



# Well-to-Wheel analysis of passenger cars fuelled with a blend of LPG, bio-LPG, and renewable DME

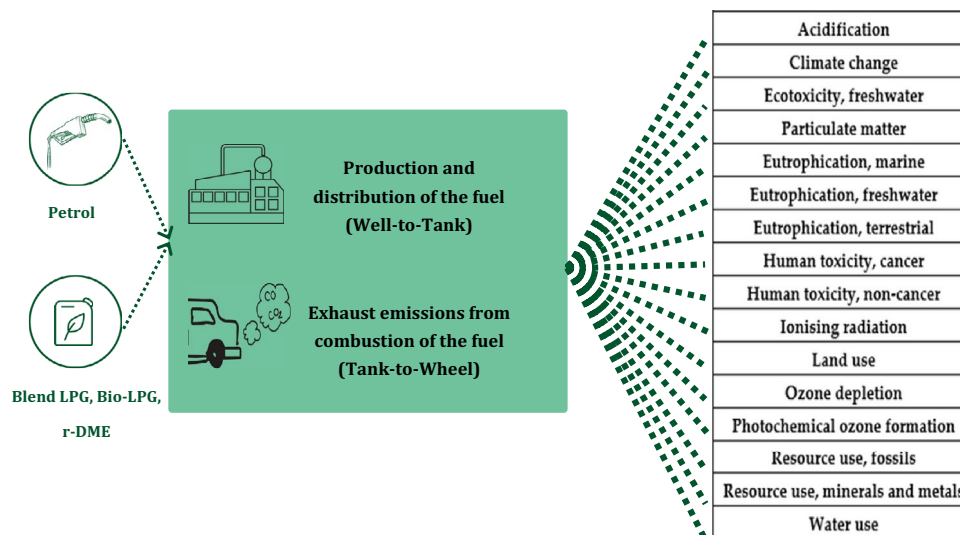
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## Abstract

This study compares environmental impacts from using petrol to those from using a fuel blend of liquefied petroleum gas (LPG), bio-LPG and renewable dimethyl ether (DME) in the form of bio-DME and electro-DME (e-DME), for two passenger car segments. Bio-LPG is produced from used cooking oils, while renewable DME is produced as both a biofuel from upgraded biogas, and an electro-fuel from captured CO<sub>2</sub> and H<sub>2</sub> produced from electrolysis using hydropower. The analysis was executed according to the life cycle assessment methodology using environmental footprint 3.1 as the impact assessment method. Results indicate that the blend offers 21% and 27% greenhouse gas emission savings compared to petrol for C- and B-segment cars, respectively. The blend with e-DME performs better than that with bio-DME, and the B-segment car offers higher savings than the C-segment car. The blend with e-DME in a B-segment car and the blend with bio-DME in a C-segment car rank as best and worst scenarios, respectively.

## Graphical abstract



**Keywords** Life cycle assessment · Transport · Passenger car · Biofuels · e-fuels · LPG · DME

## Introduction

Within the past several years, the issue of climate change has gained widespread relevance because it has become one of the most urgent global challenges with consequences on the environment and human health. From 2011 to 2020, an

increase of 1.1 °C in global surface temperature has been recorded compared to those observed during 1850–1900 (Calvin et al. 2023). Greenhouse gases (GHG) are primary contributors to global warming, and their excessive release stems from the reliance on non-renewable energy resources, unsustainable production and consumption, and improper land use (Calvin et al. 2023). In particular, the transport sector is a main contributor to GHG emissions due to its heavy reliance on fossil fuels, contributing to 23% of the total GHG emissions in 2020 in Europe, with road transport accounting for 77% of the total GHG emissions from the entire transport sector (European Commission: Directorate-General for Mobility and Transport 2022). Decarbonizing this sector has become a driving force to develop alternative cleaner fuels and technologies, with the predominant mitigation strategies being electric vehicles (EV), biofuels, and electro-fuels (e-fuels). Biofuels offer GHG emission savings if produced from sustainable feedstocks that do not result in indirect land use impacts (European Commission n.d). E-fuels are synthetic fuels produced by combining captured CO<sub>2</sub> and H<sub>2</sub> from water electrolysis utilizing renewable energy (EEA 2022).

Liquified petroleum gas (LPG) and dimethyl ether (DME) are energy carriers with fuel-like properties that allow them to be blended with petrol. LPG is a lower-emission alternative fuel typically composed of propane and butane that can substitute fossil fuels in the transport sector. It is recovered as a coproduct of primary fuel production processes, mainly natural gas processing or crude oil extraction (WLGA n.d). LPG is the most widespread alternative fuel in Europe, with around 8.2 million passenger cars utilizing it (Liquid Gas Europe 2024).

Bio-LPG or biopropane, is a biofuel generated as a coproduct of the synthesis of other biofuels. It is a suitable substitute for fossil LPG since it is analogous in chemical structure, performance, and application. The most promising production process is hydrotreatment, although it can also be produced from syngas from biomass gasification (Ricardo-AEA 2014). The primary product of hydrotreatment is a biofuel named hydrotreated vegetable oil (HVO), of which bio-LPG is a coproduct. In 2030, the potential production of bio-LPG is estimated to reach 1.4 Mt/y (Cepconsult 2022). More than 90% of bio-LPG is produced and consumed in Europe (Fairfield Consultancy Services OPC Pvt Ltd 2022).

DME is a synthetic fuel that can replace LPG since it has similar properties, storage techniques, and distribution infrastructures (Semelsberger et al. 2006). DME is an attractive alternative fuel because it releases lower amounts of particulate matter, NO<sub>x</sub>, and SO<sub>x</sub> than diesel and LPG (Parvez et al. 2018). It is usually produced through a direct or indirect synthesis pathway, with both routes relying on methanol dehydration (Fedeli et al. 2022). The indirect route is a two-step process: conversion of syngas produced from

methane reforming into methanol, followed by dehydration of methanol into DME (Semelsberger et al. 2006). The direct route is instead a single-step process where the conversion of syngas into methanol and its dehydration into DME occur simultaneously (Fedeli et al. 2022). Since methanol is usually produced from coal or natural gas, to reduce the impact of DME, the production of renewable DME (r-DME) has become more popular. Based on studies found, bio-DME and electro-DME (e-DME) are the most cited r-DME forms. Potential renewable feedstocks for bio-DME production are biosyngas from biomass gasification or upgraded biogas from anaerobic digestion of biogenic material. For the gasification pathway, biomass feedstock and techniques differ from one study to another: Parvez et al. (2018) and Tomatis et al. (2019) performed a single-step DME synthesis through CO<sub>2</sub>-enhanced gasification of gumwood, Lecksiwilai et al. (2016) compared five gasification scenarios, each for a different type of agricultural residue in Thailand using a two-step DME synthesis process, and the JEC study by Prussi et al. (2020) analysed gasification scenarios using waste wood and farmed wood. For the biogas pathway, biogas produced from anaerobic digestion is upgraded into biomethane, which is then converted to biosyngas through methane reforming. Fedeli et al. (2022) used biogas from corn silage in Italy, reformed it using a bi-methane reforming unit, and synthesized bio-DME through a single-step process, while Moghaddam et al. (2016) applied an indirect synthesis route using biomethane from maize-based biogas. For e-DME production, CO<sub>2</sub> hydrogenation is the most widespread technique suggested in the literature. The first component is “green” hydrogen obtained from water electrolysis that relies on renewable energy (wind, hydropower, etc.) as the energy source for the electrolysis process. The second component is carbon dioxide usually captured from the emissions of an industrial process such as cement production (Galusnyak et al. 2022), ethanol fermentation (Matzen and Demirel 2016), or flue gases from an industrial site (Prussi et al. 2020), and utilized for e-methanol production that then undergoes dehydration into e-DME.

This study aims to compare the environmental impacts associated with bi-fuel LPG Euro 6d passenger cars while using petrol versus those observed from using an innovative fuel blend composed of fossil LPG, bio-LPG, and r-DME. Two methods for r-DME production were considered: as a biofuel (bio-DME) and as an e-fuel (e-DME). A life cycle assessment (LCA) was performed to analyse the environmental performance of four scenarios compared to the baseline scenario of emissions from a petrol car. The first scenario involved the use of the blend with bio-DME as the source of r-DME in a B-segment car (a small car according to European Commission (1999)), while the second utilized the blend with e-DME as the source of r-DME. The remaining two scenarios are identical to the first two in terms of

fuel, with the difference being the use of a C-segment car (a medium car) instead of a B-segment car.

## Materials and methods

This section describes all the steps and methods required to perform the LCA study to compare the environmental impacts stemming from the use of petrol to those resulting from the use of the blend. It describes two of the four phases of an LCA study: goal and scope definition and inventory analysis.

### Goal definition

This LCA study compared the environmental impacts of using a B- and C-segment passenger car, compliant with the Euro 6d standard, and powered by: (1) a spark-ignition engine fuelled by petrol; (2) a spark-ignition engine fuelled by an innovative blend of LPG (60% m/m), bio-LPG (20% m/m), and r-DME (20% m/m). Two types of r-DME were assessed: bio-DME from biomass and e-DME from electricity-based hydrogen. Fuels for the internal combustion engine vehicle (ICEV) were tested in laboratory and real driving conditions and emission factors were determined from measuring exhaust emissions. Three vehicles were tested, two B-segment cars and one C-segment car, all equipped with a three-way catalyst; the C-segment car was also equipped with a gasoline particulate filter. An average of the exhaust emissions was assumed for the B-segment cars. Two car segments (B and C) were utilized to assess the influence of vehicle size and performance on the environmental impacts, mainly in terms of differences in fuel consumption and lifetime mileage. To determine the influence of the fuel composition, both vehicle segments were tested using petrol to establish the baseline scenarios, and four additional scenarios were modelled for the blend. The first two scenarios refer to the B-segment car and differ in

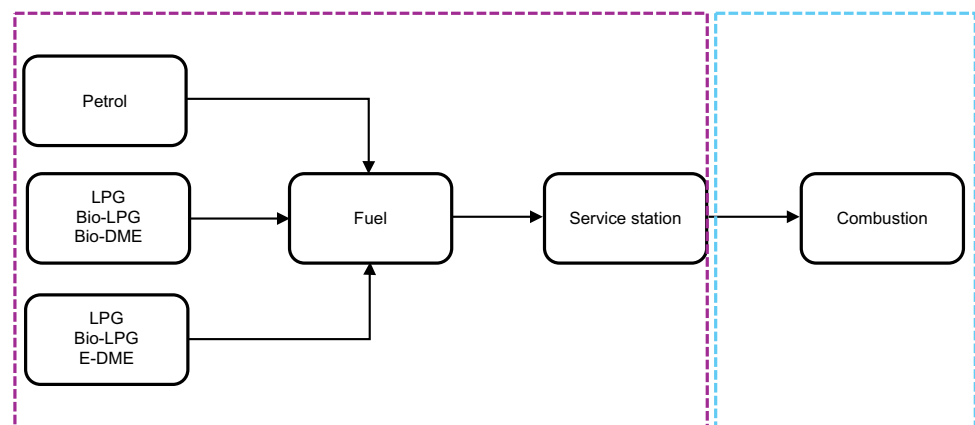
the source of r-DME incorporated (bio-DME vs. e-DME). The other two scenarios are similar with the difference being the use of a C-segment car instead.

### Scope definition

The functional unit was defined as “driving 1 km in Italy with a passenger car that fulfils the Euro 6d standard”. The lifetime mileage chosen for the cars was 190,000 km for the B-segment car and 210,000 km for the C-segment car driven over the 18 years lifetime (Weymar and Finkbeiner 2016). Possible changes in functional performances over time were not considered. The system boundary only accounted for the cradle-to-grave life cycle of the fuels (Fig. 1). The life cycle of a fuel is typically subdivided into well-to-tank (WTT: its production and distribution) and tank-to-wheels (TTW: its use in a car). The entire life cycle is called well-to-wheels (WTW: sum of WTT and TTW).

Since bio-LPG, bio-DME, and e-DME are produced from waste feedstocks, there is a problem linked to the distribution of the environmental impacts between the previous system that generated the waste and the system that uses the waste to produce fuel. In this study, the approach by the General Programme Instructions for the International EPD® System was followed based on the polluter pays principle (EPD International 2021), such that all impacts, up to the moment in which the waste no longer has a negative market value, are assigned to the system that generated the waste. Therefore, for bio-LPG, the system boundary starts with the collection and transport of used cooking oil to the biorefinery. For bio-DME, municipal organic waste is treated through anaerobic digestion, leading to the production of useful biogas, so the system boundary starts with biogas upgrading. Production of bio-DME also uses CO<sub>2</sub> that would be released into the atmosphere from a cement plant. Thus, the system boundary starts with the capture of CO<sub>2</sub> from flue gas. Similarly, for e-DME, production utilizes CO<sub>2</sub> that would be released into the atmosphere, so the system boundary starts with

**Fig. 1** Simplified overview of the system boundaries considered in this study. The purple-dashed box represents the production and distribution of the fuel (WTT phase) and the blue-dashed box represents the usage and combustion of the fuel (TTW). The combination of these two phases is the life cycle of the fuel (WTW)



CO<sub>2</sub> capture. Carbon neutrality was adopted for biofuels; therefore, biogenic CO<sub>2</sub> from biofuel combustion was considered “neutral”. Similarly, CO<sub>2</sub> captured from flue gas of a cement plant, embed in a renewable fuel and combusted, was considered as neutral. This assumption derives from the awareness that the cement is produced in both scenarios of petrol- and blend-fuelled car; in the second case, there is a single CO<sub>2</sub> emission (from the car) instead of two (from the cement plant and from the car).

Primary data for exhaust emissions were obtained from Innovhub-SSI, and background data were modelled by means of the ecoinvent 3.9.1 database (Wernet et al. 2016). This study was conducted with Italy as the geographical location. Sub-processes were substituted with Italian ones if available (e.g. the grid electricity), except if the process had to be modelled in a foreign country. Production of energy carriers was assumed to be in 2023, although several sources used also refer to several years before. The software SimaPro 9.5 was used for the LCA.

The life cycle impact assessment (LCIA) method chosen was the environmental footprint EF method 3.1, established by the Joint Research Centre for the European Commission (Andreasi Bassi et al. 2023), and it provides characterization factors at midpoint level for 16 impact categories: climate change, ozone depletion, human toxicity (cancer effects), human toxicity (non-cancer effects), particulate matter, ionizing radiation (human health), photochemical ozone formation, acidification, eutrophication (terrestrial), eutrophication (freshwater), eutrophication (marine), ecotoxicity (freshwater), land use, water use, resource use (minerals and metals), and resource use (fossil).

## Life cycle inventory

The following sections provide the detailed assumptions and quantitative data utilized to construct the inventory of each fuel required for this study. Each section describes the production pathway of the fuel, its transportation, and its distribution. A detailed explanation was also provided for the data used to construct the inventory of the exhaust emissions.

### Petrol production

Petrol production was assumed to happen in Italy, since 97% of petrol consumed in 2020 was self-produced (Unem 2021, 2022). It was modelled with an ecoinvent dataset for low-sulphur petrol production in Europe and adjusted to reflect the Italian context by modifying the market mix of crude oil and using Italian versions of natural gas consumption, water consumption, and water emissions. To determine the Italian market mix of crude oil, the countries that supplied crude oil to Italian refineries in 2020 were determined through Unem (2023), and the market mix was obtained by combining

volumes of imported (Unem 2023) and self-produced crude oil (Unem 2020). The transport distances of crude oil are calculated as average distances to Europe according to Meili et al. (2022), and in this case, the transport distance for Italian mix was determined according to the length of the Viggiano–Taranto oil pipeline. The electricity mixes in subsequent phases were also substituted with the Italian ones. The transport of petrol from the refinery to the service station was modelled with an ecoinvent dataset of a freight lorry with gross mass higher than 32 metric tonnes. The Euro mix of the Italian fleet of diesel trucks was assumed according to Automobile Club d’Italia (2023), and a 150-km standard transport distance for EU petrol was assumed (Prussi et al. 2020). Similarly to the production, the distribution infrastructure, including the filling station, was modelled using an existent ecoinvent dataset which adapted to the Italian context by modifying the petrol market mix, transportation, electricity consumption, and water emission.

### LPG production

To model the LPG supply chain for the Italian context, a questionnaire was sent to four Italian companies selling LPG, accounting for a total of 508 kt sold in 2022. It was found that 27% of LPG was produced in Italy and 73% was imported (Table 1). Regarding the imported LPG, 82% was transported by sea, 13% by train, and 4% by lorry. By combining transport modes and distances, average transport distances of one mass unit of LPG were calculated by a weighted mean: 1,602 km by oil tanker, 865 km by train, and 13 km by lorry, modelled using ecoinvent datasets. The transport of LPG from the refinery/storage to the service station was modelled with an ecoinvent dataset of a freight lorry (> than 32 tons). Based on information from the survey, an average mean of 249 km was calculated, and a Euro

**Table 1** Origin of LPG sold in Italy in 2022

| Country of origin | Production process                         | Italian market mix (%) |
|-------------------|--|------------------------|
| Algeria           | Extraction and purification of natural gas | 43.8                   |
| Libya             |  | 6.0                    |
| Egypt             |  | 5.6                    |
| Norway            |  | 2.0                    |
| U.S.A             |  | 1.9                    |
| Italy             |  | 1.0                    |
| Tunisia           |  | 0.3                    |
| United Kingdom    |  | 0.2                    |
| Italy             | Petroleum refining                         | 26.0                   |
| France            |  | 12.9                   |
| United Kingdom    |  | 0.4                    |

mix of the fleet of diesel trucks of 89% Euro 6 and 11% Euro 5. The distribution infrastructure, including the filling station, was modelled with an ecoinvent dataset for LPG production in Europe and adapted to the Italian context.

### Bio-LPG production

The production of bio-LPG is referred to an Italian biorefinery in Venice, Italy (Eni S.p.A. 2021). In this biorefinery, bio-LPG is produced through the Ecofining technology, based on a process of hydrogenation and further isomerization. According to GSE, in 2021, used cooking oil (UCO) was the most used feedstock to produce HVO and fatty acid methyl ester (FAME) in Italy (GSE S.p.A. 2022). Thus, in this LCA, bio-LPG was assumed to be from UCO. Due to lack of data specific to the Italian context, the Italian market mix for UCO was modelled by adjusting the EU market mix used in 2018 to produce HVO and FAME (European Commission 2020) as follows: European oil collected in Italy (42%) and non-European oil transported via ship to Venice (58%), and UCO collection is done by a truck driven for a standard distance of 100 km (Jungbluth et al. 2007). For sea transport of imported UCO, the process was modelled with an ecoinvent dataset with a mean distance, weighted on the import mix, of 14,352 km. The import mix was calculated using SeaRate (2023), with transport distances and import shares of each country acquired from (European Commission 2020). The layout of the “Porto Marghera” biorefinery used for the modelling is based on a future layout that will avoid the use of fossil fuels (except for energy production) described in the documentation available in the section “IPPC permit documentation” of the Italian Ministry for Environment (Eni S.p.A. 2019, 2020, 2022). The project refers to a generical input of oily biomass of 600,000 t/y (Eni S.p.A. 2022). The process starts with a pretreatment phase that reduces contaminants in the feedstocks (Eni S.p.A. 2021), and the core of the process is the ecofining unit, a process patented by Eni S.p.A and Honeywell-UOP, subdivided into two stages. In the first stage, deoxygenation of oil leads to the production of paraffinic linear chains, propane, water, and CO<sub>2</sub> (Eni S.p.A. 2021). In the second stage, called isomerization, paraffinic linear chains become ramified, with an improvement of cold properties of HVO. The coproducts of the process are bio-LPG, bionaphtha, bio-jet fuel, and surplus electrical energy. Steam and electrical energy consumption are satisfied by a natural gas-fired combined heat and power plant, and the H<sub>2</sub> needed is produced by a steam reforming plant fed with natural gas. Five products arise from the treatment of 600,000 t/y of biomass: 24,985 t/y of bio-LPG; 380,430 t/y of HVO; 28,002 t/y of bionaphtha; 47,520 t/y of bio-jet fuel; 199,118 MWh/y of electrical energy in surplus (Eni S.p.A. 2020, 2022). The impacts were subdivided among the five coproducts through energy

allocation, based on the amounts and lower heating value of each energy vector (Jungbluth et al. 2018; Prussi et al. 2020). Consequently, a factor of 5.31% was assigned to bio-LPG.

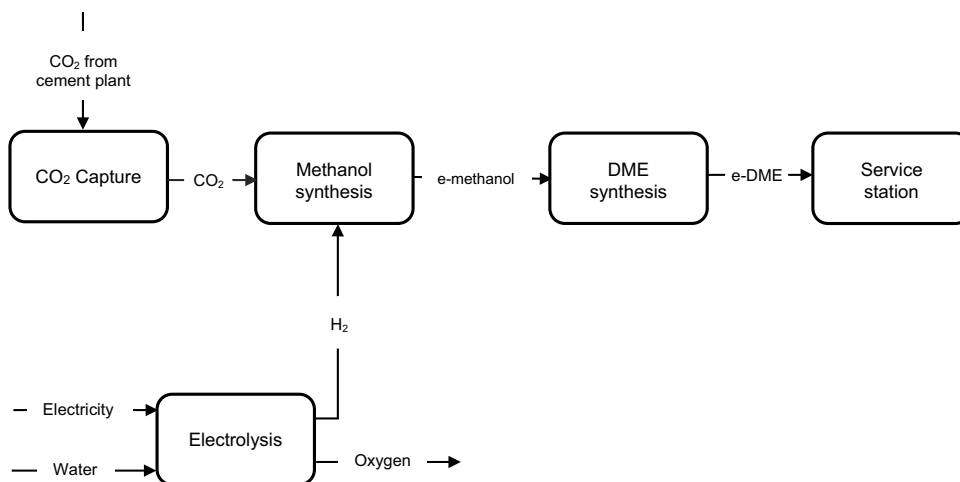
### E-DME production

E-DME production was modelled based on a study by Galusnyak et al. (2022) in which they performed an environmental assessment of methanol production and its conversion into other derived products such as e-DME. E-methanol is produced through CO<sub>2</sub> hydrogenation, with the CO<sub>2</sub> obtained from a carbon capture system and H<sub>2</sub> produced from water electrolysis (Galusnyak et al. 2022). E-DME is then obtained from methanol dehydration (Matzen and Demirel 2016). For this study, life cycle inventory (LCI) data used to model electrolysis, methanol synthesis, and DME synthesis were obtained from Galusnyak et al. (2022), and data for CO<sub>2</sub> capture from a cement plant using monoethanolamine were acquired in Meunier et al. (2020). E-fuels are associated with reduced emissions only if produced using renewable energy resources (Grahn et al. 2022). Accordingly, to model the electricity required for electrolysis, an average process for hydropower production in Italy was calculated based on statistical data by Terna on electric energy in Italy for the year 2021. Hydropower had the highest percentage of consumption among all other renewable electricity sources in Italy during that year (Terna 2022). To solve the multifunctionality from the oxygen produced as a coproduct during electrolysis, system expansion with substitution was used, and the oxygen was modelled as an avoided product. The DME synthesis infrastructure was modelled based on an ecoinvent dataset for DME production in Europe. Transport and distribution infrastructures were modelled as for the fossil LPG. Figure 2 represents the flow diagram of the production and distribution of e-DME adopted in this analysis.

### Bio-DME production

Bio-DME production was modelled based on a study by Fernández-Dacosta et al. (2019) that focused on performing an economic and environmental assessment of alternative fuels such as CO<sub>2</sub>-based DME. Production of CO<sub>2</sub>-based DME is a two-step process; the first step is the dry reforming of methane and CO<sub>2</sub> into syngas, and the second step is the direct synthesis of DME during which four simultaneous reactions occur: conversion of syngas into methanol, water–gas shift reaction, and methanol dehydration. Fossil methane was used as the source of CH<sub>4</sub> during dry reforming for syngas production. Compared to Fernández-Dacosta et al. (2019), the LCI was adjusted as follows: fossil methane was replaced with biomethane, and CO<sub>2</sub> capture was modelled using Meunier et al. (2020). Bio-methane production

**Fig. 2** Flow diagram of the production of e-DME



was obtained from Prussi et al. (2020), assuming municipal organic waste as the primary feedstock, as it represents the most common feedstock in the Italian transport sector (GSE S.p.A. 2022). Biogas upgrading via pressurized water scrubbing was considered for the purification, as it the most widely used technique in European plants (Capra et al. 2018). For the synthesis infrastructure, anecoinvent dataset for DME production in Europe was used, and its transport was modelled as that of e-DME. Figure 3 represents the flow diagram of the production and distribution of bio-DME adopted in this analysis.

### Exhaust emissions

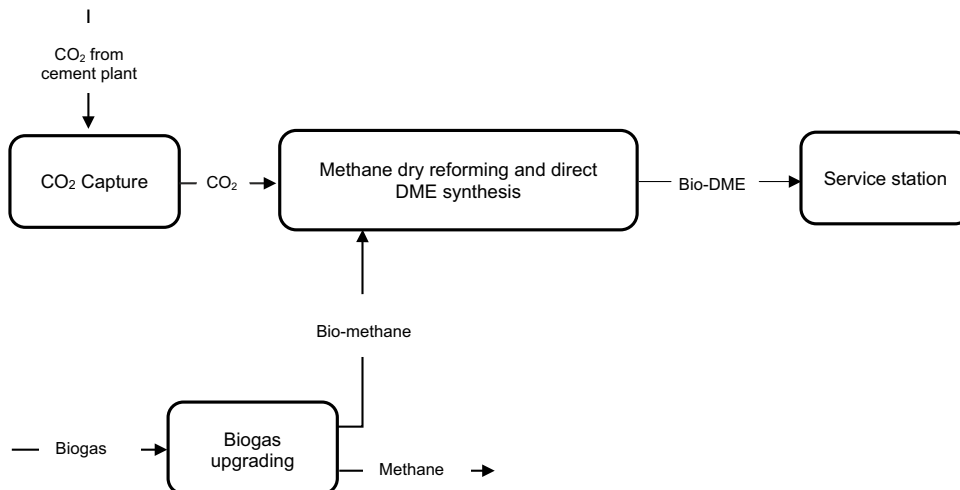
Exhaust emissions were primary data acquired from laboratory measurements done by Rossi et al. (2024) regulated according to the Euro 6d standard (European Commission 2017). Tests were performed according to the Worldwide Harmonized Light Vehicle Test Cycles (WLTC) by driving a vehicle on a chassis dynamometer to measure exhaust

emissions and fuel consumption (Table 2). For the fuel blend, CO, CO<sub>2</sub>, and CH<sub>4</sub> emissions were divided into fossil and biogenic emissions to account for the fraction of biogenic carbon in the blend coming from bio-LPG and r-DME. Secondary data used to determine other exhaust emissions was obtained from the EMEP/EEA air pollutant emission inventory guidebook 2019–Updated October 2020 (EEA 2019). Due to the absence of emission standards specifically focused on DME as a fuel, values referred to LPG passenger cars were assumed to be representative of the fuel blend emissions. Additional assumptions to determine exhaust emission factors for the different fuels and car types are summarized in Table 3.

### Results and discussion

The following section describes the remaining two steps of an LCA study, i.e. the LCIA results and an interpretation of the findings. The results highlight the climate

**Fig. 3** Flow diagram of the production of bio-DME



**Table 2** Critical inventory data referred to the functional unit (1 km driven by the passenger car)

| Fuels and exhaust emissions | Unit  | B-segment petrol | C-segment petrol | B-segment blend | C-segment blend |
|-----------------------------|-------|------------------|------------------|-----------------|-----------------|
| Petrol                      | L/km  | 5.75E-02         | 6.44E-02         | –               | –               |
| Blend                       | L/km  | –                | –                | 7.50E-02        | 9.10E-02        |
| Exhaust emissions           |       |                  |                  |                 |                 |
| CO <sub>2</sub>             | g/km  | 1.31E+02         | 1.47E+02         | 1.12E+02        | 1.36E+02        |
| CO                          | mg/km | 3.26E+02         | 1.32E+02         | 2.32E+02        | 2.05E+02        |
| CH <sub>4</sub>             | mg/km | 2.59E+00         | 2.86E+00         | 2.67E+00        | 6.10E+00        |
| Non-methane hydrocarbons    | mg/km | 3.50E+01         | 1.16E+01         | 1.94E+01        | 2.42E+01        |
| NO <sub>x</sub>             | mg/km | 5.19E+00         | 8.21E+00         | 7.88E+00        | 2.53E+01        |
| Particulate matter          | mg/km | 2.94E-03         | 6.18E-04         | 5.13E-03        | 1.03E-02        |
| NH <sub>3</sub>             | mg/km | 1.33E+01         | 1.37E+01         | 7.68E+00        | 1.02E+01        |
| N <sub>2</sub> O            | mg/km | 5.85E-01         | 1.15E+00         | 1.00E+00        | 3.08E+00        |

**Table 3** Additional assumptions for other exhaust emissions obtained from EEA (2019)

| Other exhaust emissions <sup>a</sup> | Additional assumptions  |
|--------------------------------------|---|
| SO <sub>2</sub>                      | Sulphur in the fuel is completely oxidized into SO <sub>2</sub>   |
| NO, NO <sub>2</sub>                  | NO <sub>2</sub> /NO <sub>x</sub> ratio referred to a Euro 6d petrol passenger car (P) <sup>b</sup> and a Euro 6 LPG passenger car (BL) <sup>c</sup> to divide emissions   |
| Heavy metals                         | Emission factors referred to a petrol passenger car (P). Neglected for (BL) since no emission factors were available for LPG passenger cars   |
| Lead                                 | For (P): Emission factors referred to a Euro 6d small petrol passenger car (B-segment) and Euro 6d medium petrol passenger car (C-segment). For (BL): Emission factors referred to a Euro 6d LPG passenger car (for both B- and C-segment cars) |
| PAHs, POPs                           | Emission factors referred to a Euro 1 and on petrol passenger car (P) and an LPG vehicle (BL)   |
| Other POPs (PCDD, PCDF, PCB)         | Emission factors referred to a Euro 5 and 6 petrol passenger car (P). Neglected for (BL) since no values were available for LPG vehicle   |

<sup>a</sup>Legend: PAH = polycyclic aromatic hydrocarbons, POP = persistent organic pollutants, PCDD = polychlorinated dibenzodioxins, PCDF = polychlorinated dibenzofurans, PCB = polychlorinated biphenyls

<sup>b</sup>(P) refers to the scenarios where petrol is used as fuel

<sup>c</sup>(BL) refers to the scenarios where the blend is used as fuel

change impact category as well as a summary of the overall results.

## Climate change

Climate change accounts for all emissions of greenhouse gases that ultimately increase the average global temperature (Zampori and Pant 2019). The results of the LCIA for climate change are shown in Fig. 4. For the petrol car, 75% of the impact is due to the emission of CO<sub>2</sub> from the tailpipe (TTW) and 25% to the production of petrol (WTT). Regarding the blends, almost 60% of the total impact is due to the TTW stage and specifically due to CO<sub>2</sub> emissions from fossil LPG combustion. CO<sub>2</sub> emissions from the combustion of bio-LPG, bio-DME, and e-DME were excluded since carbon neutrality was assumed for these renewable fuels. The remaining impact is caused by the WTT stage of the three

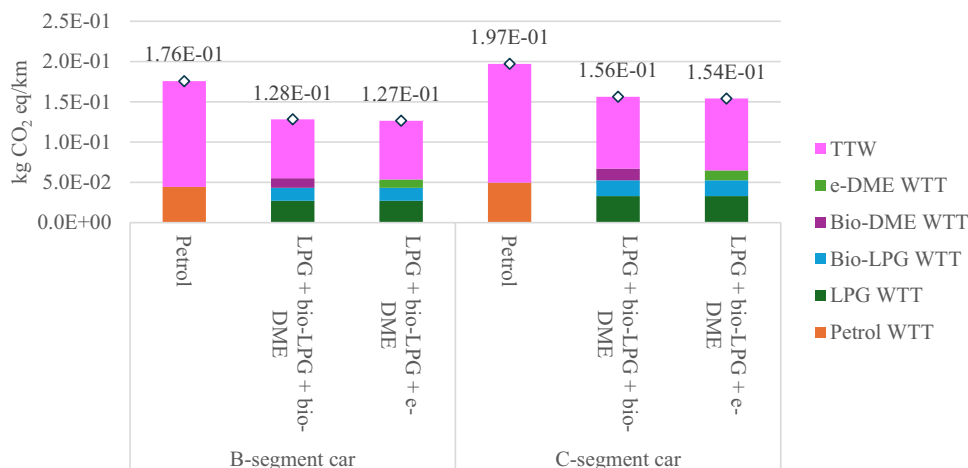
fuels (21% from fossil LPG production, 12% from bio-LPG production, and around 8% from bio-DME/e-DME production) mainly due to CO<sub>2</sub> and CH<sub>4</sub> emissions.

## Overall results

Table 4 displays the percentage change for each impact category compared with results obtained from the use of petrol as fuel. To distinguish between the two sources of r-DME considered in this analysis, Blend A will be used to refer to the blend containing the mixture of fossil LPG, bio-LPG and bio-DME, while Blend B represents that containing e-DME as the source of DME input.

The values in green represent an improvement greater than 10%, while the values in red represent a worsening greater than 10%. Variations between –10% and +10% were assumed to be negligible to account for uncertainties experienced within any LCA study. Based on these results,

**Fig. 4** Environmental impacts for the “Climate change” impact category, expressed in terms of kg CO<sub>2</sub> eq/km. The white marker refers to the “Well-to-Wheels” impact



**Table 4** Results of the LCIA obtained for 16 impact categories and expressed as a percentage change when compared with petrol as fuel source

|                                    | B-segment car |         | C-segment car |         |
|------------------------------------|---------------|---------|---------------|---------|
|                                    | Blend A       | Blend B | Blend A       | Blend B |
| Acidification                      | 19%           | 10%     | 34%           | 25%     |
| Climate change                     | -27%          | -28%    | -21%          | -22%    |
| Ecotoxicity, freshwater            | -64%          | -64%    | -61%          | -61%    |
| Particulate matter                 | -20%          | -26%    | -10%          | -17%    |
| Eutrophication, marine             | 26%           | 26%     | 53%           | 53%     |
| Eutrophication, freshwater         | 228%          | 249%    | 256%          | 278%    |
| Eutrophication, terrestrial        | 25%           | 24%     | 55%           | 53%     |
| Human toxicity, cancer             | 10%           | 22%     | 20%           | 34%     |
| Human toxicity, non-cancer         | 17%           | 17%     | 27%           | 27%     |
| Ionising radiation                 | 181%          | 6%      | 204%          | 14%     |
| Land use                           | -1%           | -3%     | 8%            | 5%      |
| Ozone depletion                    | -39%          | -54%    | -34%          | -50%    |
| Photochemical ozone formation      | -18%          | -17%    | -1%           | 1%      |
| Resource use, fossils              | -24%          | -25%    | -18%          | -19%    |
| Resource use, minerals, and metals | 930%          | 918%    | 1016%         | 1002%   |
| Water use                          | 1077%         | 4254%   | 1175%         | 4616%   |

all scenarios indicate savings in GHG emissions and use of fossil resources, reduction in freshwater ecotoxicity and ozone depletion, and decreased particulate matter emissions. This improved performance is most likely due to the avoided crude oil extraction and processing needed for petrol production. However, the blends have worse impacts on acidification, on resource use in terms of minerals and metals, on water use, on human toxicity, and all types of eutrophication. A drop in performance of the blends is expected within these categories because the production of biofuels and e-fuels is energy-intensive and relies on the use of natural resources (such as water) other than oil. Specifically, mineral and metal resource use was significantly higher for the blends, compared to petrol. These impacts are mostly caused by the requests of copper for the chemical factory used by ecoinvent in the datasets of LPG and DME production, and by the request of platinum-based catalysts in the bio-LPG production. Regarding the higher water consumption of the

blends, it is due to the high consumption of water in the bio-LPG factory, and additionally, for the e-DME, to the hydropower-based water electrolysis. The higher impact in freshwater eutrophication can be found in the disposal of wastes from lignite and hard coal extraction (fuels being part of the energy mix used in several processes) and in the disposal of waste from platinum extraction (for the catalysts used in the bio-LPG production). Lastly, high ionizing radiation (due to radioactive emissions from the nuclear portion of the electricity mix) was observed for blend A as compared to petrol. This is primarily due to high electricity demand associated with the production of the three separate fuels in the blend, especially bio-DME, which requires significant energy for carbon capture, biogas upgrading, and synthesis.

Comparing the two blends, blend B generally has a better (or identical) performance than blend A in almost all impact categories except freshwater eutrophication, cancerous human toxicity, and water use. Blend B has much larger

savings on ozone depletion, mainly because the oxygen obtained from electrolysis during e-DME production allows for an assumption of avoided oxygen production, which can offset the effect of other synthesis processes. Blend B also has a much lower impact on ionizing radiation than blend A because high electricity requirements for bio-DME production imply a larger impact on ionizing radiation due to the nuclear fraction in the electricity grid. However, the significant difference in the impact on water use between the two blends is due to the fact that the hydrogen for the production of e-DME in blend B is obtained from water and hydroelectric power. Moreover, comparing the two car segments, lower savings are observed with the C-segment car than with the B-segment car in all the categories, with decreased impact (depicted by the green values). Similarly, larger effects were observed for the C-segment car in the categories with increased impact (shown in red). This can be attributed to the fact that the C-segment car has a greater fuel consumption, which translates to larger emissions.

If each impact category is assigned equal importance, it is possible to allocate a ranking to each scenario based on its performance by counting the number of impact categories indicating an improvement in the impact in comparison to petrol use and appointing the highest rank to the scenario with the greatest number of improved categories. Accordingly, for the B-segment car, both blends result in 6 improved impact categories; however, blend B ranks first because it offers higher savings than blend A for all these categories. Similarly, for the C-segment car, both blends result in 5 improved impact categories, with blend B offering higher savings. This implies that the blend with e-DME in a B-segment car and the blend with bio-DME in a C-segment car are, respectively, the best and worst scenarios out of those analysed in this study. Since policies on biofuels and e-fuels are primarily focused on their impact on climate change, the main criterion behind the choice of an alternative energy carrier is its ability to reduce the impact on the climate change impact category. The second target would be at least to maintain the same impact on other impact categories, or if possible, to also improve their performance. Consequently, the previous ranking holds, with blend B being the best alternative to petrol since it has the best performance on climate change, it has the highest number of improved impact categories, and it is mostly associated with a lower increased impact on other impact categories than blend A.

## Conclusion

A reduced impact on climate change was observed for all scenarios as compared to using petrol, with GHG savings of around 27% for the B-segment car and 21% for the C-segment

car. All scenarios indicated savings for the following impact categories: climate change, use of fossil resources, freshwater ecotoxicity, ozone depletion, and particulate matter. The improvement can be attributed to the avoided crude oil extraction, processing, and petrol production. However, the blends had worse impacts on acidification, on water use, on human toxicity, on resource use in terms of minerals and metals, and on all types of eutrophication. This is mainly because the production of biofuels and e-fuels is energy-intensive and relies on the use of natural resources other than oil. The scenario Blend B in the B-segment car had the best environmental performance, offering the highest GHG emission savings, the largest number of impact categories with reduced impact, and the lowest increase in other impact categories. The scenario Blend A in the C-segment car has the worst environmental performance with the least number of impact categories improved. Moreover, blend B generally indicated better results than blend A, mainly due to avoided oxygen production in blend B scenarios, and C-segment cars were found to have a worse performance than B-segment cars because of higher fuel consumption and thus increased emissions.

One of the limitations of this analysis was that the performance was only evaluated for an ICEV, so future research could focus on comparing the results with EVs to gain more robust conclusions in terms of the performance of renewable fuels versus EVs. Since only 20% bio-LPG and 20% r-DME were included in the blend, it would also be interesting to test blends with higher percentages. Moreover, this analysis focused on the WTW results of the fuels, so further research could be done to perform a complete cradle-to-grave analysis, which would include additional considerations such as accounting for the non-exhaust emissions and the life cycle of the car.

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**Data availability** All data supporting the findings of this study are available within the paper and the references cited therein.

## Declarations

**Conflict of interest** The authors declare no competing interests.

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