg and Sweden). Austria and Estonia foresee dedicated biomethane refuelling points within their targets for natural gas infrastructure.

As mentioned in Section 3.2.1, LNG starts to become interesting for the heavy-duty segment and this can also be observed in terms of support measures. Purchase subsidies for LNG trucks already exist in Germany (€12,000/LNG truck) and Italy (€8000/CNG truck), while an exemption of road tolls for trucks is in place in Germany [53].

3.4.2. *Case studies – geographical distribution of CNG refuelling stations*

As for the deployment of CNG infrastructure, together with the overall number of refuelling points, the NPFs address issues of spatial distribution. Two interesting different cases worth presenting are Italy and Germany. These two MSs currently have the highest numbers in the EU of CNG refuelling points (around 64% of the total EU number), but their future plans differ: Italy has high expectations in terms of vehicles, but low infrastructure sufficiency; while Germany has low expectations in terms of infrastructure development but good infrastructure sufficiency.

In Italy, the distribution of natural gas vehicles and refuelling stations is geographically inhomogeneous, with seven provinces representing 81% of the total natural gas vehicle fleet. Measures are foreseen to eliminate the geographical inhomogeneity of the infrastructure, as this can clearly represent a serious bottleneck. Specific targets are provided for five cities: Rome, Milan, Naples, Catania and Palermo.

In Germany, the natural gas refuelling network is instead quite homogeneous and the average distance between CNG refuelling points is less than 150 km, even on the TEN-T Comprehensive Network according to the NPF. On German motorways, on average there are approximately two CNG refuelling points per 100 km within a radius of 2 km, which are often deployed along two-sided motorway service areas. The CNG refuelling points are geographically well distributed and, in most of the German territory, the nearest CNG refuelling point can be reached in a drive time below 20 min. On the other hand, the German NPF does not foresee significant further CNG infrastructure deployment.

3.5. *Further considerations on deploying biomethane for transport*

In light of the information presented in this paper, some considerations can be derived; according to observed current market trends, and MSs orientations, freight transport appears as an interesting application for biomethane, either as bio-CNG or bio-LNG. For road, heavy-duty vehicles have today a variety of alternative technologies, but due to the high energy density required in such applications, electrification (battery electric, fuel cell electric, hybrids) is currently less interesting than other alternative fuels. In this specific context, biomethane fuelled vehicles are an interesting option in the short term. For freight, either road or maritime, liquefied natural gas is considered a suitable option, particularly for long-haul carriers.

When biomethane is promoted as a means to decarbonise the transport sector, it is essential to estimate its potential savings. If on one hand the use of biomethane can show significant Tank-to-Wheel reduction benefits [7], on the other, factors like fugitive methane emissions from combustion and tanks can drastically lower real advantages [54,55]. With concerns to local pollution, several pilot initiatives [56] showed that for heavy-duty vehicles the use of gaseous fuels can lead to advantages in terms of lower pollutant emissions. At the same time, recent studies argued that CNG use in internal combustion engines can cause an increase in very fine particle emissions, below 23 nm [57]. It is worth noting that the diffusion of this technology is still too limited to draw specific conclusions: in fact the same literature sources highlight the need of further research, especially for LNG applications in newly designed engines. Additionally, social aspects related to biomethane production should be also carefully consider, as they could either be positive (contribution to rural develpmetn) or negative (NIMBY syndrome [58]). These aspects are clearly of fundamental interest, and policy makers should take them into serious consideration as to stimulate measures towards an effective greening of the sector.

While environmental benefits seem achievable by using biomethane in transport, cost issues have to be tackled in order to make this alternative fuel attractive for the sector. An EC report prepared by the Sub Group on Advanced Biofuels [59] mentions that biomethane costs in the range of 40–120 €/MWh. As a comparison, the European wholesale price of fossil natural gas corresponds to about 18 €/MWh, in 2017 [60]. It appears evident that, at the current stage of development and under the current market conditions, biomethane needs financial support to be competitive with natural gas. As a peculiar example among the feedstock useable for production, SGAB study [59] highlights that biomethane made by waste streams could potentially be cost competitive with fossil natural gas.

4. Conclusions and policy implications

The European biomethane sector seems to have an interesting production potential, able to contribute to future European energy demand in transport sector. From a mere technical production potential point of view, the calculated figure accounts already for the 2/3 of the 2020 demand for gaseous fuels in transport, estimated by JRC in 3 bcm. Even considering that only part of this biomethane production will be destined to the transport sector, it is still worth highlighting its potential to substitute a relevant share of fossil natural feedstocks.

As the fuel production potential and demand exist, refuelling infrastructure is expecting to act as a key connection between demand and supply. As observed for other alternative fuel, actual uptake in the EU transport sector is expected to be influenced by other factors, beyond the mere technical availability. This analysis, based on the MSs' NPFs in terms of CNG and LNG infrastructure deployment until 2030, revealed very different ambition levels and divergent strategies that could lead to cross-border continuity issues. According to the NPFs, some MSs, consider natural gas as a priority for their future mobility, while other NPFs report a stable CNG infrastructure scenario, with no significant increments. It is worth noting that a stable or small increment in planned infrastructure does not necessarily represent a turning point for this fuel option, as believed by some of the above-mentioned MSs, which have already invested in the sector quite significantly.

A sufficiency index - defined as the ratio of CNG vehicles per refuelling points – has been presented for 2018 and 2030. The sufficiency index has been defined as a tool to assess how the envisaged development of CNG vehicle fleet may not be properly supported by planned infrastructure. In several MSs, expecting a high increase in the number of their natural gas vehicles, the situation of the CNG sufficiency index deteriorates in 2030 compared to 2018. This is mainly because CNG vehicle values are foreseen to increase more rapidly than the CNG refuelling infrastructure values. Different commercial maturity levels of CNG and LNG and different MSs expectations are revealed by comparing 2018/2030 reported increments for the infrastructure network.

In conclusion, this study seeks to highlight the need of a policy perspective aiming to coordinate the deployment of CNG and LNG vehicles, and related refuelling infrastructure, both at Europe and Member State levels. This is needed in order to prevent infrastructure from becoming a barrier for market development of biomethane, at least in the short-to medium-term. Additionally, an increase in bio-CNG/LNG production capacity is needed, for this alternative fuel to make a significant contribution in the mitigation of GHG emission from the transport sector.

CRediT author statement

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Disclaimer

The views expressed here are purely those of the authors and may not, under any circumstances, be regarded as an official position of the European Commission.

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.

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