Journal of Environmental Management 371 (2024) 123258

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Biohydrogen with negative CO_2 emissions from municipal solid waste for decarbonising the public bus fleet. Application to the municipality of Madrid

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A R T I C L E I N F O

Handling editor: Jason Michael Evans

Keywords:
Biohydrogen
Municipal solid waste
Greenhouse gases (GHG)
Steam methane reforming
Carbon capture and storage (CCUS)
Fuel-cell electric vehicles (FCEV)

A B S T R A C T

This study assesses the production potential, environmental impact, and economic viability of generating biohydrogen from biomethane obtained from the organic fraction of municipal solid waste (MSW) using steam methane reforming with carbon capture and storage (CCS). As the emissions are biogenic, CCS results in negative emissions. The methodology is based on a previously developed model, including techno-economic analysis based on the levelised cost of hydrogen (LCOH) and mobility (LCOM), and environmental assessment, focusing on production potential, cost estimates, and emissions impact. A case study is conducted to assess the feasibility of using this biohydrogen with negative emissions to decarbonize Madrid's public bus fleet. The findings reveal that Madrid's MSW could meet the entire hydrogen fuel demand if the fleet consisted of fuel-cell buses. However, given the high costs of replacing the entire fleet, a net-zero solution is proposed, combining 60% fuel-cell buses with existing natural gas-powered buses. In this configuration, the negative emissions from biohydrogen offset the fossil emissions from natural gas and 40% of biomethane is saved. The cost of the net-zero fleet ranges between 192.55 and 209.37 €/100 km, comparable with 100% natural gas fleet, which ranges between 176.19 and 217.69 €/100 km.

1. Introduction

The road transport sector represented the first emitting Spanish economic sector, with around 29.8% of Spain's total net greenhouse gas (GHG) emissions in 2021, of which 27.8% were due to heavy-duty trucks and buses (EEA, 2023). In absolute values, road transport accounted for 84,777 kt CO_{2eq}, with heavy-duty trucks and buses being responsible for 19,794 kt CO_{2eq} (EEA greenhouse gases, 2023). A promising technology to displace these emissions is fuel cell electric vehicles (FCEV) running on renewable hydrogen. The principle of a fuel cell resides in an electrochemical reaction consuming hydrogen and oxygen, thus producing electricity to power an electrical motor (Morante et al., 2019). Water is the only by-product of fuel cell technologies used in transport applications. As an electrochemical device (direct energy conversion system), its efficiency is higher than traditional internal combustion engines (ICE) as it does not suffer from the Carnot theorem that defines a maximum efficiency in a power thermodynamic cycle to produce work from thermal energy. As public transport is one of the levers to make passenger transport more sustainable, buses powered with FCEV technology might play a key role in decarbonising transport in cities. In this way, countries such as the Netherlands have made sustainable transport powered by alternative fuels a pillar of their public transport plans for the future (Ministry of Infrastructure and Water Management, 2019).

To be considered a sustainable solution, the FCEV buses need to be fuelled with renewable hydrogen. Although the current debate is focused on the hydrogen production by electrolysis of water (Nelson et al., 2022), the technology is not fully mature. By contrast, a natural gas production technology that is fully mature and has been used by the oil industry for several decades now (Baltac et al., 2022) is steam

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https://doi.org/10.1016/j.jenvman.2024.123258
Received 21 November 2023; Received in revised form 28 October 2024; Accepted 3 November 2024
Available online 9 November 2024

Nomenclature

AD	anaerobic digestor
BECCS	bioenergy carbon capture and storage
BEV	battery electric vehicle
BGOMR	biogas-to-organic matter ratio, Nm^3/t OM
BM	biomethane
BMPp	biomethane production available, Nm^3 CH_4/(pax year)
C	yearly cost, €/year
CAPEX	Capital expenditures, €/kg H_2 of €/100 km
CCS	carbon capture and storage
CDR	carbon dioxide removal
CHMR	mass ratio of carbon dioxide to hydrogen, kg CO_2/kg H_2
CELF	constant escalation levelisation factor, p.u.
CRF	capital recovery factor, $year^{-1}$
ETS	Emissions Trade System
FCEV	Fuel cell electric vehicle
GHG	Greenhouse gases
GO	Guarantee of origin certificate
HD	hydrogen demand of a FCEV bus, kg H_2/100 km
HHV	higher heating value, kWh/Nm^3
HMR	molar ratio of hydrogen to methane, Nm^3 H_2/Nm^3 CH_4
HP	yearly hydrogen production, kg H_2/year
HPp	hydrogen production potential, kg H_2/(pax year)
HRS	hydrogen refuelling station
ICE	Internal combustion engine
ICE-NG	internal combustion engine fuelled with natural gas
ICE-BM	internal combustion engine fuelled with biomethane
INV	investment, €
LCA	Life cycle analysis
LCOH	levelised cost of hydrogen, €/kg H_2
LCOM	levelised cost of mobility, €/100 km
LHV	lower heating value, kWh/Nm^3
M	molar mass, kg/kmol
MD	methane demand of an ICE bus, Nm^3 CH_4/100 km
MF	methane fraction in volume of the biogas, Nm^3 CH_4/Nm^3
MSW	municipal solid waste
MSWP	average production of MSW, t MSW/(pax year)
NDC	Nationally Determined Contributions
Ny	life span of the project
NG	natural gas
OF	organic fraction, t OM/t MSW
OFMSW	organic fraction of the municipal solid waste
OM	organic matter
O&M	operation and maintenance
OPEX	operational costs, €/kg H_2 or €/100 km
PBMD	primary biomethane demand, Nm^3 CH_4/100 km
PTV	Technological Park of Valdemingómez
Q	volume flow rate, Nm^3/h
r	nominal escalation rate, p.u.
SMR	steam methane reforming
v	specific volume as ideal gas, 22.4 Nm^3/kmol in normal (N) conditions
wacc	weighted average capital cost, p.u.
WGSR	water gas shift reaction
WtH	waste to hydrogen

Greek symbols

η	Energy efficiency, p.u.

Subscripts and superscripts

0	zero year of the project
bg	biogas
N	normal conditions (101.325 kPa; 273.15 K)
om	operation and maintenance
smr	steam methane reforming
sto	underground geological storage
tax	tax
tpt	transport of CO_2 from the SMR plant to the underground geological storage
ug	upgrading
x	index for each type of cost

methane reforming (SMR), accounting for 62% of the 94 million tonnes of hydrogen produced worldwide in 2021. The two other main hydrogen production routes are coal gasification (19% of the total production) and hydrogen as a by-product of naphtha reforming at refineries (18%). Electrolysis only accounts for a mere 0.04% of the total production (IEA, 2022). In order to face mounting carbon emissions costs, the oil industry has been implementing carbon capture and storage (CCS) technology over the last 20 years (Lipman, 2004). Hydrogen produced from natural gas using the SMR process is categorized as blue hydrogen when carbon capture is implemented during the production process. On the other hand, if the carbon capture process is not employed, it is referred to as grey hydrogen (Nelson et al., 2022).

Waste can also be a source of renewable hydrogen. Recent research on waste-to-hydrogen (WtH) technologies usually focuses on technologies that directly produce hydrogen from waste. The thermochemical WtH technologies are the most studied (Lui et al., 2020), namely gasification and pyrolysis of waste. The research in biochemical WtH technologies is currently focused on dark fermentation and photofermentation of organic waste (Lui et al., 2020). Many of these technologies are still in their infancy commercially.

Another possible way to obtain renewable hydrogen is by using organic waste to produce biogas. After being upgraded to biomethane, it can replace natural gas in the SMR process, as considered by the Spanish Government in its renewable hydrogen roadmap (MITERD, 2020). The European Biogas Association (EBA) considers the process a mature technology and assigns it negative emissions if CCS is carried out (Pasteris et al., 2023). Lou et al. (2023) deep into such idea, analysing the decarbonising potential in different industrial sectors. They also claim that, unfortunately, biohydrogen with carbon-negative emissions is not being paid attention to by policymakers despite its potential to create a net-zero world. Biogas can be obtained thanks to the anaerobic digestion of organic waste, the origin of which can vary (crop waste, agro-industrial waste, slurry, manure, wastewater treatment plant sludge, municipal solid waste, and landfill gas). It consists of a mix of methane, carbon dioxide and various impurities (H_2S, etc.). Typical applications for biogas have included on-site combustion or its injection into the natural gas grid after the upgrading to biomethane. In the first case, biogas is burned in a boiler (Picardo et al., 2019) or in a combined heat and power (CHP) internal combustion engine or gas turbine (Amaral et al., 2020) after a purification process, while in the second case, biogas is also cleaned of its impurities, and upgraded to biomethane (CO_2 removing) to become pure methane (Feliu and Flotats, 2019). Even there are uses of biogas as chemicals feedstock, as proposed by Amaral et al. (2020). Applying anaerobic digestion to municipal solid waste (MSW) allows an integrated waste management strategy with other waste flows, as showcased by Novotny (2022), thus avoiding GHG emissions like methane leakage from landfills. It also has the advantage of avoiding the competition for land use devoted to crops, a big issue for biomass as a decarbonising route (Material Economics, 2021). Indeed, it is the waste of the necessary food production for the population. This waste management strategy is replicable in many countries, especially developing ones. In fact, anaerobic digestion has revealed itself as an

MSW management technology easily implementable in developing countries, where food represents a higher share of MSW (Khan, 2020). Finally, the biogas produced from MSW does not suffer the usual logistical issues of organic waste from other waste (crops, manure, agro-industrial …), as it is already collected and centralised in processing plants.

According to the report (United Nations Environmental Programme, 2024), approximately 2.1 billion tonnes of MSW were generated globally per year in 2020. Without urgent action, this figure is projected to reach 3.8 billion tonnes by 2050 due to economic and population growth. In 2020, the global cost of waste management was USD 252 billion, USD 361 billion if hidden costs of pollution and climate change are included. Without intervention, these costs could reach USD 640.3 billion by 2050. Implementing prevention measures and efficient waste management could limit costs to USD 270.2 billion per year. In addition, a circular economy approach could generate an annual net gain of USD 108.5 billion by preventing waste generation, encouraging sustainable business practices and ensuring integrated waste management. The report also highlights the importance of including waste generation and management in Nationally Determined Contributions (NDCs) to effectively combat climate change. The impact of waste on greenhouse gas (GHG) emissions has traditionally been underestimated, resulting in underinvestment in this area. However, recent studies suggest that improved waste management could reduce global GHG emissions by 15–25%, and underline the need to include this aspect in all countries' NDCs.

The composition of waste varies according to factors such as economy, climate, population density and cultural practices. Globally, organic waste from food and garden waste represents, on average, more than 50% of the total waste mass, while in Europe this proportion is slightly lower, at around 40%. One of the main challenges is to transform this organic matter into valuable resources, e.g. through anaerobic digestion, generating biogas and digestate. The digestate can be used for agricultural purposes, either as a fertilizer or as an amendment to improve soil quality. In this context, while improving waste management globally requires significant investments, the most cost-effective and efficient strategy remains to reduce waste generation and recover secondary materials. This highlights the importance of moving towards circular and waste-free economies, generating clear benefits in economic, social and environmental terms.

One advantage of using MSW as feedstock for biohydrogen with negative emissions is that its cost remains stable, as there is no speculation on its demand. This waste is collected by the municipality as a service, even charging a tax to the inhabitants. Additionally, the collection infrastructure is already in place. These factors contribute to the expected stable price of biohydrogen with negative emissions.

Adding carbon dioxide capture to the proposed technological route unblocks the potential for negative CO_2 emissions, as the captured CO_2 is considered biogenic. Such a setting follows the principles of bioenergy carbon capture and storage (BECCS), where photosynthesis is leveraged to capture atmospheric carbon dioxide, being included in the carbon dioxide removals (CDR) (European Commission, 2024a). A UK government initiative has been in place since 2021 in the shape of an innovation program to foster the hydrogen produced following a BECCS approach GOV.UK, 2022. Lou et al. (2023) assign a carbon footprint of up to -26.5 kg CO_{2eq}/kg H_2 to biohydrogen from SMR of biomethane with CCS, depending on the origin of the feedstock. The technology readiness level (TRL) assigned by Pasteris et al. (2023) to this technology ranges between 8 and 9, that is, the maximum.

Many studies have employed life cycle analysis (LCA) to assess and compare the sustainability of different routes to produce hydrogen. This method has also been used to compare biohydrogen's sustainability with electrolytic and with fossil hydrogen. Among these studies, the techno-environmental assessment of hydrogen production by different reforming processes using natural gas and biomethane, both with and without CCS, is found (Antonini et al., 2020). Arfan et al. (2023) analyse biohydrogen production from different feedstocks (organic waste and biomass) using different technologies. Kolahchian Tabrizi et al. (2023) assessed the global warming potential of hydrogen production through alkaline electrolysis using state-of-the-art photovoltaic panels in Italy. Several authors have compared the global sustainability (environmental, economic and social) of different routes to produce hydrogen: biohydrogen and hydrogen in Valente et al. (2021) and biotechnological and thermochemical routes to produce biohydrogen in Morya et al. (2022). The use of biohydrogen in fuel cell electric vehicles has also been assessed using LCA techniques, as in Lui et al. (2022).

This new type of renewable hydrogen might help to compensate with its negative emissions the unavoidable emissions from hard-to-abate sectors like the cement industry, the second-largest industrial CO_2 emitter in the world (IEA, 2018). It has been named *golden* hydrogen by Soler et al. (2022), and the conceptual process is sketched in Fig. 1. Organic waste (in this case, MSW) feeds an anaerobic digestor (AD), which produces biogas and digestate, a by-product which can be used as organic fertilizer once treated (Song et al., 2021). The second step is the upgrading (UG), where biogenic CO_2 is removed. The third step is analogous to the procedure to produce fossil hydrogen from natural gas: a steam methane reformer unit (SMR) is used, producing hydrogen and biogenic CO_2. If this CO_2 is released into the environment, renewable (CO_2 neutral) hydrogen is obtained (green); on the contrary, if CO_2 is captured and stored, negative emissions are produced, designating this kind of hydrogen as golden hydrogen. The reason for this name is that blue hydrogen is associated with CO_2 capture and subtracting the blue colour from the green one, yellow colour is obtained. As this colour is usually associated with the hydrogen produced by electrolysis fed by the grid, it has been transformed into "golden", taking into account its high value associated with negative emissions. While CO_2 extracted from biogas is typically released into the environment, there is a growing interest in utilizing it, as it is neutral and can be employed in the production of neutral e-fuels (Lorin et al., 2022).

The objective of this work is to assess the technical feasibility, environmental impact, and economic viability of using biohydrogen for public transport, produced by SMR of biomethane obtained from MSW, with carbon capture and storage. A key point in hydrogen projects is the accounting for the demand, which is solved in this case through the public bus fleet. The work analyses the feasibility of obtaining a net-zero fleet using the self-produced golden hydrogen from the MSW. The current fleet has a small quantity of battery electric vehicles (BEV), whereas most buses are powered with internal combustion engines (ICE) fuelled with natural gas. The final proposal is to maintain a share of buses with ICE fuelled with natural gas, whose CO_2 emissions would be compensated by the golden hydrogen used as fuel in the rest of the buses powered by a fuel cell. If the resource in the municipality of Madrid allows such fleet composition, the trinomial of energy transition would be solved: a net-zero fleet would be achieved (sustainability) with self-produced resources (security supply) and affordable costs (economy). The solution proposed tackles organic waste management and the decarbonising of public transport, converting the former into the fuel of the latter, compensating the emissions of the remaining fossil buses, thus taking advantage of a new production process of renewable biohydrogen with negative emissions which has not received the due attention so far.

2. Methodology

2.1. Production

As explained in the introduction, the cornerstone of the golden hydrogen production technological route is the steam methane reforming (SMR) process using biomethane as feedstock. The process consists of two phases. The first phase is the reforming reaction expressed in Eq. (1), where each mole of methane theoretically produces 3 mol of hydrogen. It is followed by the water gas shift reaction (WGSR), summarised in Eq. (2), that maximises the hydrogen yield of the steam

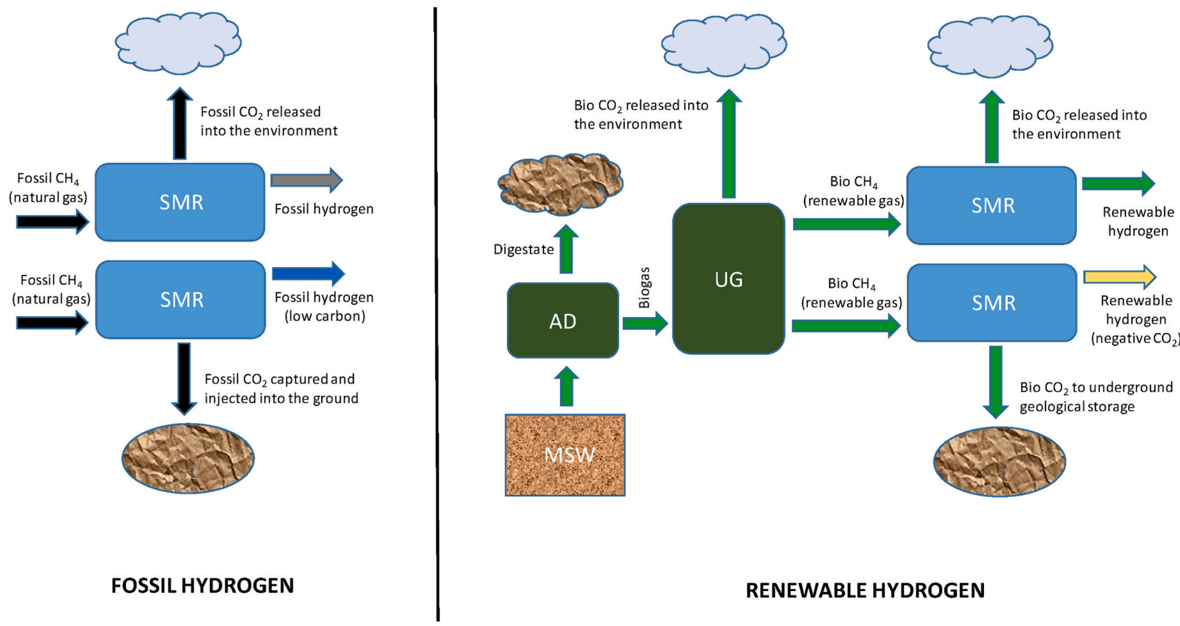


Fig. 1. Alternative routes to produce hydrogen. Fossil hydrogen (grey and blue one) is sketched on the left, whereas renewable one (green and golden) is on the right.

methane reforming process by completing the oxidation of the carbon atom in the carbon monoxide molecule, thus producing an additional fourth mole of hydrogen. As the reforming reaction is endothermal and requires high temperatures, around 700-1100 °C (Morante et al., 2019), part of the input methane is self-consumed to maintain those thermal conditions. Soler et al. (2022) compute the molar ratio of hydrogen to methane (*HMR*) and the mass ratio of carbon dioxide to hydrogen (*CHMR*) through Eqs. (3) and (4), where η_{smr} is the energy efficiency of the SMR and *LHV* is the lower heating value of both gases (3 kWh/Nm^3 for hydrogen and 9.952 kWh/Nm^3 for methane). Regarding the carbon dioxide capture potential, if the CO_2 capture system is placed on the flue gas the most optimal capture rate can be obtained (90%) (Baltac et al., 2022). Employing the usual values of efficiencies (Baltac et al., 2022), Soler et al. (2022) obtain the results listed in Table 1. Taking into account the higher heating value (*HHV*) of methane (11.04 kWh/Nm^3) the specific consumption of SMR is assessed, resulting 49.11 MWh-HHV of methane per ton of hydrogen when no CCS is used or 53.94 MWh-HHV/t when CCS is used. In terms of hydrogen production, these figures are 20.36 t H_2/GWh-HHV CH_4 and 18.54 t H_2/GWh-HHV CH_4, respectively.

$$CH_4 + H_2O \rightarrow CO + 3\,H_2 \tag{1}$$

$$CO + H_2O \rightarrow CO_2 + H_2 \tag{2}$$

$$HMR = \eta_{smr} \cdot \left(\frac{LHV_{CH_4}}{LHV_{H_2}} \right) \tag{3}$$

$$CHMR = \frac{M_{CO_2}}{HMR \cdot M_{H_2}} \tag{4}$$

The resulting hydrogen production potential, modelled by the variable *HPp*, is calculated with Eq. (5a), where *MSWP* is the average production of MSW and *BGOMR* is the biogas-to-organic matter ratio; *OF* is the organic fraction (%) of the MSW and *MF* is the methane fraction in volume (%) of the biogas. Joining the first terms in Eq. (5a) as the biomethane production available *BMPp*, Eq. (5b) is found. Using this formulation, Eq. (5a) can be expressed in a more compact form as in Eq. (5c).

$$HPp = \frac{MSWP \cdot OF \cdot BGOMR \cdot MF \cdot HMR \cdot M_{H_2}}{v_N} \tag{5a}$$

$$BMPp = MSWP \cdot OF \cdot BGOMR \cdot MF \tag{5b}$$

$$HPp = \frac{BMPp \cdot HMR \cdot M_{H_2}}{v_N} \tag{5c}$$

There is a certain variability in the municipal solid waste data and even in its leverage to produce biomethane. Table 2 collects data from Sedigas (2023), reflecting the national average of Spain, taken from national statistics of population and MSW between 2019 and 2021 and National Plan for Waste Management (MITERD, 2023). Currently, there are two biomethane production plants from MSW in Madrid, both in the waste management complex of Technological Park of Valdemingómez (PTV) (General Direction of Technological Park of Valdemingómez, 2021). These plants are La Paloma and Las Dehesas. Their data are also compiled in Table 2, showing that production yield in PTV is lower than the estimations made for the national average. This is mainly due to the lower waste production in Madrid, along with a lower organic fraction. The actual production from PTV is 176 GWh/year of biomethane (GASNAM, 2023) and the limited capacity of Las Dehesas and La Paloma plants does not allow to leverage all the biomethane potential yield. The average composition of the clean biogas produced is 51.6% of CH_4 and 48.4% of CO_2. According to General Direction of Technological Park of Valdemingómez, (2021), the PTV consists of 8 large facilities where MSW is subjected to separation, classification and recovery processes. These include anaerobic digestion of organic matter, enrichment of biogas to biomethane for injection into the natural gas grid and

Table 1
Conversion ratios for SMR with or without CO_2 capture. Adapted from Soler et al. (2022). Note that the units given for HMR are equivalent to [Nm^3 H_2/Nm^3 CH_4].

	η_{smr} p.u.	$HMR\ \frac{kmol\ H_2}{kmol\ CH_4}$	$CHMR\ \frac{kg\ CO_2}{kg\ H_2}$	H2 production $\frac{t\ H_2}{GWh - HHV\ CH_4}$	Capture efficiency %	CO_2 captured $\frac{kg\ CO_2}{kg\ H_2}$
Without CCS	0.759	2.52	8.74	20.36	–	0
With CCS	0.691	2.29	0.96	18.54	90	8.64

Table 2
Production potentials considered.

Source	*BGOMR·MF* [Nm^3 CH_4/t organic matter]	*MSWP* [kg/(pax·year)]	*OF* [%]	*BMPp* [Nm^3 CH_4/(pax·year)]	*HPp* [kg H_2/(pax·year)]
Sedigas (2023)	85.3	482	37	15.21	3.11
PTV La Paloma (*)	105.9	394	31.94	13.33	2.73
PTV Las Dehesas (*)	77.5	394	31.94	9.75	1.99

(*) General Direction of the Technological Park of Valdemingómez (2021)

production of biostabilised material and compost. The report details the volume of each waste fraction entering the park, based on the recorded weight of the trucks. For fractions containing organic matter, their composition is characterised, specifying the percentage of organic matter in each. By summing up the organic matter contributions of each fraction, it is calculated that the waste entering the park contains an average of 31.94% organic matter.

In this study, potential seasonal variations in waste composition were not considered. Instead, the annual average data provided by the report has been used, reflecting the actual figures throughout the year. This approach provides a comprehensive and consistent picture of waste behaviour, though it excludes fluctuations that might occur during different seasons. However, using these average values ensures a solid and representative basis for analysis, from which relevant conclusions can be drawn.

Fig. 2 depicts the supply chain required to produce golden hydrogen. The biomethane is produced in a decentralised scheme at different MSW treatment plants distributed along the outskirts of the city of Madrid. The biomethane produced is injected into the natural gas grid making use of guarantee of origin (GO) certificates. A centralised SMR plant is supplied with a quantity of natural gas from the grid equivalent to the previously injected biomethane and produces golden hydrogen and CO_2. At this point, two options are conceptually available: in the upper route in Fig. 2, a CO_2 geological storage is situated close to the SMR facility, and the hydrogen is transported by a grid to the demand location (a bus parking lot with a hydrogen refuelling station); in the lower route the SMR facility is located close to the demand, and the CO_2 is transported by a new grid to the geological storage. This second option is preferred in order to avoid the transport of hydrogen, with higher costs. The transport of hydrogen in volumes between 1 and 10 t/day over distances less than 100 km is typically done by truck, with costs estimated between 0.65 and 1.73 €/kg H_2 (MITERD, 2023). However, CO_2 transport costs in short onshore pipelines (up to 180 km) within the EU are estimated at 5 €/t CO_2 (0.043 €/kg H_2) (Itul et al., 2023). In this paper, a variant of the second route has been chosen: locating the SMR facilities in the MSW treatment plant, close to the biomethane production plant. This choice avoids the injection of biomethane into the natural gas grid, although it increases the hydrogen production costs due to lower economies of scale. However, this approach avoids the need for a large SMR facility by splitting it into smaller units, which is expected to be more widely accepted by public opinion. Biogenic CO_2 will serve as a raw material in the future defossilised economy, necessary for the production of synthetic fuels or other chemicals. So, to avoid competition between industries, only the carbon captured at the SMR plant is sent to underground geological storage while the CO_2 captured during the upgrading process remains available for utilization, as Fig. 2 shows.

2.2. Demand for buses

Cities such as Madrid (EMT Madrid, 2018) have strived in recent years to reduce emissions from their urban bus fleet by choosing internal combustion engines (ICE) models typically fuelled by natural gas. In Spain, these models represent the most significant alternative fuel technology in terms of the number of buses, accounting for 84.2% of all alternative fuel buses in 2022 (European Alternative Fuels Observatory, 2023). Unlike ICE buses, fuel-cell electric (FCEV) buses do not emit any GHG since the product of the fuel cell reaction is water. Additionally, when powered by golden hydrogen, FCEV buses can also compensate CO_2 emissions through the biogenic carbon dioxide captured in the SMR process (8.64 kg CO_2/kg H_2).

As mentioned earlier, the ICE bus model fuelled with natural gas is becoming widespread in city bus fleets, serving as a reference for comparing the performance of the FCEV bus. The natural gas (methane) consumption of an ICE bus (*MD*) has been assumed as 41.5 kg/100 km, according to actual measurements in a municipality near Madrid (Julià, 2016), while the hydrogen consumption of an FCEV bus (*HD*) is assumed as 9 kg/100 km (Stolzenburg et al., 2020).

One of the issues with biomass is its limited and inelastic production

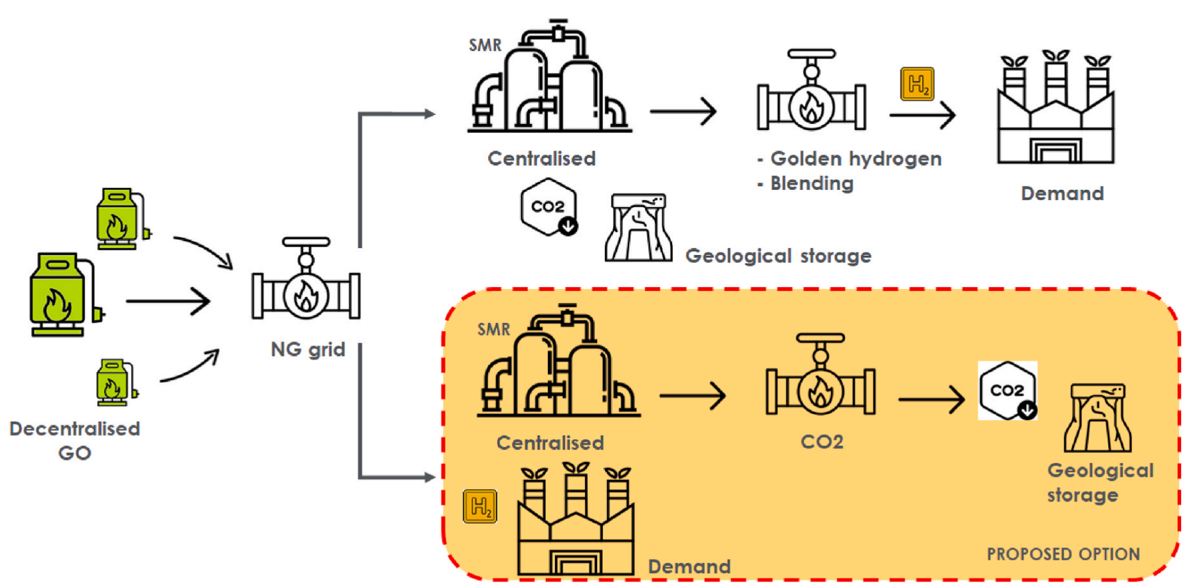


Fig. 2. Alternative supply chain in the production of golden hydrogen.

(Material Economics, 2021). Therefore, energy efficiency is paramount when using this renewable energy source. Consequently, the biomethane consumed by an ICE bus (*MD*) and the required biomethane to produce the golden hydrogen consumed by a FCEV are compared with the help of Eq. (6). This equation computes the biomethane needed to cover the hydrogen demand of an FCEV bus, where *PBMD* stands for the primary biomethane demand.

$$PBMD = \frac{v_N \cdot HD}{HMR \cdot M_{H_2}} \tag{6}$$

2.3. Emissions

The scope of this work is limited to direct emissions in the SMR process and in the combustion taking place in the ICE buses. The former relates to FCEV and is represented by Eq. (7), where only the captured emissions (negative) are considered (Table 1), as the CO_2 leaks have biogenic origin and are thus neutral. The latter are fossil and are given by Eq. (8), considering that all the CO_2 comes from the methane consumption, that is, there is a complete combustion (no CO is formed). Both equations represent relative emissions, that is, kg CO_2 are referred to 100 km.

$$CO2_{FCEV} = -8.64 \cdot HD \tag{7}$$

$$CO2_{ICE-NG} = \frac{M_{CO_2} \cdot MD}{v_N} \tag{8}$$

Although studies assessing the environmental impacts of hydrogen production by various technologies using Life Cycle Assessment (LCA) have been mentioned in the introduction, the objective of this study is not to perform an assessment of global warming potential through LCA. Instead, this study focuses exclusively on calculating the direct emissions from the SMR process and ICE buses. Conducting a full LCA of this process would require analysing the impacts of all stages involved, from the anaerobic digestion of waste and biogas enrichment to methane, to steam methane reforming, along with CO_2 capture and storage. It would also be essential to include the construction and maintenance of the vehicles and infrastructure, as well as the fuel use in the well-to-wheel cycle. These impacts would then need to be integrated into a comprehensive analysis. It should be noted that LCA results can vary significantly depending on the process modelling, scope, approach and assessment method used.

Existing literature includes several articles using LCA to focus on the first stage of the process, the anaerobic digestion of waste for biogas production. Emissions at this stage depend on factors such as the type of waste, energy self-sufficiency, the steps included in the analysis, and whether or not the agricultural use of the digestate is considered, as well as the allocation method applied (Duan et al., 2020; Wang et al., 2024). In addition, there are studies that evaluate different technologies for biomethane enrichment (Ardolino et al., 2021), and reports that examine hydrogen production from methane by reforming processes, with or without carbon capture (IEAGHG, 2022–07). Finally, studies by Bekel and Pauliuk (2019) and Cox et al. (2020) explore the impacts of fuels use in different types of vehicles, providing a broader view of the effects of transport technologies.

A study by Antonini et al. (2020) conducted a cradle-to-gate LCA to evaluate hydrogen production from natural gas and biomethane. The results showed that hydrogen produced from natural gas with CO_2 capture and storage had greenhouse gas emissions ranging from 2.6 to 5.6 kg CO_{2eq}/kg H_2, depending on the technology combinations evaluated. Without CCS, emissions increased to approximately 10.8 kg CO_{2eq}/kg H_2. When analysing hydrogen production using biomethane as feedstock, the study found that negative GHG emissions could be achieved if the resulting digestate is used as fertilizer and part of the carbon is sequestered in the soil. In this scenario, CCS would not be necessary to achieve negative emissions. However, if the digestate is incinerated or its land application does not result in long-term carbon sequestration, CCS would be indispensable to achieve negative emissions. In the most favourable configuration of technologies, combining biomethane with carbon capture, negative emissions of up to −15 kg CO_{2eq}/kg H_2 were achieved. In comparison, using the same configuration with natural gas resulted in emissions of approximately 3 kg CO_{2eq}/kg H_2.

2.4. Costs

2.4.1. Levelised cost of hydrogen

The levelised cost of hydrogen have been developed by Yagüe et al. (2024). To determine the cost of hydrogen production, the levelised cost of hydrogen (*LCOH*) ratio will be employed, using the formulation of Bejan et al. (1996). The *LCOH* is computed employing Eq. (9), where *INV* represents the investment, *HP* is the annual hydrogen production, *CRF* is the capital recovery factor, $CELF_x$ is the constant escalation levelisation factor for cost *x,* and *C* is the annual cost. The superscript *bg* stands for biogas, *ug* for upgrading, *om* for operation and maintenance, *CO2 tax* for the carbon tax, *CO2 tpt* for the transport of CO_2 to the storage and *CO2 sto* for the storage of the CO_2 at the underground site. The subscript *0* refers to the costs in year zero. The capital recovery *CRF* is calculated with Eq. (10), and $CELF_x$ using Eq. (11). For all three equations, *r* is the nominal escalation rate (equal to zero for all items except for the carbon tax), *wacc* is the weighted average capital cost, and *Ny* is the lifespan of the project. Considering *r* equal to zero leads to the factor in brackets in Eq. (12) being equal to the inverse of the capital recovery factor *CRF*, thus the constant levelisation factor $CELF_X$ becomes one. The term associated with the investment is usually denoted as "capital expenditures" (CAPEX), whereas the rest of terms are also designated as "operational expenditures" (OPEX).

$$LCOH = \frac{INV \cdot CRF + C_0^{om} \cdot CELF^{om} + C_0^{bg} \cdot CELF^{bg} + C_0^{ug} \cdot CELF^{ug}}{HP} + \frac{-C_0^{CO2\ tax} \cdot CELF^{CO2\ tax} + C_0^{CO2\ tpt} \cdot CELF^{CO2\ tpt} + C_0^{CO2\ sto} \cdot CELF^{CO2\ sto}}{HP} \tag{9}$$

$$CRF = \frac{wacc \cdot (1+wacc)^{Ny}}{(1+wacc)^{Ny} - 1} \tag{10}$$

$$CELF_x = \left[\frac{k_x \cdot (1-k_x^{Ny})}{1-k_x}\right] \cdot CRF \tag{11}$$

$$k_x = \frac{1+r_x}{1+wacc} \tag{12}$$

Here, the carbon tax is considered as a negative cost in Eq. (9), based on the assumption that capturing biogenic carbon dioxide emissions results in carbon credits for negative emissions. While this is not current possible in the existing Emissions Trading System (ETS), it could serve as a powerful policy mechanism for developing large-scale carbon capture technologies, such as Bioenergy Carbon Capture and Storage (BECCS), that go beyond merely offsetting emissions from the associated processes. So, the European Commission is promoting BECCS as a carbon dioxide removal technology (CDR), establishing funding mechanisms other than the ETS (European Commission, 2024a). There is a broad consensus within the scientific community regarding the role that CDRs should play in the ETS. For example, Fridahl et al. (2023) suggest that CO_2 removals cannot be limited to forestry and other land-use activities if climate policy objectives are to be achieved, but novel CO_2 removals such as BECCS are essential. Also, Rickels et al. (2021) claim that suitable incentive systems for CO_2 removal have to be designed and ETS must be opened to negative emissions technologies from a regulatory perspective. In the short term, a more realistic assumption for this component in Eq. (10) is that selling emissions rights is not possible, and thus, it does not constitute a revenue stream for hydrogen production. Under this assumption, $C_0^{CO2\ tax}$ is equal to zero, and the LCOH is referred to as the "gross cost", being designated as "net cost" if carbon tax generates a negative cost. Table 3 lists the values for each of the economic parameters in Eqs. (9)–(12).

For the investment, Yagüe et al. (2024) developed a scale law equation based on data from Lipman (2004), as presented in Eq. (13). This law has been updated to 2020, incorporating costs from Baltac et al. (2022). Maintenance costs have been assumed based on Lipman (2004), as this is consistent with the findings of Baltac et al. (2022). These costs are calculated using Eq. (14).

$$INV = 413.04 \cdot HP^{0.713} + 22.08 \cdot HP^{0.8592} \tag{13}$$

$$C_0^{om} = 0.148 \cdot HP \tag{14}$$

Feliu and Flotats (2019) provide a biogas cost of 35 €/MWh (LHV based). The cost of the upgrading process, calculated using Eq. (15) from Feliu and Flotats (2019), depends on the input volume flow rate of the treated biogas (Q_{bg}).

$$C_0^{ug} = \begin{cases} 39.276 \cdot HP \cdot Q_{bg}^{-0.705} & \text{if } Q_{bg} < 200\ Nm^3/h \\ 3.8400 \cdot HP \cdot Q_{bg}^{-0.265} & \textit{otherwise} \end{cases} \tag{15}$$

The carbon tax is set as 80 €/t, which corresponds to the average carbon emission price over the last 12 months up to March 2023 (Carbon Credits.com, 2023). Considering the *CELF* and the captured CO_2 (8.64 kg CO_2/kg H_2), this translates to 1.62 €/kg H_2. Itul et al. (2023) estimate CO_2 transport costs in the US to range between 1.8 and 12 €/t CO_2, depending on distance and volume. For the EU, a typical cost of 5 €/t CO_2 was considered for short onshore pipelines (180 km). To be conservative, an average value of 6.90 €/t CO_2 was applied, which converts to 0.06 €/kg H_2. In Spain, the available underground geological storage consists of deep saline aquifers, distributed from the centre of the Iberian Mainland to the northeast. Specifically, in Tres Cantos (28 km from Madrid), there is a site with an estimated capacity exceeding 2000 Mt CO_2 (IGME, 2014). Itul et al. (2023) also provided cost estimates for CO_2 storage in underground sites. For deep saline aquifers, the estimated cost range was 2–12 €/t CO_2, while higher costs (2–20 €/t CO_2) was expected for off-shore depleted oil and gas reservoirs. An average value of 11 €/t CO_2 was considered in this work, which converts into 0.1 €/kg H_2.

2.4.2. *Levelised cost of mobility*

To assess the economic competitiveness of the fuel-cell electric vehicle (FCEV) bus fuelled with golden hydrogen, its levelised cost per each 100 km (LCOM) will be compared with that of an internal combustion engine bus fuelled with natural gas (ICE-NG). The latter technology is the most representative of alternative fuel technologies in bus fleets in Spain (European Alternative Fuels Observatory, 2023). For the FCEV, the LCOM includes the LCOH, the levelised costs of the hydrogen refuelling station (HRS) (including investment and operation and maintenance) and the levelised costs of the bus (including investment and operation and maintenance). The nominal rates used in the LCOM have been set to zero, assuming the same project lifespan and weighted average capital cost as in the LCOH (Table 3).

Regarding the capital costs of the buses, EMT (2022) quotes 640,000 € for an FCEV bus, while Cano (2024) estimates 300,000 € for an ICE bus. For maintenance costs, Palencia (2023) reports similar values for an FCEV bus and a battery electric bus (BEV), at 28 €/100 km Quatrin (2022). In contrast, the maintenance costs for an ICE bus are double than those for a BEV (ENEL X, 2024) at 56 €/100 km.

Table 3
Assumed economic levelising parameters.

Parameter	Value
Weighted average capital cost, *wacc* (%)	8
Nominal escalation rate of fuel, r_{bg} (%)	0
Nominal escalation rate of maintenance, r_{om} (%)	0
Nominal escalation rate of upgrading, r_{ug} (%)	0
Nominal escalation rate of the carbon tax, $r_{CO2\ tax}$ (%)	8
Nominal escalation rate of the carbon transport, $r_{CO2\ tpt}$ (%)	0
Nominal escalation rate of the carbon storage, $r_{CO2\ sto}$ (%)	0
Lifespan of the project, N_y (years)	25

The costs for the hydrogen refuelling station (HRS) are provided by (Griñán, 2023). For an HRS with a capacity of 1000 kg H_2/day, they report the levelised costs (investment and operational costs excluding hydrogen cost) as 3.8 €/kg H_2, with an investment of 3.2 M€.

The costs of natural gas for an ICE-NG bus in the retail market in Madrid fluctuated between 1 €/kg CH_4 in January 2022 and 2 €/kg CH_4 in December 2022 (Gasolineras GNC, 2023). Therefore, the fuel cost for an ICE bus consuming 41.5 kg of methane per 100 km ranged from 41.5 €/100 km in January 2022 to 83 €/100 km in December 2022. As mentioned earlier, the price of golden hydrogen is expected to remain relatively stable.

In the near term, a second phase of the Emissions Trading System, known as ETS 2 (European Commission, 2024b), is planned. This phase will include the transportation and building sectors, leading to carbon taxes being applied to road transport. In this work, the tax for ICE engines fuelled by fossil fuels is set at 80 €/t CO_2. Considering the natural gas consumption of 41.5 kg/100 km, this results in a cost of 9.13 €/100 km in the baseline year.

3. Results and discussion

The performance in terms of fuel consumptions and CO_2 emissions will be compared among the three powertrain technologies analysed (ICE-NG, ICE-BM and FCEV). Then, a case study will be conducted in the city of Madrid, involving the computation of fuel production potential, fuel requirements for the bus fleet, and the corresponding costs to achieve a net-zero fleet of buses.

3.1. *Comparison of technologies*

Considering the assumed hydrogen demand (Stolzenburg et al., 2020) for FCEV buses (9 kg H2/100 km) and the hydrogen production conversion given in Table 1 (18.54 t H_2/GWh-HHV CH_4), a primary biomethane demand of 44.02 Nm^3 CH_4/100 km is obtained. For ICE buses (whether fuelled with natural gas or biomethane), the methane demand is 58.1 Nm^3 CH_4/100 km, based on the natural gas consumption of 41.5 kg/100 km (Julià, 2016). These results are summarised in Fig. 3, along with the CO_2 emissions. The FCEV bus allows for higher efficiency in the valorisation of the MSW resource as it consumes 24% less methane despite involving an additional phase -the SMR process, which introduces irreversibility losses, as its efficiency only reaches 69.1%. This is due to the fuel cell's higher efficiency compared to the thermal

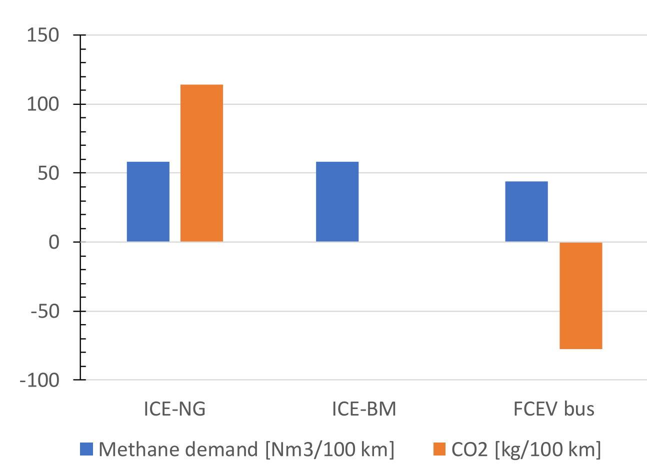


Fig. 3. Methane demand and CO_2 emissions for each of the three technological alternatives.

efficiency of the internal combustion engine. In terms of end use, the energy consumption of an FCEV is 302.4 kWh/100 km (based on a lower heating value of 33.6 kWh/kg H_2 a) whereas for an ICE it is 578.2 kWh/100 km (based on 9.952 kWh/Nm^3 CH_4).

Regarding carbon dioxide emission, again, the FCEV bus is the best alternative thanks to the biogenic carbon capture in the flue gas of the SMR process, achieving −77.4 kg CO_2/100 km. The emissions reached with ICE powertrains are, in the best case (ICE-BM), neutral or 114.1 kg CO_2/100 km when natural gas is used. Considering both fuel consumption and CO_2 emissions, the FCEV bus emerges as the best option, as it shows 24% lower methane consumption than the ICE-BM to travel the same distance. In addition, it generates negative emissions that can be used to offset other emissions. Therefore, taking the emissions of a car as a reference, a FCEV bus powered by golden hydrogen compensates for up to 8 cars emitting 95 g CO_2/km, the authorised emission limit in the EU (European Comission, 2023).

3.2. Case study Madrid

The city of Madrid has a total bus fleet of 2049 vehicles organised in 212 lines covering a total of 100,475,522 km/year (EMT Madrid, 2018). Currently, they are all ICE-NG. If all of these buses were converted into the fuel cell technology, with an average hydrogen consumption of 9 kg/100 km, this would result in a hydrogen demand of 9043 t/year.

On the production side, the city of Madrid has 3,334,730 inhabitants (INE, 2023). According to Table 2, the expected production of golden hydrogen at the PTV Las Dehesas facility is 6635 t/year, whereas at PTV La Paloma is 9070 t/year, corresponding to demand coverages of 73.37% and 100.3%, respectively. The higher yield in the PTV La Paloma biomethane production facility can be attributed to its more advanced technology, as it was inaugurated in 2008 while PTV Las Dehesas opened in 2000 (Madrid City Hall, 2023). For the assessment carried out in this work, the production from PTV La Paloma is considered, taking into account that new facilities are required to exploit the entire potential.

In terms of carbon dioxide emissions, the production potential of 9070 t H_2/year translates to 78,365 t CO_2/year of captured emissions in the SMR production. Considering that the average greenhouse gas (GHG) emissions per capita of Spain were 6.7 t $CO_{2,\ eq}$/(pax·year) in 2019 (Naturgy Foundation, 2019), the SMR process could contribute to offsetting the annual GHG emissions of a population of nearly 11,700 Spanish individuals. Regarding the biogenic CO_2 captured in the upgrading process from biogas to biomethane, up to 81,863 t CO_2/year could be produced, utilizing the full potential as indicated by La Paloma performance. As previously mentioned, in the proposed model, this CO_2 is reserved for potential future use in chemical applications within the defossilisation economy.

Although the resource in Madrid is enough to meet the demand, the high investment required for FCEV buses and the potential increase in the bus fleet suggest a hybrid solution that leverages the negative emissions associated with the golden hydrogen. For these calculations, each bus is assumed to run the average annual distance (49,036.4 km/bus). The idea is to divide the fleet into two segments: one comprising FCEV buses whose negative emissions fully offset the fossil emissions generated by the remaining fleet, composed of ICE-NG. This fleet configuration results in 59.48% FCEV buses and 40.53% ICE-NG buses, creating a surplus of biomethane (199.3 GWh-HHV). This surplus is sufficient to fuel an additional fleet of ICE-BM buses, capable of covering 31.1 million kilometres (30.93% of the current routes). In essence, the hybrid fleet could accommodate a 30.93% increase in routes with new ICE-BM buses while remaining a net-zero emissions fleet. Fig. 4 displays both the coverage level with each technology and their associated emissions: as previously mentioned, the more efficient utilization of biomethane by the FCEV results in broader coverage. The proposed hybrid solution enables the retention of part of the current fleet (40.53%) and its infrastructure, thereby reducing the investment in new FCEV buses, a key factor in the early stages of commercialisation.

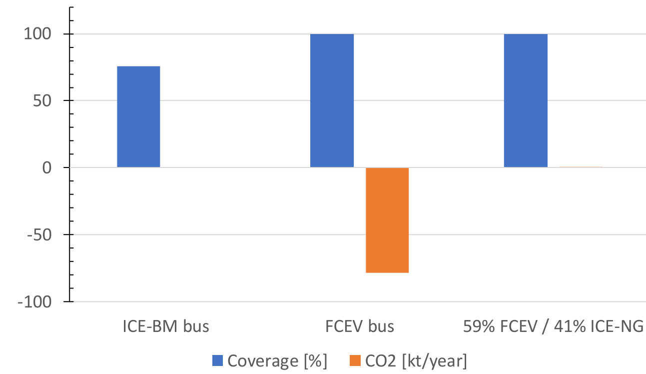


Fig. 4. Coverage levels of demand and resulting CO_2 emissions.

Table 4 shows a global balance of resources and CO_2 (both fossil and biogenic). The hybrid fleet, not only is a net-zero emissions but also exhibits the following advantages: (i) 59.48% reduction of natural gas; (ii) a surplus of biomethane (199.34 GWh-HHV) is available, able to increase the hybrid fleet with ICE-BM buses still being net-zero; (iii) as the upgrading takes place in a centralised facility, there are 81.9 kt of biogenic CO_2 available to be recovered for utilization without compromising the net-zero feature of the hybrid fleet.

Economically, given the logistics involved in municipal solid waste (MSW) collection, there is a need to establish multiple MSW management centres that would also function as hydrogen production facilities. A reasonable compromise between economies of scale in production and logistical restrictions in MSW collection suggests having one centre for every 1,000,000 inhabitants, with a hydrogen production potential of 2730 t/year. Three SMR plants are proposed for Madrid, each with a production capacity of 2000 t H_2/year. Although this size is smaller than typical SMR plants, Spain has two units in this capacity range (Sabiñánigo, with 1598 t/year and Gajano, with 985 t/year (European Hydrogen Observatory, 2022)). Fig. 5 shows the different contributions of the LCOH for this SMR plant size, including credits for the capture and storage of biogenic CO_2 (net LCOH), resulting in a net cost of 2.14 €/kg H_2. Fig. 6 shows the same costs without CO_2 credits (gross LCOH), resulting in a gross cost of 3.76 €/kg H_2. It is evident that the CAPEX for the SMR with CCS plant is comparable to the biogas cost.

Fig. 7 shows the net levelised cost of mobility with FCEV buses, while Fig. 8 presents the gross cost. The sum of refuelling infrastructure and bus costs accounts for the highest share of both net and gross LCOM (91% and 85%, respectively), with bus costs being the key factor, contributing 64% and 69% of the total, respectively. Fig. 9 illustrates the net and gross levelised cost of mobility with ICE buses fuelled by natural gas at two different costs: 1 €/kg and 2 €/kg. In this case, the refuelling infrastructure cost is included in the natural gas cost. The bus costs (CAPEX and O&M) range from 64% of the net LCOM to 73% of the gross LCOM with a natural gas cost of 1 €/kg, and from 52% to 58% with a natural gas cost of 2 €/kg. The maturity of the ICE bus reduces its share (CAPEX plus OPEX O&M) in the LCOM, although it remains the highest cost due to the higher maintenance cost compared to FCEVs, which are similar to the CAPEX of the bus. Finally, Fig. 10 summarises the comparison between FCEV and ICE-NG buses, showing that both technologies exhibit comparable costs when natural gas is expensive (2 €/kg). However, ICE-NG is more competitive than FCEV when natural gas is cheap (1 €/kg), even with CO_2 taxes/credits included. Specifically, with natural gas priced at 1 €/kg, the LCOM of FCEV exceeds that of ICE-NG by 15.6% when CO_2 taxes/credits are considered (net costs) and by 41% when CO_2 taxes/credits are not considered (gross costs). This indicates that the CO_2 trading system (net costs), along with high natural gas costs, facilitates the introduction of the FCEVs.

Table 4
Comparative balance between current and proposed hybrid fleet.

	NG consumption [GWh-HHV]	BM consumption [GWh-HHV]	Fossil CO_2 [kt]	Captured Biogenic CO_2 [kt]	Biogenic CO_2 ICE-BM [kt]	Biogenic CO_2 upgrading [kt]	Biogenic CO_2 leaks at CCS [kt]
Current fleet	644.47		114.67				
Hybrid fleet	261.17	290.39	46.47	−46.47		48.60	5.16
Additional ICE-BM		199.34			35.47	33.26	

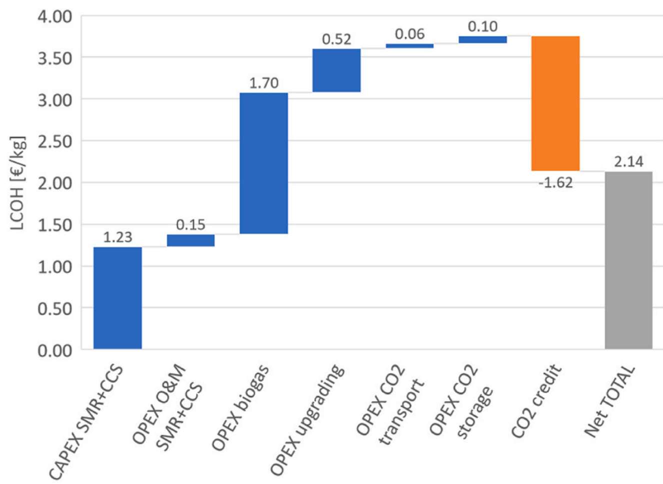


Fig. 5. Breakdown of net levelised cost of golden hydrogen using as feedstock the MSW of 1,000,000 inhabitants in Madrid.

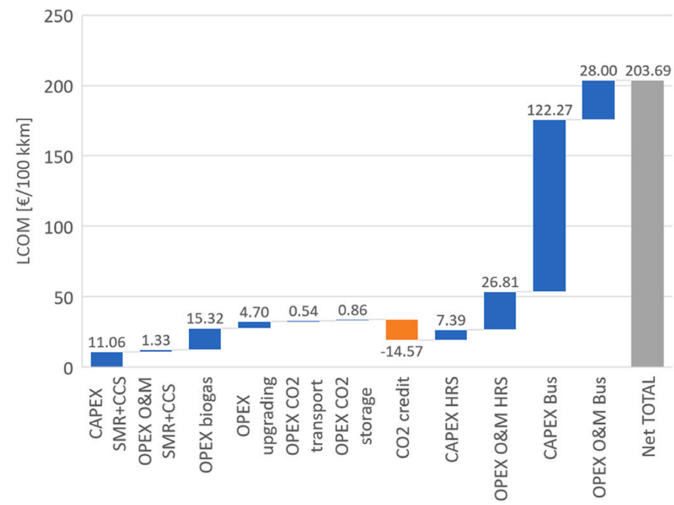


Fig. 7. Breakdown of net levelised cost of mobility with FCEV buses.

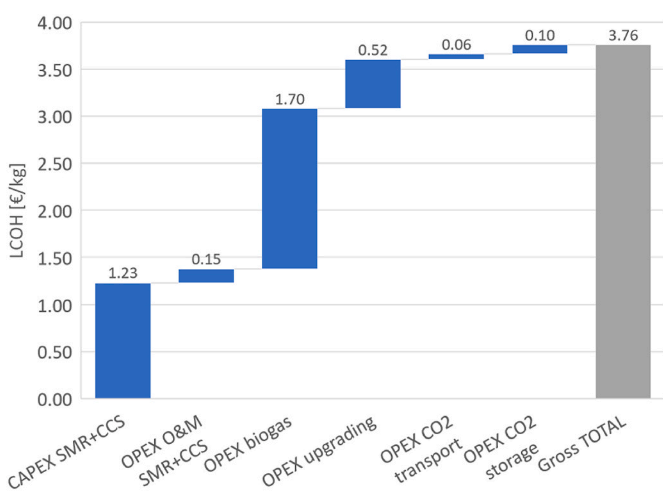


Fig. 6. Breakdown of gross levelised cost of golden hydrogen using as feedstock the MSW of 1,000,000 inhabitants in Madrid.

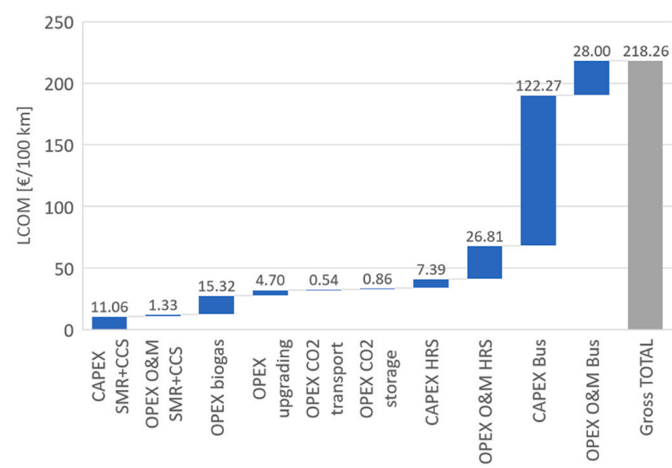
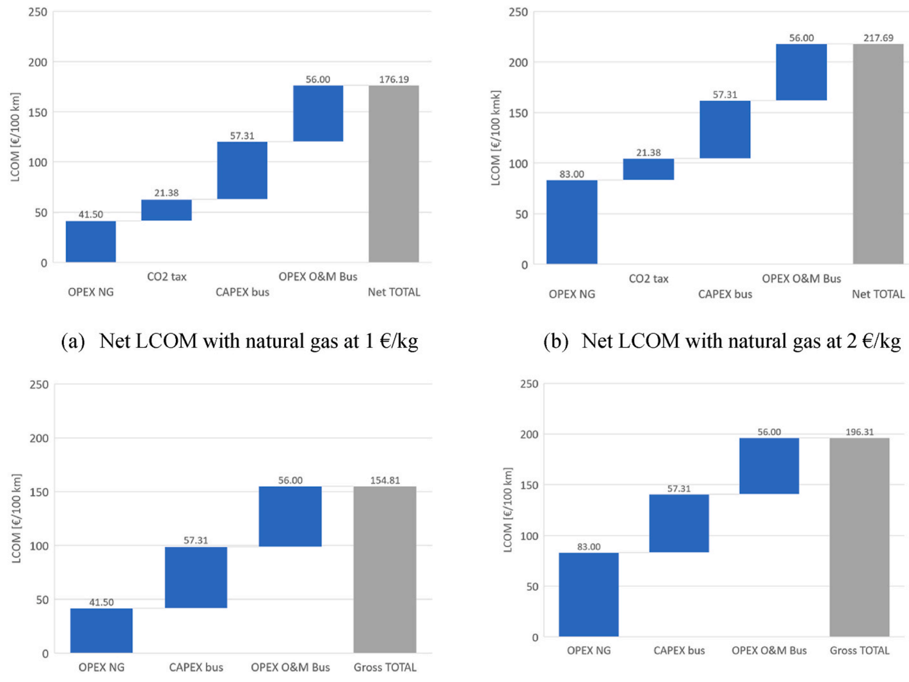


Fig. 8. Breakdown of gross levelised cost of mobility with FCEV buses.

Fig. 11 presents the net and gross LCOM for the net-zero fleet under two natural gas cost scenarios. It shows that, for the same natural gas cost, there is not difference between the gross and net costs, because the technology mix has been chosen to balance CO_2 emissions. With natural gas priced at 1 €/kg, the fleet cost is lower than the FCEV bus cost (both net and gross), but higher than the ICE-NG cost. Conversely, with natural gas at 2 €/kg, the net cost of the fleet is lower than that of the ICE-NG bus, while the gross cost of the fleet is higher than that of the ICE-NG bus. This is a consequence of the results shown in Fig. 10, where both net and gross LCOM of FCEVs are higher compared to ICE-NG when natural gas costs 1 €/kg. However, when the price of natural gas is 2 €/kg, the net LCOM for FCEVs is lower than that for ICE-NGs, whereas the gross LCOM for FCVEs is higher than for ICE-NGs.

The CO_2 tax/credit, along with the natural gas cost, have proven to be key factors in making the FCEV competitive. Figs. 12 and 13 present a sensitivity analysis of these parameters. Each figure plots the net LCOM of the net zero fleet (solid lines) at natural gas prices of 1 €/kg and 2 €/kg, overlaid with the net LCOM of ICE-NG at the same fuel costs. In Fig. 12, the nominal escalation rate of the CO_2 tax is 8%, as in previous cases, while Fig. 13 uses a value of 4% to reflect the expected future reduction (Enerdata, 2023).

It is notable that the net cost of the net-zero fleet depends on the natural gas cost (192.55 €/100 km at 1 €/kg and 209.37 €/100 km at 2 €/kg), but not on the CO_2 tax or its nominal escalation rate. This is due to the balancing of emissions in the fleet, similar to what is shown in Fig. 11. The difference between the net LCOM of the ICE-NG buses remains constant at 41.5 €/100 km, increasing with both the CO_2 tax (price and nominal escalation rate) and the natural gas cost.



(a) Net LCOM with natural gas at 1 €/kg (b) Net LCOM with natural gas at 2 €/kg

(c) Gross LCOM with natural gas at 1 €/kg (d) Gross LCOM with natural gas at 2 €/kg

Fig. 9. Breakdown of levelised cost of mobility with ICE-NG bus.

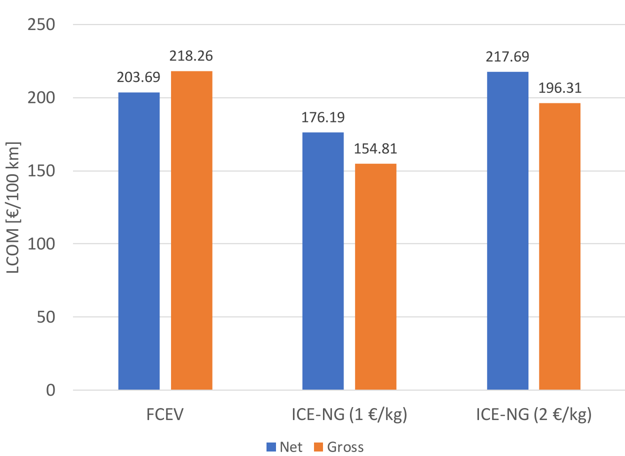


Fig. 10. Cost comparison between FCEV and ICE-NG buses.

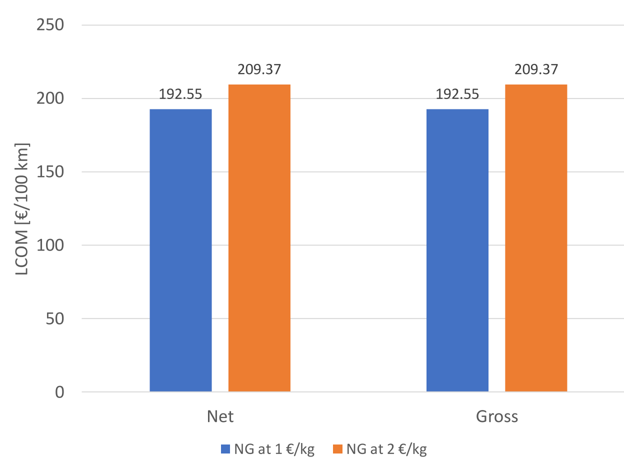


Fig. 11. Summary of net-zero fleet costs.

On the other hand, Figs. 12 and 13 confirm that the proposed net-zero fleet has lower costs compared to ICE-NG buses when natural gas prices are high and CO_2 credits/taxes are considered. The higher the CO_2 price or its nominal rate, the more competitive the net-zero fleet becomes relative to the ICE-NG buses.

4. Conclusions

4.1. *Summary of key findings*

The centralised MSW collection infrastructure allows for the establishment of SMR plants with CCS for every 1,000,000 inhabitants, with a capacity of 2 kt H_2/year, similar to some current SMR units in Spain. Locating the SMR with CCS plant next to the MSW treatment plant eliminates biomethane injection costs and reduces dependence on the natural gas grid. As municipal buses typically have dedicated parking lots, these can be positioned near the hydrogen production complex, which would include a hydrogen refuelling station, thereby avoiding the need to transport hydrogen. Consequently, in this proposal, only the CO_2 would need to be transported to underground geological storage. The levelised cost of hydrogen produced ranges from 2.14 €/kg to 3.76 €/kg, depending on whether CO_2 credits are accounted for (net LCOH) or not (gross LCOH).

It has been found that using hydrogen in FCEVs reduces primary biomethane demand by 24% compared to its direct use in ICE-BM buses. This is due to the higher efficiency of FCEVs (302 kWh/100 km) compared to ICEs (576 kWh/100 km), which offsets the inefficiency of the SMR with CCS process, resulting in a primary biomethane demand of 438 kWh/100 km for FCEVs.

The biomethane potential from treating all of Madrid's MSW is 490 GWh, which could produce 9070 t H2/year—enough to fully meet the bus fleet's demand if all were FCEVs (9043 t H2/year). Although

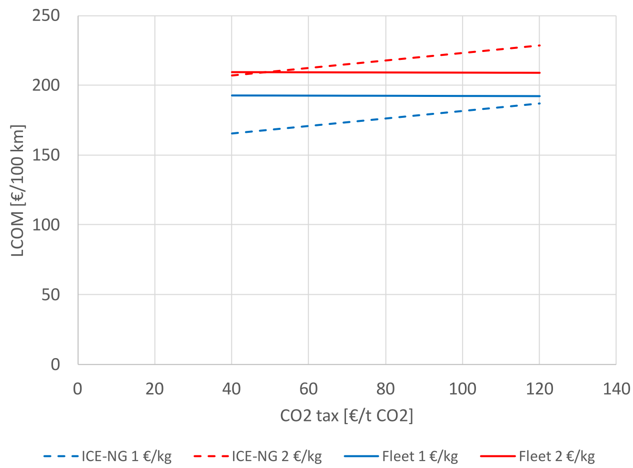


Fig. 12. Net LCOM of net-zero fleet and ICE-NG at $r_{CO2\ tax} = 8\%$.

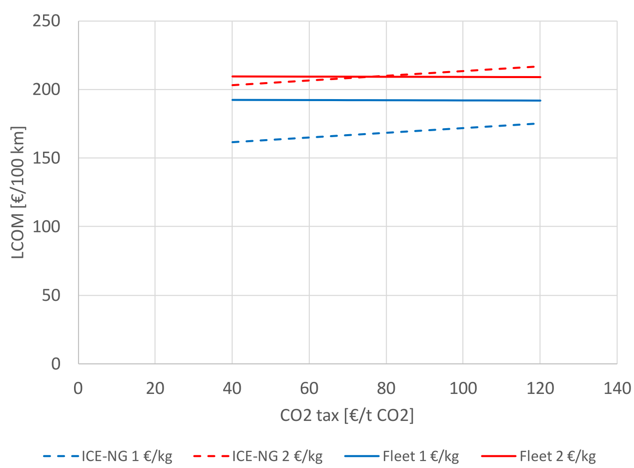


Fig. 13. Net LCOM of net-zero fleet and ICE-NG at $r_{CO2\ tax} = 4\%$.

converting the entire fleet to FCEV buses would result in negative emissions, compensating for the emissions of 11,700 Spaniards, the investment required would be prohibitively high. Additionally, this solution would render current natural gas buses obsolete, which could instead be powered by biomethane to achieve a net-zero fleet.

As a compromise, this work proposes a hybrid fleet comprising 60% FCEV buses (consuming 5378 t H_2/year) and 40% current ICE buses running on natural gas (261 GWh). The biogenic CO_2 captured and stored (46 kt/year) can offset the CO_2 emissions from the natural gas buses, thereby preserving existing infrastructure and achieving a net-zero fleet. This solution leaves 199 GWh of biomethane available to power an additional fleet of 30% of the current size in Madrid, while maintaining a net-zero status. As the captured biogenic CO_2 comes only from the SMR plant, 82 kt/year of biogenic CO_2 from the upgrading process could be available for market use in synthetic fuels and other chemical applications.

Regarding costs, the LCOM of an FCEV ranges from 203.69 €/100 km to 218.26 €/100 km (depending on whether CO2 credits are included), with the dominant cost components being the bus and the refuelling station. These costs are higher than the LCOM of an ICE-NG bus when the gas price is 1 €/kg (154.81 €/100 km to 176.19 €/100 km) but become comparable when the gas price is 2 €/kg (196.31 €/kg to 217.69 €/kg). In fact, the LCOM of the proposed hybrid fleet (192.55 €/100 km to 209.37 €/100 km) is similar to that of a fleet composed entirely of ICE-NG buses when the gas price is 2 €/kg. The emissions balance in the hybrid fleet eliminates dependence on CO_2 taxes (both value and escalation rate), whereas ICE-NG buses remain affected. Finally, while the LCOM of the hybrid fleet is still tied to natural gas prices, its sensitivity is lower than that of a fleet composed solely of ICE-NG buses (16.82 €/100 km for each 1 €/kg increase versus 41.5 €/100 km for each 1 €/kg increase).

4.2. Limitations and recommendation for policymakers

The potential of biomethane is based on the performance of the current La Paloma plant, which according to Table 2, represents an intermediate value between another biomethanization plant in Madrid (Las Dehesas) and a study carried out by Sedigas (2023) in Spain. Therefore, there is a certain level of uncertainty regarding the actual potential for biomethane production from MSW. Additionally, the biomethane yield depends on the composition of MSW, which may differ between Madrid and other regions of Spain. In fact, using MSW as a raw material presents challenges for scaling the technology, as separating organic matter at the household level is desirable to facilitate pre-treatment before digestion. Although selective MSW collection has been implemented in several municipalities, people collaboration is essential. This limitation is partially addressed by the hybrid fleet, which reduces biomethane demand to 59% of what would be required to power a fleet composed solely of FCEV buses.

Another significant limitation is the availability and capacity of underground geological storage for captured CO_2. In Spain, deep saline aquifers are the most common geological storage option, primarily located from the centre of the Iberian mainland to the northeast, leaving large areas in Galicia, Extremadura and Andalucía without storage possibilities. The economic limit for CO_2 transport is typically 180 km, and these regions exceed that distance. Therefore, the proposal of utilizing the CO_2 captured in the upgrading process, rather than storing it, could mitigate this restriction.

From the policymakers' perspectives, the key aspect is the development of the CO_2 market, which is crucial to ensuring the proposed model's economic competitiveness. Although ETS 2 is expected in the near-term, it is necessary to develop CO_2 credits for stored biogenic CO_2. Carbon dioxide removal is being promoted in the EU, but proper economic valuation must accompany its recognition in emissions accounting.

4.3. Recommendations for future studies

Some recommendations for future studies arise from the identified limitations. From the perspective of biomethane yield, a comprehensive study using actual compositions of MSW is necessary, along with an analysis of potential pre-treatments that could enhance production. To properly assess CO_2 accounting, life cycle analyses should be conducted, considering additional contributions to global warming potential, as well as expanding the system boundaries to include upstream and downstream processes. Other factors, such as the effects of digestate use—whether for stabilization, as an organic amendment or fertilizer, or even as a raw material for industries—should also be investigated.

4.4. Final thoughts

Water electrolysis is currently the primary method for producing green hydrogen, but other methods, such as steam methane reforming (SMR), also hold potential. Historically, SMR has been used in the oil industry to produce hydrogen from natural gas. In recent years, carbon capture technology has been integrated into SMR to reduce greenhouse gas emissions, creating blue hydrogen. SMR is a mature technology that could be adapted for renewable hydrogen production by using biomethane instead of natural gas. Biomethane, derived from the anaerobic digestion of organic waste, could play a key role in the energy transition.

Producing hydrogen from biomethane aligns with a circular economy by integrating urban transport with waste management.

This work introduces golden hydrogen (biohydrogen with negative emissions), as a potential solution for this integrated strategy. By capturing biogenic CO_2, golden hydrogen achieves negative emissions (−8.64 kg CO_2/kg H_2), offering a pre-combustion carbon capture solution that compensates for emissions from other industries while supporting the circular economy.

In a case study assessing the decarbonisation of the Madrid's public buses fleet, a net-zero bus fleet is proposed, combining new FCEV buses with the existing ICE-NG buses. Net-zero emissions are achieved by offsetting the CO_2 emitted by the ICE-NG buses with the negative emissions generated by the FCEV buses. The key aspect is that the FCEV buses are fuelled with golden hydrogen, produced via steam methane reforming of biomethane locally produced by the anaerobic digestion of the organic fraction of MSW. Capturing and storing the biogenic CO_2 released during the reforming process creates negative emissions. The proposal leverages the circular economy by converting waste into energy, which compensates for fossil CO_2 emissions and allows part of the current ICE-NG fleet to remain operational. The hybridization requires only 59% of the biomethane potential, helping to manage uncertainties and fluctuations in biomethane production. Additionally, the biogenic CO_2 captured during the upgrading process from biogas to biomethane is left available for use as a chemical raw material, essential for the future defossilisation of the economy.

Regarding the economy, the proposed hybrid fleet is competitive compared to a pure ICE-NG fleet when CO_2 tax and high prices of natural gas are considered. In summary, biohydrogen from MSW contributes significantly to long-term sustainability by providing a low-carbon, renewable energy source while addressing waste management challenges. It offers a dual benefit by reducing landfill use and emissions, making it a key player in achieving global sustainability targets.

CRediT authorship contribution statement

Léonard Lefranc: Writing – original draft, Investigation. **José Ignacio Linares:** Supervision, Methodology, Investigation, Conceptualization. **Ana María Santos:** Validation, Methodology, Formal analysis, Conceptualization. **Eva Arenas:** Writing – review & editing, Validation, Supervision, Methodology, Funding acquisition, Conceptualization. **Carlos Martín:** Writing – review & editing, Formal analysis, Conceptualization. **Yolanda Moratilla:** Supervision, Formal analysis, Conceptualization.

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.

Acknowledgments

Authors acknowledge to the Rafael Mariño Chair on New Energy Technologies and to the Repsol Foundation Chair in Energy Transition its their support to carry out this research.

Data availability

No data was used for the research described in the article.

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