Science of the Total Environment 771 (2021) 145432

Contents lists available at ScienceDirect

Science of the Total Environment

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

Short Communication

Revisiting the role of steam methane reforming with CO_2 capture and storage for long-term hydrogen production

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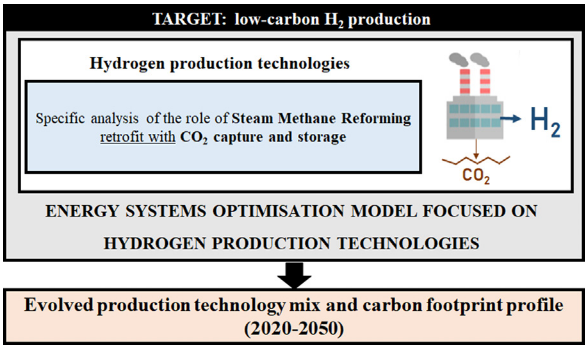
HIGHLIGHTS

- Updated energy systems model on hydrogen production for road transport (2020–2050)
- Inclusion of steam methane reforming (SMR) retrofit with CO_2 capture and storage (CCS)
- SMR would satisfy the hydrogen demand in the short term.
- Low-carbon hydrogen would be produced via electrolysis in the medium-to-long term.
- Low sensitivity of the hydrogen production trends to alternative investment costs

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 19 November 2020
Received in revised form 14 January 2021
Accepted 21 January 2021
Available online 28 January 2021

Editor: Kuishuang Feng

Keywords:
Blue hydrogen
Carbon footprint
Electrolysis
Energy systems modelling
Road transport
Steam methane reforming

ABSTRACT

Road transport is associated with high greenhouse gas emissions due to its current dependence on fossil fuels. In this regard, the implementation of alternative fuels such as hydrogen is expected to play a key role in decarbonising the transport system. Nevertheless, attention should be paid to the suitability of hydrogen production pathways as low-carbon solutions. In this work, an energy systems optimisation model for the prospective assessment of a national hydrogen production mix was upgraded in order to unveil the potential role of grey hydrogen from steam methane reforming (SMR) and blue hydrogen from SMR with CO_2 capture and storage (CCS) in satisfying the hydrogen demanded by fuel cell electric vehicles in Spain from 2020 to 2050. This was done by including CCS retrofit of SMR plants in the energy systems model, as a potential strategy within the scope of the European Hydrogen Strategy. Considering three hypothetical years for banning hydrogen from fossil-based plants without CCS (2030, 2035, and 2040), it was found that SMR could satisfy the whole demand for hydrogen for road transport in the short term (2020–2030), while being substituted by water electrolysis in the medium-to-long term (2030–2050). Furthermore, this trend was found to be associated with an appropriate prospective behaviour in terms of carbon footprint.

1. Introduction

Transport is currently responsible for 24% of the direct CO_2 emissions from fossil fuel combustion. Road vehicles account for nearly three quarters of the transport-related CO_2 emissions. In order to mitigate these emissions, the implementation of alternative fuels is needed

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https://doi.org/10.1016/j.scitotenv.2021.145432

(International Energy Agency, 2019). In particular, hydrogen could play a key role in decarbonising the transport system (Ajanovic and Haas, 2018). Fuel cells in fuel cell electric vehicles (FCEV) convert the energy stored in hydrogen into electricity: hydrogen is fed to the anode and oxygen (from air) to the cathode in order to produce electricity through redox reactions. During this process the only emissions are just water vapour and warm air, avoiding undesirable tailpipe emissions such as CO_2 or NO_x (US Department of Energy, 2020).

The global FCEV stock in 2018 reached 11,200 units, mainly concentrated in California, Japan, Korea, and Germany. Moreover, several countries have announced ambitious targets towards 2030, tentatively resulting in 2.5 million FCEV (International Energy Agency, 2019). Hence, the role of hydrogen in transport could be essential to reach a decarbonised system, especially in the long term (European Commission, 2020). Nevertheless, attention should be paid to the suitability of hydrogen production pathways as actual low-carbon solutions, which calls for a life-cycle perspective (Valente et al., 2019, 2020). In this regard, renewable and low-carbon hydrogen are not yet cost-competitive when compared to fossil-based hydrogen, and the achievement of a clean hydrogen economy demands a strategic approach (European Commission, 2020). Depending on the hydrogen production pathways, hydrogen is often classified as "grey hydrogen" –when produced from fossil resources, e.g. through steam methane reforming (SMR) of natural gas as the currently most mature and extended technology–, "blue hydrogen" –when the production technology is based on fossil resources but includes a CO_2 capture system–, and "green hydrogen" –when produced from renewable sources such as biomass gasification or wind-powered electrolysis– (Velazquez Abad and Dodds, 2020). According to the European Hydrogen Strategy, green hydrogen is also called renewable hydrogen (European Commission, 2020). The main challenge to produce blue or green hydrogen refers to the economic factor (Hydrogen Council, 2020). The trade-off for grey versus blue hydrogen production relates to CO_2 emissions prices and CO_2 capture and storage (CCS) costs (World Energy Council, 2018). On the other hand, the production cost of green hydrogen is expected to drop significantly over the coming decade, with the optimal production option being highly dependent on the region (Hydrogen Council, 2020).

Within this context, a detailed study on the prospective technology mix for hydrogen production as a decarbonisation solution within the road transport sector is required. Navas-Anguita et al. (2020) prospectively assessed the techno-economic and environmental performance of a national hydrogen production mix by following a methodological framework based on energy systems modelling. Such a prospective study showed that the production of blue hydrogen would not be techno-economically competitive in comparison with other production technologies. However, the energy systems model in Navas-Anguita et al. (2020) only considered the option of SMR with CCS as a new technology, whereas a retrofit from grey to blue hydrogen was left out of the scope of the study. In order to overcome this limitation, and due to the international interest in progressively developing a low-carbon hydrogen economy (European Commission, 2020), the present study aims to revisit the potential role of grey and blue hydrogen by upgrading the original energy systems model (Navas-Anguita et al., 2020) through the consideration of SMR plants' retrofit with CCS.

After this introduction to the prospective study of hydrogen production for road transport, Section 2 focuses on the energy systems optimisation model, with emphasis on modelling the option of CCS retrofit in SMR plants and the techno-economic characterisation of the hydrogen production technologies. Considering three hypothetical years for banning hydrogen from fossil-based plants without CCS, Section 3 presents the evolution of a national hydrogen production mix and its corresponding carbon footprint profile as the main results of the study, also analysing its sensitivity to alternative projections of electrolysis investment costs. Finally, Section 4 draws the main conclusions from the study.

2. Materials and methods

The goal of the study is to explore the prospective role of SMR with CCS as an option for hydrogen production for road transport. According to this goal, the energy systems model developed in Navas-Anguita et al. (2020) for the optimisation of a national hydrogen production mix with time frame 2020–2050 was updated. This model refers to Spain as an illustrative country without specific hydrogen strategies and whose results could be extended to other countries with a still underdeveloped hydrogen economy. As a distinguishing feature, the present study includes –for the first time– the option of CCS retrofit in SMR plants, competing with the rest of hydrogen production technologies techno-economically and environmentally characterised as summarised in Table 1 (investment costs, carbon footprints and transformation efficiencies based on World Energy Council (2018), Hydrogen Council (2020), and Navas-Anguita et al. (2020)).

Since SMR using fossil-based natural gas as the feedstock is a very mature technology, no significant reductions in investment costs are expected (World Energy Council, 2018). The overall process can be represented by Eq. (1) (Muradov and Veziroglu, 2012):

$$CH_4 + 2H_2O \leftrightarrow 4H_2 + CO_2 \quad \Delta H^{\circ} = 253.1\ kJ \cdot mol^{-1} \tag{1}$$

The endothermic reforming reaction is performed over a (usually Ni-based) catalyst at 800–900 °C. Heat is supplied to the reactor by combusting part of the natural gas feedstock. The resultant syngas undergoes a water gas shift (WGS) process to increase the hydrogen content. Afterwards, a pressure swing adsorption (PSA) unit is used for hydrogen purification.

The production of blue hydrogen is mainly focused on SMR. In this regard, chemical absorption is a common option for CO_2 capture from the syngas or the PSA off-gas (Shahani and Kandziora, 2014). A liquid sorbent is typically used to separate the CO_2 from the gas stream. The most extended ones are based on amines, with capture efficiencies over 90% (Leung et al., 2014). The main challenge behind the integration of CO_2 capture into a plant is that the complexity of the plant and the production costs increase (National Research Council and National Academy of Engineering, 2004). According to the Global CCS Institute (2019), a short number of hydrogen production plants with CCS were operating globally in 2019 and several were in progress, with a capture capacity between 1.0 and 2.5 Mt per year. Millions of tonnes of CO_2 can be stored in geological formations such as salt caverns. General requirements for CO_2 geological storage include appropriate porosity, thickness, and permeability of the reservoir rock, a cap rock with good sealing capability, and a stable geological environment (Leung et al., 2014). Regarding the final cost of hydrogen from SMR, other parameters such as the natural gas price play a key role (World Energy Council, 2018). In this study, an increase in the natural gas industrial price for Spain from 16 $€ \cdot MWh^{-1}$ to $37€ \cdot MWh^{-1}$ in 2030, $44€ \cdot MWh^{-1}$ in 2040 and 48 $€ \cdot MWh^{-1}$ in 2050 was assumed (U.S. Energy Information Administration, 2019; Enagas, 2020).

Apart from the integration of CCS systems, another way to avoid grey hydrogen consists in the use of renewable options such as biomass gasification and water electrolysis powered by renewable electricity. Gasification involves the thermochemical conversion of the feedstock at high temperature in a gasification medium such as air, oxygen and/or steam to produce syngas, which is subsequently processed as in the SMR pathway (Navas-Anguita et al., 2019). While the use of coal as the feedstock for gasification is not an actual option for countries such as Spain –where coal for power generation is being retired (García-Gusano et al., 2018; Interministerial Group for Ecological Transition, 2020)–, the use of biomass could be an option in the long term (Navas-Anguita et al., 2020; Valente et al., 2020). Electrochemical pathways based on water electrolysis involve the decomposition of water into hydrogen and oxygen using an electric current (International Renewable Energy Agency, 2018).

Table 1
Investment cost, efficiency and carbon footprint of hydrogen production technologies.

Technology	Investment cost ($€_{2019} \cdot GJ^{-1} \cdot y$) in year 2020; year 2030; year 2050	Efficiency (%)	Carbon footprint (kg CO_2 eq$\cdot kg^{-1}$ H_2)
Steam methane reforming (SMR)[a]	8.8; 7.3; 7.0	76–85	11.4
Retrofit with CCS on an existing SMR plant[a,b]	+5.6 (Δ investment cost)	65–70	−6.7 (Δ carbon footprint)
Steam methane reforming with CCS[a]	14.4; 13.7; 13.4	65–70	4.7
Coal gasification[c]	9.1; 7.6; 7.3	60–70	26.99
Coal gasification with CCS[c]	14.6; 13.9; 13.6	56–60	7.66
Electrolysis[d]	39.4; 19.7; 9.8	68–85	From 6.1 in 2020 to 1.4 in 2050
Biomass gasification[e]	48.3; 21.1; 18.0	43–46	0.18

[a] 300 MW plant capacity.
[b] The investment cost refers only to the extra cost of retrofit assuming the whole life of the existing plant (25 years), and the carbon footprint refers only to the reduction in the carbon footprint of conventional SMR.
[c] 100 MW plant capacity.
[d] 20 MW plant capacity.
[e] 50 MW plant capacity.

Hydrogen production should be based on low-carbon options (European Commission, 2020; MITERD, 2020). The main hindrance is that low-carbon hydrogen options are not yet cost-competitive compared to SMR hydrogen, which leaves the door open to the use of grey hydrogen to satisfy the short-term demand until low-carbon alternatives become techno-economically competitive (World Energy Council, 2019). In this sense, retrofitting hydrogen production plants with CCS could be a future option for low-carbon hydrogen production.

Within this context, three scenarios were modelled to prospectively assess the effect –on the hydrogen production mix– of banning hydrogen from fossil-based plants without CCS from three alternative years: 2030 in the scenario BAN_2030, 2035 in BAN_2035, and 2040 in BAN_2040. As a novel feature in comparison with the original energy systems model (Navas-Anguita et al., 2020), the extra investment cost associated with the implementation of CCS as a retrofit solution in SMR plants was modelled as a constant value that increases the investment cost of the SMR plant throughout its whole lifespan (Table 1). Regarding operating costs of SMR plants with CCS retrofit, the same operating cost as for SMR without CCS was assumed until the ban year, and –from then on– the operating cost increases due to the actual necessity of consuming more feedstock to compensate for the energy penalties associated with CCS. These penalties were considered in the model via decreased efficiency values (Table 1).

The national energy systems model on hydrogen production for road transport –updated from the original one built by Navas-Anguita et al. (2020) using the software LEAP (Heaps, 2017)– is represented in Fig. 1. All the technological options in Table 1 –including SMR plants with CCS retrofit– were implemented in the model. The techno-economic characterisation of the technologies (Table 1) allowed the subsequent optimisation –through OSeMOSYS (Howells et al., 2011)– of the production technology mix that would satisfy the demand in each scenario. Furthermore, the fact that carbon footprints of the hydrogen options are integrated into the model allowed assessing the evolution of the carbon footprint of the hydrogen production mix. The exogenous hydrogen demand was directly taken from the medium scenario (15% of FCEV in 2050) considered in Navas-Anguita et al. (2020), thus assuming the need for 41 PJ in 2030, 156 PJ in 2040, and 290 PJ in 2050. Given the current lack of a transport-related hydrogen demand in Spain, these growing needs call for the installation of new plants. This scenario implies the consideration of hydrogen demands specific to the road transport sector, leaving the hydrogen demand linked to other sectors (e.g., industry) out of the scope of the study.

3. Results

This section presents the results coming from the application of the model detailed in Section 2. Three main outcomes are reported: the prospective role of grey and blue hydrogen from SMR in the production mix under three alternative scenarios banning hydrogen from fossil-based plants without CCS (Section 3.1), its sensitivity to the electrolysis investment costs (Section 3.2), and its carbon footprint profile (Section 3.3).

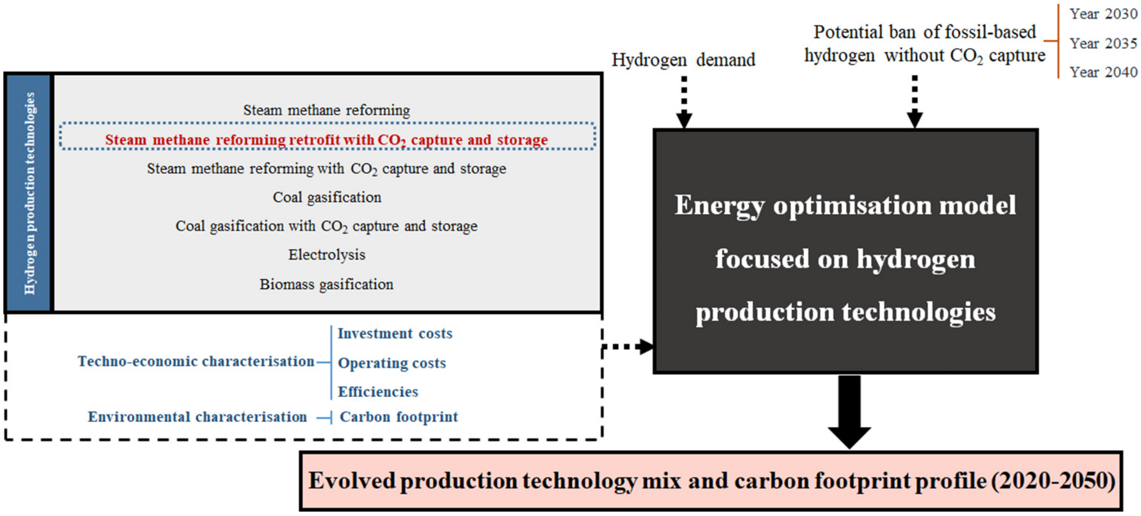

Fig. 1. Updated energy systems model on hydrogen production for road transport.

3.1. Base case

Fig. 2 shows the resultant evolution of the hydrogen production technology mix from 2020 to 2050. A similar behaviour was found in each of the scenarios under assessment: SMR with CCS retrofit (which can be simplistically understood as grey hydrogen from SMR until the ban year and blue hydrogen from SMR from then on) would emerge as the leading option in the short-to-medium term (2020–2030), but substituted by water electrolysis in the medium-to-long term (2030–2050). In the three scenarios, SMR with CCS retrofit would satisfy the whole hydrogen demand until 2028. From then on, water electrolysis starts to substitute SMR hydrogen production, rapidly becoming the only used technology. This is closely linked to the significant reduction in the investment cost of water electrolysis as well as to competitive electricity prices (Navas-Anguita et al., 2020).

Hydrogen production through SMR with CCS retrofit would end by 2034, 2035 and 2036 in the scenarios BAN_2030, BAN_2035 and BAN_2040, respectively. In other words, actual CCS operation was found only in the scenario BAN_2030. After the above-mentioned years, the whole hydrogen demand would be fulfilled via water electrolysis. These results indicate that, regardless of the ban, water electrolysis would be techno-economically more competitive than SMR with CCS retrofit well before 2040.

In contrast to the previous prospective study on the national hydrogen production mix for road transport (Navas-Anguita et al., 2020), the inclusion of the CCS retrofit option for SMR in the model was found to unveil the potential role of grey and blue hydrogen from SMR as a transitional solution in the short-to-medium term. In this regard, the European Hydrogen Strategy leaves room for a period of transition towards green hydrogen, which emphasises the convenience of the present study (European Commission, 2020). In particular, though relatively minor, the unveiled role of blue hydrogen highlights the convenience of modelling SMR with CCS not only as a new technology but also as a retrofit. On the other hand, the key role of water electrolysis in the long-term national hydrogen production mix is in agreement with the original study (Navas-Anguita et al., 2020) as well as with the national vision (MITERD, 2020). Since water electrolysis is expected to play a key role in hydrogen production in the medium-to-long term and its

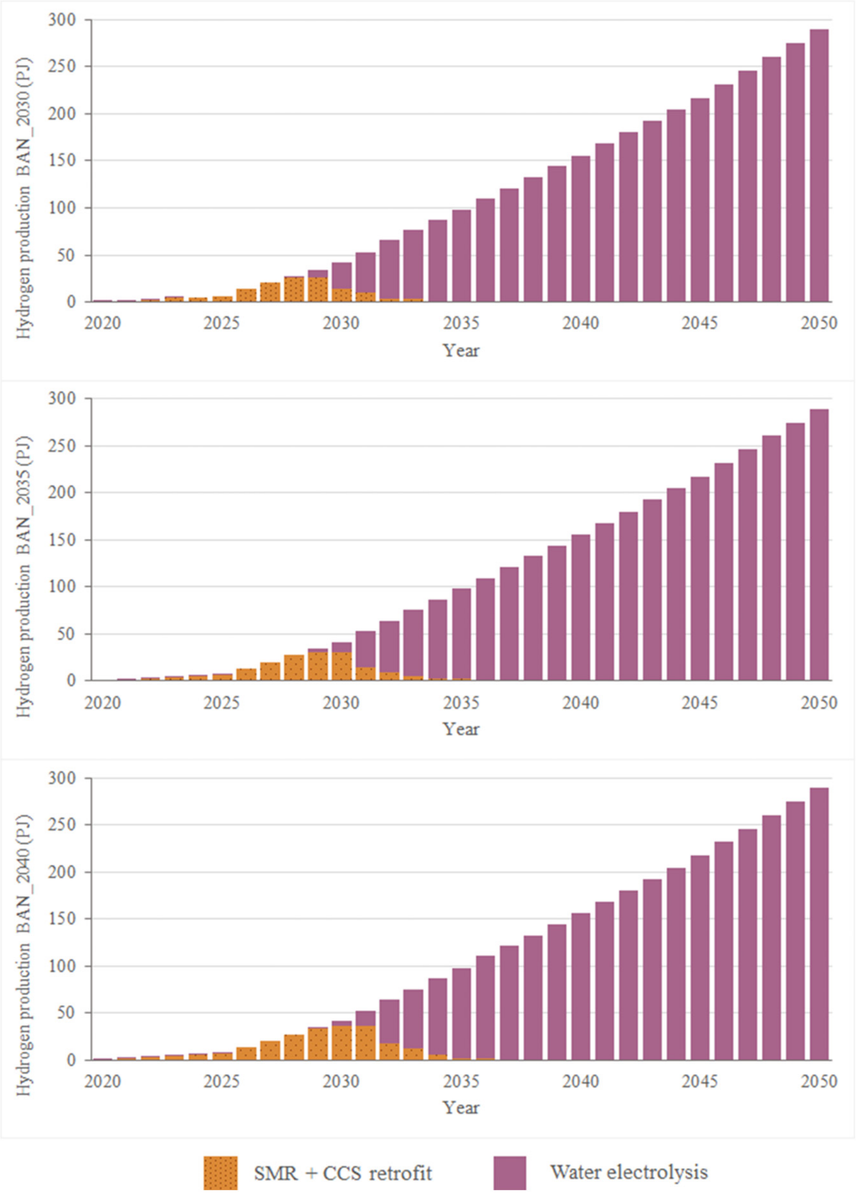

Fig. 2. Evolution of the hydrogen production technology mix in the three scenarios under evaluation.

Table 2
Prospective investment costs assumed for water electrolysis in sensitivity analysis.

Sensitivity analysis to electrolysis investment cost	Scenario	Investment cost in 2020 ($€_{2019}\cdot GJ^{-1}\cdot y$)	Investment cost in 2030 ($€_{2019}\cdot GJ^{-1}\cdot y$)	Investment cost in 2050 ($€_{2019}\cdot GJ^{-1}\cdot y$)
Base case (50% reduction cost in 2030)	A	39.4	19.7	9.8
40% reduction cost in 2030	B	39.4	23.6	14.2
70% reduction cost in 2030	C	39.4	11.8	8.3

current investment cost is expected to decrease significantly, a more detailed analysis on the potential consequences of different assumptions in cost reduction would be convenient, as addressed in Section 3.2. Even though the consideration of hydrogen demands not related to the road transport sector was left out of the scope of the study, its influence on the results is expected to dissipate when approaching the time horizon.

3.2. Sensitivity analysis

The investment cost projection assumed for water electrolysis could be a key aspect influencing the techno-economic optimisation of the national hydrogen production mix. In this regard, projected values can represent international commitments (Hydrogen Europe, 2018; Hydrogen Council, 2020) and/or technological progress (learning curves) (Saba et al., 2018). Taking into account the expected leading role of water electrolysis in the long-term hydrogen production mix (Fig. 2), a sensitivity analysis to alternative investment cost reductions for water electrolysis was carried out. Three scenarios with different investment cost reductions for water electrolysis were defined. Scenario A represents the base case already addressed: 50% reduction from 2020 to 2030 as well as from 2030 to 2050. Scenario B is more conservative, with a reduction of 40% from 2020 to 2030 as well as from 2030 to 2050. Scenario C is the most optimistic one, assuming an investment cost reduction of 70% from 2020 to 2030 and a reduction of 30% from 2030 to 2050. Table 2 presents the values assumed in the three scenarios.

Fig. 3 shows the results of the sensitivity analysis in terms of hydrogen production and share attributed to SMR with CCS retrofit in BAN_2035. Overall, a relatively low sensitivity of the results to alternative electrolysis investment costs was observed. In Scenario B, which involves a conservative investment cost reduction, the contribution of SMR with CCS retrofit to hydrogen production would slightly increase in the period 2029–2035 with respect to the base case (Scenario A). On the other hand, in scenario C (optimistic investment cost reduction), electrolysis would enhance its techno-economic competitiveness, leading to a moderate reduction in the contribution of SMR with CCS retrofit to hydrogen production in the medium term.

There are two periods in which hydrogen production via SMR with CCS retrofit shows the same profile for the three sensitivity scenarios: 2020–2028 (satisfying the whole demand for hydrogen) and 2036–2050 (zero contribution). Hence, differences between scenarios A, B and C were found to be slight and limited to the medium term (2029–2035), which highlights the expected competitiveness of water electrolysis with respect to the other low-carbon hydrogen production technologies implemented in the model.

While a low sensitivity of the hydrogen production trends to alternative investment costs was found, variations in the operational costs could significantly affect these trends. In this sense, in scenarios with natural gas prices above 79 €·MWh^{-1}, the total hydrogen demand would be produced by water electrolysis for the whole time frame.

Finally, assuming an upsurge in hydrogen demand for transport according to the great expectations from many governments and companies, efforts in deepening the technical feasibility of hydrogen narratives should be made, which is out of the scope of this work. Examples include a potential lack of space to place electrolysers in areas with access to water and the necessity of evaluating infrastructure needs (pipelines, H_2 storage units, etc.) to develop optimal configurations at every scale and sector.

3.3. Carbon footprint profile

Fig. 4 shows the evolution of the carbon footprint associated with the hydrogen production technology mix for the scenarios BAN_2030, BAN_2035, and BAN_2040. These results were directly obtained from the energy systems model thanks to the direct integration of the carbon footprint of each hydrogen option into the model (Navas-Anguita et al., 2020). A change in the behaviour of life-cycle greenhouse gas emissions was observed around 2030 as a result of the proposed bans and the corresponding substitution of blue and green hydrogen for grey hydrogen. After 2036, the same behaviour was found for the three scenarios given the role of electrolysis as the only hydrogen production technology in the mix.

The trend for growing life-cycle greenhouse gas emissions from 2040 is not motivated by an unfavourable hydrogen carbon footprint

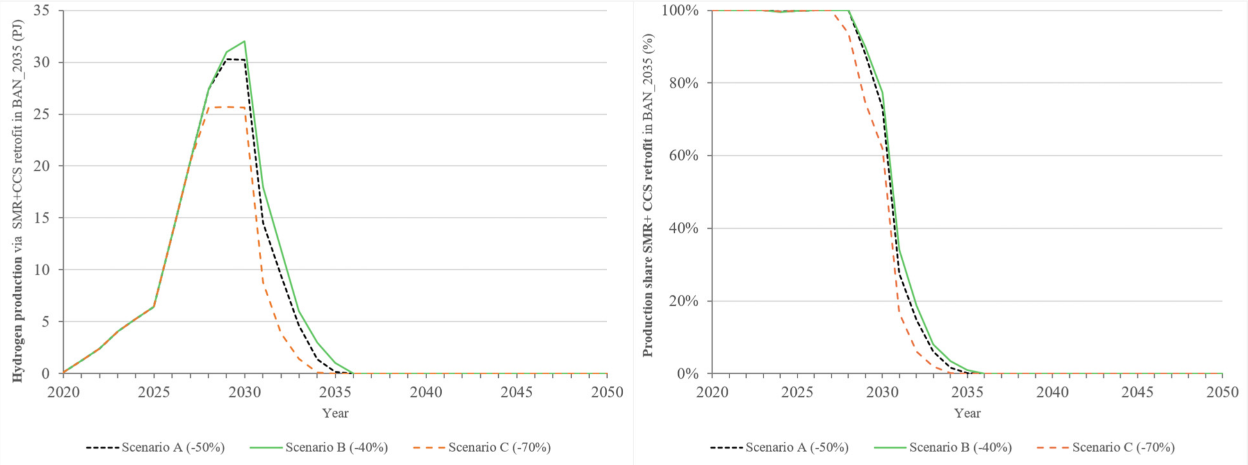

Fig. 3. Hydrogen production and share attributed to SMR with CCS retrofit in BAN_2035 under alternative electrolysis investment costs.

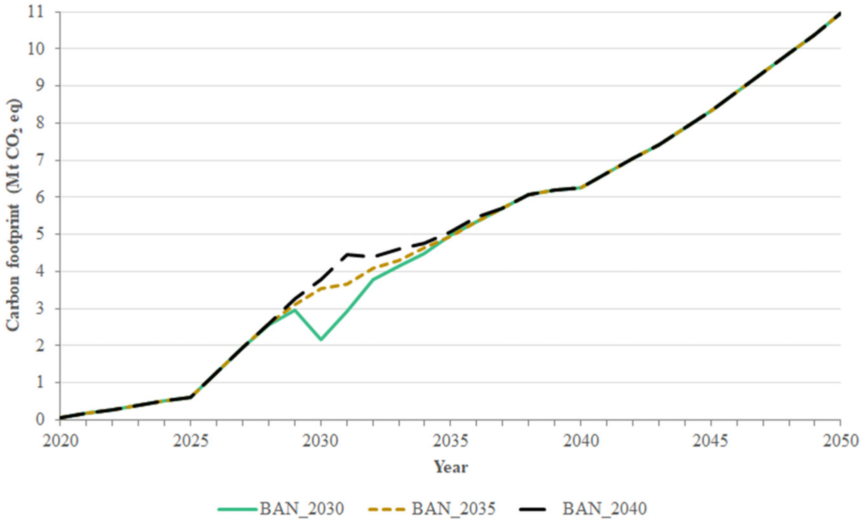

Fig. 4. Evolution of the carbon footprint of the national hydrogen production technology mix in the three scenarios under evaluation.

but by the increased hydrogen demand. In fact, an appropriate prospective behaviour in terms of carbon footprint was concluded, in line with the national and international expectations of hydrogen as a decarbonisation solution (European Commission, 2020; MITERD, 2020). This favourable carbon footprint behaviour would be further enhanced if the avoidance of conventional fuels was also considered as already addressed in Navas-Anguita et al. (2020). Finally, it should be noted that the prospective nature of this carbon footprint assessment was limited to the evolution of the hydrogen and electricity production technology, disregarding the potential evolution of other aspects (Valente et al., 2020).

4. Conclusions

Considering different years for banning the use of hydrogen from fossil-based plants without CCS (2030, 2035, and 2040), grey and blue hydrogen from SMR could satisfy the hydrogen demand for road transport in the short-to-medium term. However, due to the expected decrease in water electrolysis investment costs and competitive electricity prices, hydrogen would be partly produced via electrolysis since 2028 and would fulfil the whole demand from ca. 2035, which is associated with a favourable prospective behaviour in terms of carbon footprint. Further reductions in electrolysis investment costs and/or a significant increase in natural gas prices could accelerate the transition from SMR to electrolysis as the dominating hydrogen production technology. Within the context of the European Hydrogen Strategy, it is concluded that –for a period of transition to green hydrogen– production through SMR could be relevant. Nevertheless, international strategies for developing a clean hydrogen economy should consider further techno-economic, environmental and social aspects.

Since national energy and climate plans should address the role of hydrogen, this work opens the door to the consideration of hydrogen production alternatives, and in particular SMR plants with CCS retrofit, in these plans as well as in other specific documents such as hydrogen roadmaps and strategies. This opportunity would support decision-making at company and policy levels, being of special interest within the context of the recent European Hydrogen Strategy and the current upsurge in hydrogen roadmaps and plans complementing national energy and climate plans.

CRediT authorship contribution statement

Zaira Navas-Anguita: Methodology, Formal analysis, Investigation, Writing – original draft, Visualization. **Diego García-Gusano:** Methodology, Formal analysis, Writing – review & editing, Supervision. **Javier Dufour:** Writing – review & editing. **Diego Iribarren:** Conceptualization, Methodology, Formal analysis, Writing – review & editing, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare no conflict of interest.

Acknowledgements

This research has been partly supported by the Spanish Ministry of Economy, Industry and Competitiveness (ENE2015-74607-JIN AEI/FEDER/UE).

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