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Long-term production technology mix of alternative fuels for road transport: A focus on Spain

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A B S T R A C T

Road transport is one of the main sources of greenhouse gas emissions due to the current dependence on fossil fuels such as diesel and gasoline. This situation needs to be changed through the retirement of fossil fuels and the implementation of alternative fuels and vehicles such as biofuels, battery electric vehicles, and fuel cell electric vehicles fueled by hydrogen. Nevertheless, the environmental suitability of alternative fuels is conditioned by how they are produced. Through the case study of Spain, this article prospectively assesses – from a techno-economic and carbon footprint perspective – the production technology mix of alternative fuels from 2020 to 2050. The proposed energy systems optimisation model includes a large number of production technologies regarding biofuels (bioethanol, biodiesel, synthetic diesel/gasoline, and hydrotreated vegetable oil), electricity, and hydrogen. The combined study of these fuels provides a relevant framework to discuss the targets established for the road transport sector with a high level of detail not only regarding fuel type but also technology breakdown. The results show the relevance of second-generation biofuel production technologies in fulfilling the future biofuel demand. Regarding the extra electricity demand associated with the penetration of electric vehicles, the results suggest a key role of wind- and solar-based technologies in meeting such a need. Concerning hydrogen as an option to decarbonise the transport system, even though steam methane reforming is the most mature and cost-competitive production technology, hydrogen production would be satisfied through electrolysis in order to avoid relying on fossil resources as the main feedstock. Overall, this integrated approach to the long-term production technology mix of alternative fuels for road transport is expected to be relevant to a wide range of decision-makers willing to prospectively assess road transport systems from a technology perspective.

1. Introduction

Nowadays, the transport sector arises as one of the major contributors to the global carbon dioxide (CO₂) emissions, accounting for almost 8 million tonnes in 2018. Three quarters of these emissions come from road transport due to the high dependence on conventional fossil fuels such as gasoline and diesel [1]. At the European level, the situation is similar, with 27% of the CO₂ emissions coming from road transport [1]. Hence, measures to decarbonise this sector are required. The Member States of the European Union (EU) established that at least 14% of the energy consumed in road and rail transport should be renewable energy by 2030 [2]. In this sense, the Member States have included measures against climate change in their integrated national energy and climate plans (NECPs) for the period 2021–2030. These NECPs address subjects such as energy efficiency, renewables, greenhouse gas (GHG) emission reductions, and research and innovation. Among the transport targets in the NECPs, all countries share the common goal of increasing the presence of alternative fuels in the transport sector in 2030, promoting the implementation of fuels such as natural gas (NG), liquefied petroleum gas (LPG), biofuels, electricity, and hydrogen [3].

Several authors have studied the changes expected in the transport sector under different approaches. For instance, Kim et al. [4] assessed the optimal energy supply configuration in the transport sector through several case studies. García-Olivares et al. [5] reviewed global transport conditions and the main issues for full decarbonisation. Brand et al. [6] investigated the impacts of more ambitious targets, the disruption level needed to meet climate goals, the role of lifestyle and social change, and the potential implications for key actors in transport energy systems.
García-Sánchez et al. [7] assessed the historical and prospective impacts associated with electric, hybrid and diesel vehicles in a regional case study from an environmental point of view. Akilu et al. [8] estimated short- and long-run price and income elasticities of gasoline and diesel for the EU-28 countries, examining whether the extant EU fuel tax policy is sufficient to achieve the 2030 transport emissions target. Krause et al. [9] analysed CO₂ emission reduction options for the European road transport by 2050 under several scenarios with different electrification levels. Other authors have focused their studies on the technological pathways to produce energy in the long term. Seck et al. [10] used an energy system optimisation model to take into account short-term power grid operation conditions in long-term prospective analysis for France. Colbertaldo et al. [11] developed a multi-model to represent an integrated energy system, including additional electrical load from plug-in electric vehicles, energy storage, and hydrogen production scenarios in Italy.

Based on the endogenous growth theory, the growth rate of an economy highly depends on policy measures, being energy and climate policies especially relevant [12]. Nevertheless, plans or studies focused on the technological pathways to produce alternative fuels in the long term are not common and suffer from a lack of both a wide portfolio of production technologies and an overall view of several fuels. In fact, the suitability (and sustainability) of alternative fuels is conditioned by their origin and production method. This calls for a thorough prospective assessment of the production technology mix of alternative fuels for road transport. In this sense, this article aims to fill the gap in national roadmaps on prospective technology mixes for the production of alternative road transportation fuels such as biofuels, electricity, and hydrogen.

Hence, this work addresses a prospective techno-economic assessment of a national technology mix that could satisfy the demand for alternative fuels for road transport under an exploratory vision. After this introduction, Section 2 focuses on the explanation of the proposed energy systems optimisation model, including the definition of the exploratory case study and the techno-economic characterisation of the fuel production technologies. Afterwards, Section 3 presents and discusses the results of the prospective study, focusing on the evolution of the technology mix for the production of biofuels, electricity, and hydrogen in the period 2020–2050. Section 3 also includes a prospective assessment of the carbon footprint associated with the production and use of the alternative fuels, as well as a discussion of the main potentials and limitations of the study. Finally, the main conclusions are drawn in Section 4.

2. Materials and methods

This section presents the main features of the proposed energy system optimisation model on the production of alternative fuels (Section 2.1) as well as the demands assumed for the specific case of Spain (Section 2.2) and the techno-economic characterisation of the biofuel, electricity and hydrogen production technologies (Section 2.3).

2.1. Modelling alternative fuel production

According to the goal of the study, an Energy Systems Modelling (ESM) approach was used, focusing on the main technologies that could satisfy the prospective demand for alternative fuels for road transport in the period 2020–2050. The role of sustainability as the motivating factor behind the study is a growing trend in ESM [13], which has led to its enrichment by integrating other approaches such as life cycle assessment [14]. Scenarios such as Representative Concentration Pathways (which include time series of emissions and concentrations of the full suite of greenhouse gases, aerosols, chemically active gases, and land use) and Shared Socio-economic Pathways (which describe alternative future socio-economic development in the absence of climate policy intervention) also show a common motivation: achieving a low-carbon energy system [15]. Nevertheless, the present study is a specific prospective analysis addressing the optimisation of a national production technology mix of alternative fuels for road transport while considering a wide range of production technologies.

In particular, a national energy systems optimisation model including technologies for the production of biofuels –divided into bioethanol, biodiesel, synthetic diesel/gasoline, and hydrotreated vegetable oil (HVO)–, electricity and hydrogen was developed, using the software LEAP [16] for model implementation. It should be noted that NG and LPG were left out of the scope of this study not only because they are based on fossil resources but mainly because their production does not involve competition between technologies for each fuel (natural gas is directly extracted from geological reservoirs [17] and LPG comes mainly from refineries [18]). Spain—as an illustrative country with representative goals on the implementation of alternative fuels— was selected as the case study.

The representation of the energy systems optimisation model is shown in Fig. 1. The combined focus on biofuels, electricity and hydrogen allows an integrative modelling approach, which is especially relevant for electricity and hydrogen. According to its intended use for prospective assessment of production technology mixes, a key feature of the model refers to the inclusion of a large number of production pathways for each fuel (block 1 in Fig. 1). Every production technology was defined by techno-economic data such as prospective investment costs and efficiencies (Section 2.3). The techno-economic characterisation of the technologies in the model allowed the subsequent optimisation—through OSeMOSYS [19]—of the production technology mix that could satisfy a given exogenous demand (block 2 in Fig. 1). The demand assumed for each fuel is detailed in Section 2.2. Trade aspects such as imports and exports were left out of the scope of the study, and an equivalence between production and demand was assumed.

2.2. Demands assumed for transportation fuels in Spain

The evolution of the demand for each fuel was exogenously implemented in the model. In order to set these demands, technical parameters of the different vehicle types were considered as presented in Table 1 [20–23], which gathers key assumptions made for gasoline, diesel, electric (EV) and fuel cell electric (FCEV) vehicles.

One of the most ambitious goals of the Spanish NECP is to achieve a total fleet without CO₂ direct emissions by 2050, while new fossil-based vehicles will be banned by 2040. However, there is not a defined transition to reach this goal. In 2018, there were 32.9 million vehicles in Spain: 56.6% based on diesel, 43.2% based on gasoline, and only 0.2% classified as others (mainly involving NG, LPG, and hybrid electric vehicles) [22]. Diesel engines have a compression-ignited injection system [24] and gasoline ones are based on spark-ignited internal combustion [25]. The associated emissions include different pollutants such as CO₂, hydrocarbons, carbon monoxide (CO), particulate matter and nitrogen oxides (NOₓ), which are detrimental to the environment and the human health [26]. In this regard, the main transport-related policies focus on decreasing the amount of these vehicle types. Taking into account the historical retirement of vehicles per year in Spain and the expected sales of fossil-based vehicles, a retirement profile was considered. The historical retirement of vehicles per year in Spain is around 0.9 million vehicles: 14.7% trucks and vans, 0.3% buses, 80.8% cars, 3.0% motorcycles, and 1.2% tractors [27]. Regarding expected sales, diesel and gasoline vehicles will continue to be registered [28]. The share of diesel vehicles in terms of sales is expected to be within the range 22–28% in 2025, 2–5% in 2030, and 0–2% in 2040. Concurrently, the sales of gasoline vehicles could mean 40–45% in 2025, 25–28% in 2030, and 1–3% in 2040 [29]. In the case of gasoline, the counter-effect associated with the upsurge in hybrid vehicles (gasoline-electric) should be borne in mind. The decrease in diesel and gasoline vehicles from now to 2050 could reach 97% and 82%, respectively.

In order to set the prospective demand for biofuels, biodiesel and
bioethanol blending with diesel and gasoline, respectively, was assumed according to the Directive 2009/30/EC. The maximum volumes of blending allowed in Spain in regular diesel and gasoline are 7% of biodiesel (B7) and 10% of bioethanol (E10), respectively [30]. Nevertheless, it should be noted that other options could emerge in other countries, e.g., E85 (85% of bioethanol in gasoline) in France [31]. The main challenge for fuels such as E85 is the need for specific vehicles with adapted engines [32]. In fact, Spain is not currently prepared for this type of fuels and there is not a plan for their implementation. In this model, the blending assumption implies that biodiesel and bioethanol demands are directly affected by the retirement of fossil fuels since the only demand for bioethanol and biodiesel would correspond to 10% of the blended gasoline volume and 7% of the blended diesel volume, respectively.

The Spanish NECP also promotes the use of advanced biofuels. While there is not a common definition for advanced biofuels, they generally include all second-generation biofuels (based on the utilisation of non-food crops) [33] and are typically associated with compatibility with the current transportation infrastructure [34]. Thus, promotion of advanced biofuels may involve the use of synthetic diesel, synthetic gasoline, and HVO. Since synthetic diesel and HVO could replace diesel completely [35], it was assumed that synthetic diesel and HVO could equally represent – in 2050 – 10% of the vehicles currently fuelled by diesel. Since synthetic fuel production typically involves 70% synthetic diesel and 30% synthetic gasoline [36], the synthetic gasoline demand was assumed in proportion to that for synthetic diesel.

Regarding electric vehicles rechargeable by external sources, they can be classified into battery electric vehicles (BEVs), plug-in hybrid electric vehicles (PHEVs), and FCEVs. BEVs just use an electrical motor to move the vehicle, while PHEVs combine electricity with a conventional combustion system. FCEVs use hydrogen as a fuel, which is electrochemically combined with oxygen in a fuel cell producing electricity to power the motor [37]. Since BEVs and PHEVs were jointly addressed in this study, they were renamed EVs in order to simplify the nomenclature. On the other hand, FCEVs were separately studied. The prospective demands for EVs and for FCEVs were based on the medium scenarios from previous studies: references [20] and [23], respectively. In this regard, the penetration of electric vehicles is in line with the Spanish NECP, which includes a goal of 5 million electric vehicles in 2030. In particular, this study involves 4 million EVs and 1 million FCEVs in 2030. In 2050, EV and FCEV penetration was assumed to continue, with EVs and FCEVs representing around 40% and 15% of the total fleet, respectively.

Overall, Table 2 presents the fuel demands assumed in this study. As stated in Section 1, EU countries established the common goal of 14% renewability in the energy consumed in the transport sector in 2030 [2]. In the Spanish NECP, this goal of renewable energy consumption in the transport sector is much higher: 28% in 2030 (linked to electrification and biofuel implementation). The demand assumptions in this study would lead to attain the 14% goal of renewable energy consumption in 2030. Nevertheless, this value is lower than that established in the Spanish NECP. In this sense, the potential gap determined in Table 2
Table 2

| Fuel       | Year 2020       | Energy demand (TWh) | Year 2030       | Energy demand (TWh) | Year 2040       | Energy demand (TWh) | Year 2050       | Energy demand (TWh) |
|------------|-----------------|---------------------|-----------------|---------------------|-----------------|---------------------|-----------------|---------------------|
| Diesel a   | 17.3            | 404.3               | 11.6            | 277.6               | 6.1             | 155.2               | 0.6             | 38.6                |
| Gasoline a | 14.3            | 123.1               | 10.3            | 84.2                | 6.4             | 45.0                | 2.6             | 9.7                 |
| Biodiesel b | 17.3            | 28.2                | 11.6            | 19.4                | 6.1             | 10.8                | 0.6             | 2.7                 |
| Bioethanol b | 14.3           | 9.0                 | 10.3            | 6.2                 | 6.4             | 3.3                 | 2.6             | 0.7                 |
| Synthetic diesel | 0.03       | 0.5                 | 0.3             | 5.0                 | 0.6             | 9.5                 | 0.9             | 14.0                |
| Synthetic gasoline | 0.04     | 0.2                 | 0.4             | 2.0                 | 0.8             | 3.8                 | 1.2             | 5.6                 |
| HVO       | 0.03            | 0.5                 | 0.3             | 5.0                 | 0.6             | 9.5                 | 0.9             | 14.0                |
| Electricity | 0.08            | 0.2                 | 4.0             | 7.7                 | 8.5             | 16.5                | 14.0            | 27.2                |
| Hydrogen | 0.01            | 0.2                 | 0.7             | 11.5                | 2.6             | 43.3                | 4.8             | 80.4                |
| Gap | 0.2 – 4.4 – 6.5 – 7.0 – | | | | | | | |

a The energy demands of diesel and gasoline refer to vehicles using 93% of fossil diesel and 90% of fossil gasoline, respectively.
b The number of vehicles is the same as that for diesel due to blending.
c The number of vehicles is the same as that for gasoline due to blending.

2.3. Techno-economic characterisation of production technologies

Biofuels are liquid or gaseous fuels produced from biomass feedstock that can be used directly or blended with conventional (fossil-based) fuels. They are often classified into first- (1G), second- (2G) and third-generation (3G) biofuels depending on the type of biomass. 1G biofuels are based on food-competing biomass. This type is the most developed one, but it is criticised due to direct competition with the food sector [38]. This is the reason why current research efforts focus on the production of advanced biofuels, including 2G and 3G biofuels. The feedstock used for advanced biofuels does not compete with food or feed, e.g., waste materials (waste vegetable oils and animal fats), energy-specific crops, and algal biomass [33]. The biofuels considered in this study include bioethanol, biodiesel, HVO, and synthetic diesel and gasoline.

Bioethanol is generally produced through the liquefaction of starchy or sugary biomass, followed by hydrolysis or saccharification (in which glucose monomers are released into the solution) and then glucose fermentation. 2G bioethanol uses lignocellulosic material as the feedstock [39]. On the other hand, biodiesel is made from vegetable oils and animal fats. 1G biodiesel involves oil crops such as rapeseed or soybean oil, while 2G biodiesel involves feedstocks such as animal fats and used cooking oil. They are typically converted into biodiesel via extraction and esterification of triglycerides, which react with alcohol in the presence of a catalyst [40]. The same type of feedstock can be used to produce HVO through hydrogenation of vegetable oils or animal fats, followed by alkane isomerisation and cracking [33]. Finally, 3G biodiesel is produced through microalgae transesterification [41].

Concerning synthetic diesel and gasoline, they are typically produced through thermochemical processes. During biomass pyrolysis, the feedstock is heated without oxygen to produce bio-oil, which is then hydrotreated and distilled to produce diesel and gasoline. On the other hand, in biomass gasification, the feedstock is converted into syngas under an atmosphere with oxygen, air and/or steam. The syngas is then transformed into diesel and gasoline via the Fischer-Tropsch synthesis and distillation [42-43].

Electric vehicles can use electricity directly (EVs) or they can use hydrogen subsequently converted into electricity (FCEVs). The Spanish electricity production mix has a significant contribution from renewable technologies (e.g., photovoltaics, hydropower and wind power), which is expected to grow considerably in the medium and long term [44]. Regarding FCEVs, hydrogen could be produced through a variety of technological pathways. In the steam reforming of natural gas, steam and hydrocarbons are heated up to 750–900 °C to produce syngas, which then undergoes a water-gas-shift process followed by hydrogen purification via pressure swing adsorption. The fossil feedstock can be substituted by biomethane or other biofuels, but requiring additional technical improvements [45]. In other thermochemical processes such as coal or biomass gasification, the feedstock is converted into syngas at elevated temperature in a gasification medium such as air, oxygen and/or steam, and then syngas is further processed to hydrogen as explained above (water-gas-shift process followed by hydrogen purification via pressure swing adsorption) [46]. Finally, in water electrolysis, electrical energy is transformed into chemical energy in the form of hydrogen [47].

The large number of fuel production technologies implemented in the model were techno-economically characterised as summarised in Table 3. This table presents the investment cost evolution assumed for the different technologies for biofuel, electricity and hydrogen production, as well as their efficiency [41–64]. These data are not significantly country-dependent, thus boosting the international relevance of the study. On the other hand, data such as demands, electricity prices and legal measures are specific to Spain. Even though investment costs and efficiencies are typically used to characterise the production technologies involved in a model, other parameters such as operating costs, maximum capacities and availability factors were implemented. Further details regarding electricity production technologies can be found in [48].

3. Results and discussion

This section presents the resulting biofuel (Section 3.1), electricity (Section 3.2) and hydrogen (Section 3.3) production technology mixes. Additionally, Section 3.4 includes an analysis of the results from a carbon footprint perspective, while Section 3.5 addresses potentials and limitations of the study.

3.1. Biofuel production technology mix

Fig. 2 shows the resultant evolution of the production technology mix for bioethanol, biodiesel, synthetic diesel/gasoline and HVO in the time frame 2020–2050. Although 1G bioethanol could partly contribute to meeting the bioethanol demand, it was found to be replaced by 2G bioethanol from biomass fermentation as the main production technology. This transition is linked to the avoidance of the competition with the food sector, which leads to concentrate efforts on reducing the technical and economic barriers associated with the fermentation of 2G...
As regards 1G biodiesel, it would be produced through oil esterification in the short term (2020–2023). However, for the evaluated period, the satisfaction of the biodiesel demand would be led by 2G biodiesel from oil esterification. This behaviour is linked to the position of the European Commission to not consider biofuels from feedstocks with high indirect land-use change emissions (e.g., palm oil) as renewable from 2030 [69].
Regarding advanced biofuels, synthetic diesel and gasoline would be produced by pyrolysis in the short and medium term. This technology would be gradually substituted by gasification from 2034, according to the techno-economic progress achieved by the gasification pathway. Additionally, from 2027, HVO production would require the use of new plants in order to fulfil the ambitious demand associated with the road transport sector. Overall, the deployment of technologies to produce advanced (2G) biofuels—rather than 1G biofuels—was identified as a key finding.

A low sensitivity of the biofuel production trends to different investment costs was found. On the other hand, aspects such as the biomass price could play a relevant role. For instance, affordable 2G investment costs was found. On the other hand, aspects such as the biomass price could play a relevant role. For instance, affordable 2G biomass prices under 9 €t⁻¹ are needed to produce bioethanol via 2G fermentation. The ambitious biofuel demands in this study (especially regarding synthetic fuels and HVO) involve the need to guarantee a steady and reliable supply of biomass feedstock for biofuel production. To that end, the International Renewable Energy Agency (IRENA) highlights the need for national bioenergy policies with well-defined and realistic targets, as well as financial incentives to collect feedstock for energy purposes [70].

### 3.2. Electricity production technology mix

The Spanish NECP includes measures related to the implementation of renewable technologies in the electricity system. In this sense, Iribarren et al. [71] updated former versions of a national power generation model and—to a large extent—aligned it with the targets presented in the Spanish NECP. However, the additional electricity demand associated with EV penetration had not yet been considered when applying this model. Fig. 3 shows the evolution of the electricity production mix for Spain in the period 2020–2050. The total electricity demand will increase with the penetration of EV. This extra demand corresponds to the white area in Fig. 5, and it was further explored in Fig. 4. In this regard, Fig. 4 shows the evolution of the electricity production mix that could satisfy the additional electricity demand from the Spanish road transport sector due to EV penetration. Hence, this figure represents the difference between the power generation scenarios with and without EV penetration.

The electricity demand specifically associated with EV penetration means around 7% of extra electricity in 2050. While—in broad terms—the Spanish electricity system is expected to be able to handle such an extra demand, challenges such as infrastructure development and other technical issues (e.g., demand response management) remain out of the scope of this study. As shown in Fig. 4, the additional demand for electricity due to EV penetration would be satisfied mainly by renewable technologies. In the short term (until 2025), the extra demand would be fulfilled mainly by wind plants. From 2026 to 2050, solar plants would satisfy most of the additional electricity needed. From 2033 to 2037, waste-to-energy plants would partly contribute to meeting the electricity demand. Nevertheless, it should be noted that above 95% of the total electricity from the grid would be produced by renewable sources by 2050. The negative values observed in several years correspond to a reduction in the contribution of specific types of technologies when compared to a reference scenario without EV penetration.

Several parameters could affect electricity production results. For instance, the reduction in capital cost could be relevant with regard to technologies such as wind offshore plants. For instance, if the investment cost of wind offshore plants was kept constant, the electricity production with this technology in 2050 would be 40% lower than when using the costs assumed in Table 3. Other parameters such as capacity factors could also play a significant role in the results. Technologies such as solar photovoltaic plants have the capacity limited. It was assumed that the maximum capacity of these plants is 30 GW [71]. In this regard, a limit of 40 GW would lead to a 25% increase in photovoltaic electricity production in 2050.

### 3.3. Hydrogen production technology mix

The resultant evolution of the hydrogen production technology mix for road transport is shown in Fig. 5. Even though the most widespread and mature technology to produce hydrogen is steam methane reforming (SMR) using natural gas as the feedstock, the establishment of hydrogen as a transportation fuel requires its qualification as a clean fuel effectively contributing to the decarbonisation of the transport system [72]. In this sense, since a techno-economic optimisation without restrictions would lead to meet the whole hydrogen demand by SMR without CO₂ capture from 2020 to 2050, the optimisation exercise was rerun by excluding this technology pathway as an actual hydrogen production option within the transport sector. In this regard, under a clean hydrogen scenario, water electrolysis was identified as the main

![Fig. 3. Evolution of the total electricity production by technology.](image-url)
technology for hydrogen production.

While the sensitivity of the hydrogen production results to alternative investment costs was found to be low, changes in the operating costs could significantly affect the results. In this regard, it should be noted that a reduction in electricity prices from 74 €⋅MWh\(^{-1}\) in 2020 to 51 €⋅MWh\(^{-1}\) in 2050 was considered in the model. The identification of water electrolysis as the key hydrogen production technology is in line with the expectations coming from several international organisations. For instance, the Hydrogen Council points to electrolysis as the most common method to produce renewable hydrogen [73]. Similarly, Hydrogen Europe also considers water electrolysis as a key option enabling a decarbonised energy system. This organisation estimates that 20–40 GW of electrolysis could be installed in Europe in 2030, producing hydrogen at a cost below 3 €⋅kg\(^{-1}\) [62].

Although other technology alternatives included in the energy systems optimisation model such as SMR with CO\(_2\) capture could become an option (especially for a period of transition), they were not found to be present in the prospective national hydrogen production mix. In other words, they would not yet be techno-economically competitive. In this respect, the potential contribution of SMR with CO\(_2\) capture technology will depend on its actual techno-economic evolution in comparison with that of water electrolysis, as well as on the formulation of environmental regulations on hydrogen (regarding e.g. the use of fossil feedstock). It should be noted that the consideration of SMR plants retrofitted with CO\(_2\) capture systems could affect this finding, which would require a separate assessment.

3.4. Carbon footprint perspective

In addition to the prospective assessment of the technology mix for the production of transportation fuels, the prospective assessment of the corresponding environmental life-cycle performance would further support decision- and policy-making processes on the national road transport system. In this regard, the carbon footprint of each fuel (including production and combustion) was endogenously implemented in the energy systems model according to data available for biodiesel
value (year 2020) exceeds 80 Mt CO\textsubscript{2} eq, which is in line with the latest values available for the GHG emissions associated with the road transport sector in Spain (which refer to the year 2018)\footnote{78}.

According to the results shown in Fig. 6, the NECP objective of reducing 27 Mt CO\textsubscript{2} eq in 2030 would be achieved. In this sense, the retirement of fossil fuels and the penetration of alternative fuels would lead to significant GHG emission reductions in the medium and long term. In particular, the GHG emissions related to fossil diesel and gasoline would decrease around 96% in the evaluated period, at the expense of a slight increase in the GHG emissions associated with the alternative fuels (from 6 Mt CO\textsubscript{2} eq in 2020 to 10 Mt CO\textsubscript{2} eq in 2050).

When focusing only on alternative fuels, a GHG contribution around 5 Mt CO\textsubscript{2} eq from bioethanol and biodiesel was observed in the short term, mainly due to the involvement of 1G biomass. In the medium-to-long term, despite the high demand for synthetic fuels and HVO, the carbon footprint associated with the production and use of these 2G biofuels would be low (<5 Mt CO\textsubscript{2} eq in 2050). In the medium-to-long term, a relatively low carbon footprint was also found for transport-related electricity and hydrogen, which is closely linked to their increasingly high renewability\footnote{79}. Even though the prospective carbon footprint associated with the FCEV-related hydrogen is higher than that linked to the EV-related electricity, and the total amount of FCEVs is lower than that of EVs, it should be noted that the portfolio of vehicles substituted by FCEVs is a key factor leading to a higher reduction in fossil-related GHG emissions\footnote{23}.  

### 3.5. Potentials and limitations

The analytical focus on a large portfolio of technologies for the production of alternative fuels arose as a valuable complement to the measures and goals set in national plans. The combined study of biofuels, electricity and hydrogen with a long-term perspective succeeded in providing a global vision on the role of alternative fuels in an illustrative national road transport system, while filling the gap regarding a high level of detail in fuel and technology categorisation and enabling the consideration of linkages between modelled options (e.g., hydrogen and electricity). Nevertheless, other aspects concerning the development of alternative fuels and vehicles – e.g., infrastructure deployment and vehicle production – remain out of the scope of this study. Additional analyses addressing these issues are needed in order to further support the definition of new policies for transport. Future works could also address a stochastic techno-economic analysis to further explore uncertainty.

Regarding the definition of fuel demands, the current situation of pandemic caused by COVID-19 will affect the behaviour of the transport system, especially in the short term. However, the key outcomes of this energy systems optimisation study (i.e., the prospective technology mixes for fuel production) are not expected to be significantly affected by the associated demand variations, with the main findings (i.e., technology trends) remaining the same. Furthermore, the exogenous definition of fuel demands would benefit from the future specification of fuel targets in NECPs regarding currently underspecified options such as synthetic biofuels and HVO.

Alternative fossil fuels (NG and LPG) were not included in this study since they essentially involve one production technology per option. Moreover, further analyses are needed to check their suitability for a high decarbonisation of the transport system. In this sense, their renewable alternatives – such as biomethane for NG – still need further studies for their complete techno-economic and environmental characterisation. Nevertheless, in this study, there is a fuel demand gap (Table 2) that could be partially filled by these fuel options.

As shown in Section 3.4, even though the alternative fuels considered in this study (biofuels, electricity, and hydrogen) do contribute to a high decarbonisation of the transport system, they also involve some GHG emissions when following a life-cycle perspective. In this respect, a more complete prospective environmental assessment should include additional indicators (beyond carbon footprints) as well as additional stages (beyond fuel production and combustion) and aspects (e.g., land use change emissions).

Overall, this type of energy systems modelling study was found to complement and support current national plans. It should be noted that, even though some findings are specific to the Spanish case study (e.g., the specific renewability of the electricity mix), the modelling approach and key technology trends could be extrapolated to a large number of countries facing similar energy transition issues. Hence, this study shows how the enrichment of national plans with the analysis of technology pathways for the production of alternative transportation fuels strengthens the assessment of their suitability within the context of the

![Fig. 6. Prospective carbon footprint of the fuel production mix.](image-url)
ambitious goals established for the road transport system in NECPs.

4. Conclusions

A national energy systems optimisation model focused on technologies for the production of alternative fuels for road transport was developed. The optimisation of the technology mix for the production of alternative transportation fuels enhances the assessment of the suitability of the different fuels by providing an integrated perspective that widens the frame of discussion on national and international targets for the road transport system with a high level of detail regarding both fuel and technology breakdown. According to the prospective study with time frame 2020–2050, alternative fuels (biofuels, electricity, and hydrogen) would be produced mainly by technologies based on renewable energy. The main findings are:

(i) Bioethanol (for blending with fossil gasoline) and biodiesel (for blending with fossil diesel) would be produced through fermentation and esterification of second-generation biomass feedstocks, respectively. Synthetic biofuels would be produced from second-generation biomass by pyrolysis in the short-to-medium term and by gasification in the long term. HVO production would be based on hydrogenation of second-generation biomass.

(ii) Regarding the electricity associated with EV penetration, it would be mainly supplied by renewable technologies such as wind and solar plants.

(iii) Clean hydrogen for road transport would be produced through electrolysis, potentially without contribution from other technology options such as SMR with CO₂ capture.

(iv) The retirement of fossil fuels and their substitution by alternative fuels would involve a high reduction in the life-cycle GHG emissions of the road transport system: from near 90 Mt CO₂ eq in 2020 to 13 Mt CO₂ eq in 2050.

Beyond these findings, the model structure and characterisation developed for the prospective techno-economic assessment of the production technology mix of alternative fuels for road transport is expected to be relevant to national and international analysts and decision-makers, contributing to the overall goal of building sustainable energy systems. Further studies could address stochastic techno-economic analysis and pending topics such as infrastructure deployment.

Zaira Navas-Anguita: Methodology, Formal analysis, Investigation.
Diego García-Gusano: Methodology, Formal analysis, Supervision.
Diego Iribarren: Methodology, Formal analysis, Supervision, Funding acquisition.

Declaration of Competing Interest

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

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