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ORIGINAL PAPER

Environmental performance of non-thermal plasma methane splitting across European hydrogen pathways: a prospective LCA

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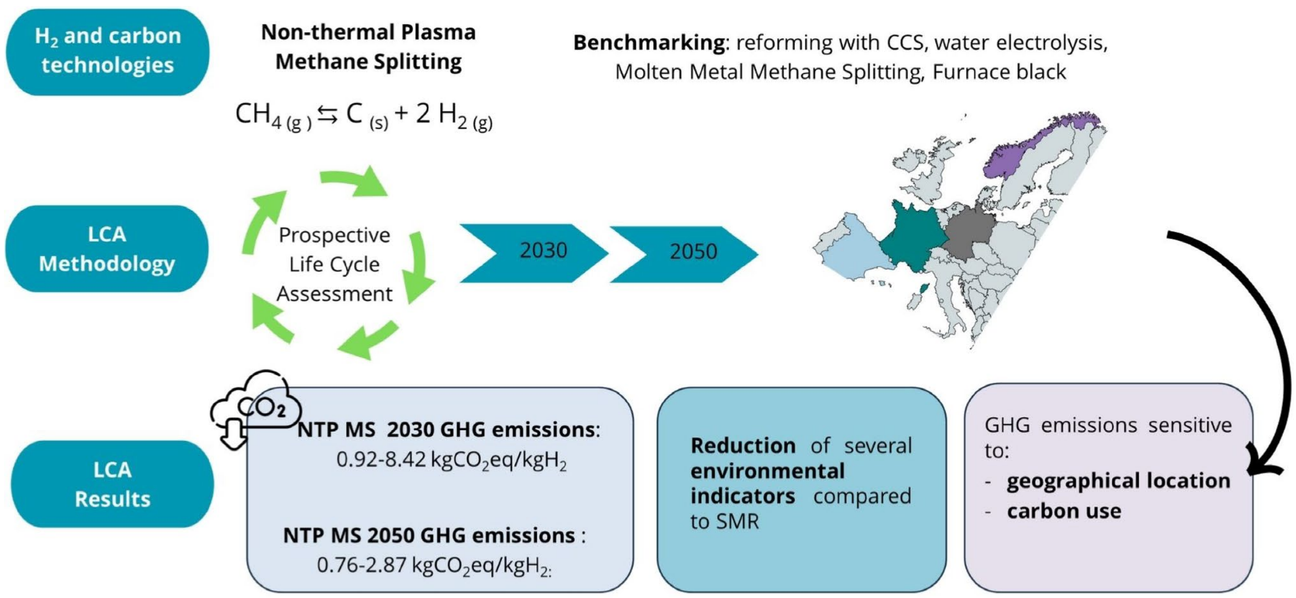
Abstract

Methane splitting is emerging as a promising technology for the coproduction of hydrogen and solid carbon. This study presents the first prospective life cycle assessment of non-thermal plasma methane splitting (NTP MS), benchmarking its environmental performance against conventional and low-emission pathways for hydrogen and carbon production in Norway, Germany, Spain, and France. Life cycle inventories for NTP MS are developed using process simulations based on experimental data. Results show that NTP MS is an environmentally competitive option compared with water electrolysis, reforming processes with carbon capture and storage, and furnace black production, with greenhouse gas (GHG) emissions ranging from 0.76 to 3.33 $kgCO_2eq/kgH_2$; reaching a reduction of up to 92% relative to conventional steam methane reforming by 2050 in Norway. Germany represents an exception, as the environmental competitiveness of NTP MS depends on the decarbonization of the electricity mix by 2050. Across additional environmental indicators, NTP MS offers a favorable trade-off between GHG reduction and other environmental impacts, benefiting from catalyst-free operation and process multifunctionality. Sensitivity analyses highlight the influence of reactor electricity demand and solid carbon utilization on GHG emissions. Solid carbon use reduces hydrogen GHG emissions, decreasing the hydrogen allocation factor. These findings support NTP MS as a viable low-carbon pathway under specific regional and system conditions and open reflections on the EU low-carbon hydrogen policy approach, which favors solid carbon storage.

Graphical abstract



Extended author information available on the last page of the article

Abbreviations

LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
TRL	Technology readiness level
FB	Furnace black
ATR	Autothermal reforming
SMR	Steam methane reforming
SMR CCS	Steam methane reforming with carbon capture and storage
NTP	Non thermal plasma
MS	Methane splitting
MM	Molten metal
CG	Conventional gas
TP	Thermal plasma
GHG	Greenhouse Gas
pLCA	Prospective life cycle assessment
PEMEL	Protone exchange membrane
FU	Functional unit
BoP	Bill of plant

Introduction

Climate change and the consequent challenge of reducing greenhouse gas (GHG) emissions are driving changes in energy production processes. Hydrogen is intended to support key sectors such as electricity generation, heavy goods traffic, and hard-to-abate industries (Andrean et al. 2024). According to the Net Zero Scenario of the IEA, 97.6% of the hydrogen produced by 2050 shall be targeted as low-carbon emission, reaching already 46.7% by 2030 (IEA 2023). Currently, low-carbon emission hydrogen represents approximately 1% of global production, while the hydrogen sector emits almost 920 Mt CO_2 annually (IEA 2023). The hydrogen challenge is double: increasing capacity and changing the production pathway from high to low-carbon emissions processes. Methane Splitting (MS) is a possible bridging technology for climate-friendly and cost-effective hydrogen (Weger et al. 2017). The reaction itself does not produce CO_2 emissions directly, avoiding the need for a storage system and consequential geological constraints. The process demands less electricity than water electrolysis and uses less water than both reforming and water electrolysis. In addition, added-value carbon and short-chain hydrocarbons, such as ethylene and acetylene, can contribute to reducing the hydrogen production cost. The implementation of the process in recent decades has been limited by high temperature requirements, catalyst deactivation, and the separation of solid carbon. To overcome these technical challenges, a variety of reactor concepts have been proposed over the last decades, including (1) Conventional Gas (CG) systems with and without catalysts, (2) Molten Media systems (MM), and (3) Thermal Plasma (TP) and Non-Thermal Plasma (NTP) systems. All the systems are reaching industrial interest, with a technology readiness level (TRL) ranging from 6 to 8 (Muron et al. 2024).

Given the rapid uptake of MS technologies, evaluating their environmental performance is pivotal to ensuring an environmentally sustainable future. Additionally, it helps to position the technology relative to the low-carbon GHG emissions threshold of 3.4 $kgCO_2eq/kgH_2$ defined by the European Parliament and the Council of the European Union (2024).

The scientific literature presents a fragmented discussion of methodological approaches and results (Bulfaro et al. 2026). Most of the environmental analyses focus only on the climate change impact, while the analysis by Hermesmann and Müller (2022) shows that the presence of molten metal in the reactor can dramatically increase the process's environmental impact in terms of eutrophication and material resources. The MS GHG emissions vary deeply according to the process location, reactor heating system, and reaction efficiency, reaching values comparable to the traditional reforming process when heated by carbon (Okeke et al. 2023) to 1.9 $kgCO_2eq/kgH_2$ when the NTP system is powered by wind energy (Kerscher et al. 2021). In addition, across the different reactor systems, Plasma systems are underrepresented compared to MM and CG technologies. This mismatch is further deepened for NTP, where only one paper addressing the technoeconomic and carbon footprint analysis was identified (Kerscher et al. 2021).

This study aims to enhance understanding of the environmental performance of the MS process, with a prospective LCA evaluation of NTP MS technology. Under the author's knowledge, this is the first study applying a prospective approach to MS, although this methodology is the most suitable for low TRL processes (Bargiacchi et al. 2022; Arvidsson et al. 2024). In addition, in the scientific discussion of NTP, it is the first study to apply a holistic LCA approach, encompassing environmental impact categories beyond climate change and including the Bill of Plant (BoP, aka the capital goods) within the scope.

The analysis has a European geographical context, specifically Norway, Germany, Spain, and France. These countries are selected for their roles in EU hydrogen production and their specific characteristics in natural gas (NG) and electricity supply mixes (Deasy-Millar et al. 2025). The environmental performance of the NTP MS process will be compared with the traditional SMR and the most relevant low-carbon emissions production pathways: SMR with carbon capture and storage (SMR CCS), autothermal reforming with CCS (ATR CCS), proton exchange membrane water electrolysis (PEMEL), and molten media (MM) MS.

This study aims to answer the following questions:

- What are the environmental impacts of the NTP MS process in 2030 and 2050 compared to other low-carbon hydrogen and solid carbon technologies?
- What is the sensitivity of MS processes on multifunctional approach adoption, carbon application, and process technical parameters?

To answer these questions, a prospective LCA (pLCA) was performed. The technologies selection and methodological description are discussed in the next section, "Methods." The pLCA results and sensitivity analysis are presented in Results and Discussion.

Methods

The hydrogen production technologies selected in this study are SMR, SMR CCS, ATR CCS, PEMEL, MM MS, and NTP MS. This selection involves the main traditional reforming processes and the low-carbon emissions production pathway with the highest TRL (Andrean et al. 2024). For the detailed description of each process, refer to Supplementary Note 1.

Biomass-based production processes have been excluded from this study, given the limited availability of the feedstock and, consequently, the lower total capacity of these technologies compared to NG-based processes and water splitting.

The furnace black (FB) is the technology analyzed as a benchmark for carbon black synthesis, representing 95% of the total production (Wang et al. 2003).

The comparative environmental performance of hydrogen and carbon production technologies is assessed by applying the LCA methodology supported by ISO 14040 and 14,044 (ISO 2006a, b). It involves the systematic analysis of the potential environmental impacts of a product or service throughout its life cycle, including production, distribution, use, storage, recycling, and end of life (Hunkeler 2016). It is structured into four phases: (1) Goal and Scope, (2) Life Cycle Inventory (LCI), (3) Life Cycle Impact Assessment (LCIA), and (4) Interpretation.

Considering the lower TRL of NTP MS technology, a prospective life cycle assessment (pLCA) is adopted. An LCA is prospective when the (emerging) technology studied is in an early phase of development, but the technology is modeled at a future, more developed phase (Arvidsson et al. 2024).

Goal and scope

The goal of this pLCA is to evaluate the environmental performance of NTP MS technology, comparing it with the hydrogen benchmarking technologies: SMR, ATR, SMR CCS, ATR CCS, MM MS, PEMEL and the carbon black production process, the FB. The LCA was performed based on the ISO 14040 and 14044 standards (ISO 2006a, b) and in alignment with the FCH-LCA guidelines developed in the framework of the EU Project SH2E (Bargiacchi et al. 2022). Given the process's technological maturity, the pLCA approach was adopted to evaluate environmental impacts in future scenarios: 2030 and 2050. Four different geographical locations were selected: Norway (NO), Germany (DE), France (FR), and Spain (ES). In this study, two functional units (FUs) are adopted: (i) 1 kg of hydrogen at 200 bar; (ii) 1 kg of carbon. The use of two FUs is necessary to compare the NTP MS with two different benchmarking processes: hydrogen and carbon production. Acetylene is the second NTP MS byproduct by mass. However, at this stage, its production is not compared with the benchmark due to a lack of experimental data on its separation from hydrogen and unreacted gases.

The scope of the performed pLCA is cradle-to-gate, from resource extraction to the factory gate (Fig. 1). The remaining phases of the life cycle, such as transport, storage, and utilization of hydrogen, and the associated environmental impacts, were excluded since they do not depend on the hydrogen production technology, as recommended by the FCH-LCA Guidelines (Bargiacchi et al. 2022). In the reforming processes with CCS, CO_2 transport and storage were included. To solve the process multifunctionality, the energy allocation was selected, in alignment with the Red III Directives and the decarbonized natural gas (The European Parliament and the Council of the European Union 2018) and hydrogen package (European Commission 2025). In the analysis, the following byproducts were considered: (1) electricity generation from SMR, (2) carbon black and acetylene from MS processes. With regard to the products of water electrolysis, it is usually assumed that oxygen is an unintended and nonharmful byproduct, and therefore, all environmental impacts are attributed to hydrogen (Koj et al. 2024). Although the use of oxygen in fuel cells and for medical and other applications is expected to increase in the future, it is questionable whether it is possible to fully utilize the quantities of oxygen that are likely to be produced (Koj et al. 2024), while cheaper technology processes for its production are available (IRENA 2022).

A sensitivity analysis was performed on the 2050 scenarios to assess the influence of key technical parameters, including methane conversion efficiency and reactor electricity demand, as well as methodological choices regarding multifunctionality and carbon utilization.

All pLCA modeling was conducted using the Activity Browser software (Steubing et al. 2020).

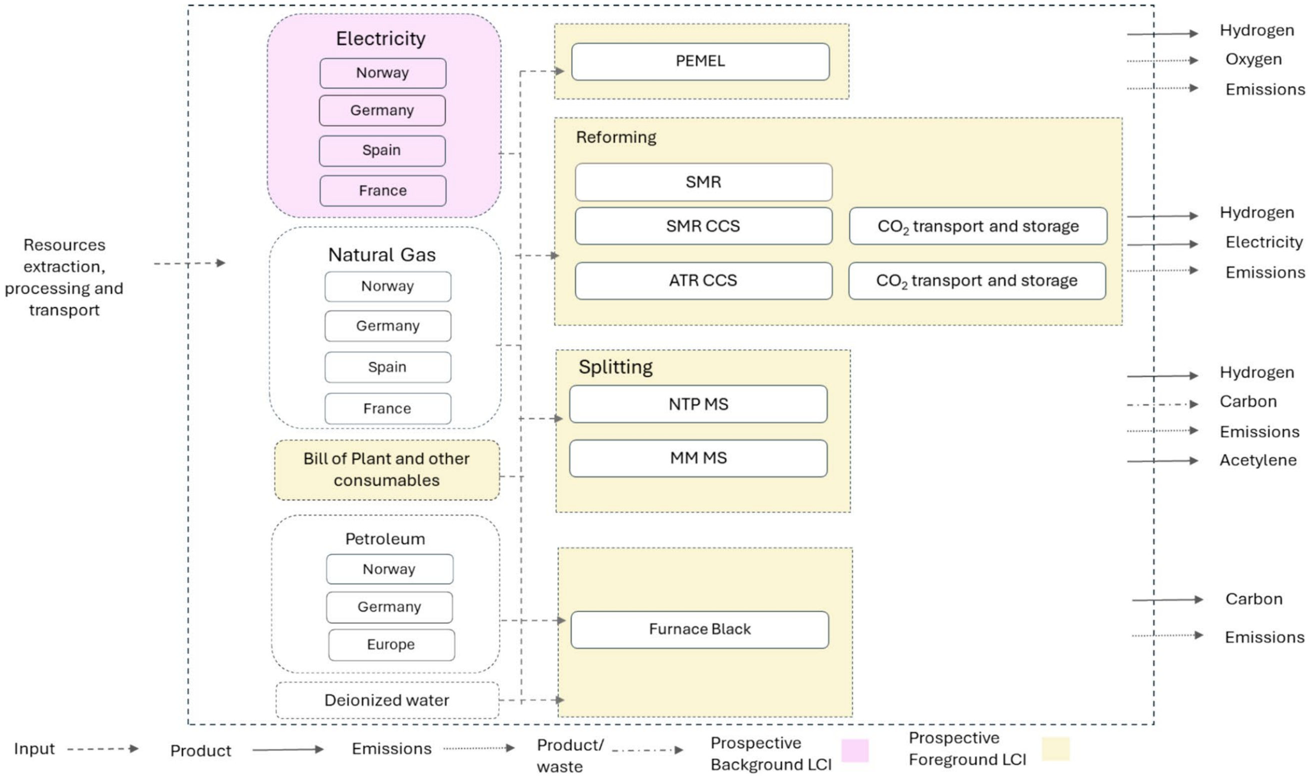


Fig. 1 System boundary for the analyzed hydrogen production processes

LCI

During the inventory analysis phase, all mass and energy flows occurring within and across the system boundaries of the investigated product system are quantified. The resulting dataset constitutes the LCI.

Foreground LCI was modeled for all the technologies analyzed in the study, considering technical parameters and the future evolution of capital goods by 2030 and 2050.

The prospective background data modeling is focused on the electricity mix, in alignment with the pLCA studies on hydrogen (Martinez et al. 2024.) The uncertainty around the NG input was deemed too high to inform future changes in European imports/exports or to reduce methane emissions from extraction and transport, as it is strongly dependent on geopolitical relationships. The dataset applied is ecoinvent v3.11 using the "allocation, cut-off by classification" system mode (Wernet et al. 2016).

Foreground LCI benchmarking processes

The prospective technical assumptions of the benchmark processes are described in Table 1. The detailed information on the modeling is reported in the Supplementary Notes 2–4. Prospective foreground LCIs were developed for all assessed technologies in alignment with the target defined by the Clean Hydrogen Joint Undertaking (CHJU) within the European Commission framework, the US Department of Energy (DOE), and scientific literature. SMR, ATR, and FB traditional processes have reached their efficiency plateau; therefore, their technical characteristics remain unchanged throughout the study timeline. The reforming innovation research focuses on sustainability improvement through the implementation of electrification and carbon capture systems (IEA 2024). The same is intended for FB, where the research involves the reactor electrification (Chikri and Wetzels 2017). Process electrification is out of scope for this study, which focuses on process optimization. For reforming CCS, the development of capture efficiency improvement is modeled from today to 2030 by 90–98%, in alignment with the announced project targets (Deasy-Millar et al. 2025). At 98%, the improvement margin is low, so no major increase is defined. Additionally, both processes have a lifetime of 25 plant lifetimes, which is sufficient for the paper's time analysis (Antonini et al. 2020). For MM, Hermesmann and Müller (2022) report an industrial scenario efficiency of 45.6% in the H_2 combustion setup, with 60% as the maximum set by the reaction stoichiometry. The process achieves the EU target for process energy consumption. In the lack of further improvement information and targets, this study focuses on the combustion of the purge gas, as defined by (Shokrollahi et al. 2024) and its emissions avoidance by 2050. In PEMEL, the improvement is modeled for

Table 1 Prospective LCI foreground assumptions for 2030 and 2050 scenarios

	Technical parameter and capital goods 2030	Technical parameter andcapital goods 2050	References
SMR	State of the art 2020	State of art 2020	Antonini et al. (2020)
SMR CCS	Total Capture efficiency 69%	Total Capture efficiency 69%	Antonini et al. (2020)
ATR	State of the art 2020	State of the art 2020	Antonini et al. (2020)
ATR CCS	Total Capture efficiency 98%	Total Capture efficiency 98%	Antonini et al. (2020)
MM MS	Industrial upscale with purge gas combustion	Industrial upscale w/o purge gas combustion	Hermesmann and Müller (2022); Shokrollahi et al. (2024)
PEMEL	DOE and CHJU target for efficiency, critical material contents and durability 2026–2030	DOE and CHJU target for efficiency, critical material contents and durability 2050	Clean Hydrogen Partnership (2025a); U.S Department of energy (2025)
FB	State of art	State of art	Wernet et al. (2016)

Table 2 SMR, SMR CCS, ATR CCS, MM MS technical assumptions (Antonini et al. 2020)

	NG consumption (m^3/kg H_2)	Electricity demand (kWh/kg H_2)	Direct CO_2 emissions (kg CO_2/kg H_2)
SMR 2030	3.89	−0.14	8.95
SMR 2050	3.89	−0.14	8.95
SMR CCS 2030	3.89	0.68	2.61
SMR CCS 2050	3.89	0.68	2.61
ATRC CCS 2030	3.92	1.14	0.59
ATR CCS 2050	3.92	1.14	0.59
MM MS 2030	7.59	3.68	0.28
MM MS 2050	7.44	3.68	0

Table 3 Water electrolysis technical assumptions (Clean Hydrogen Partnership 2025a; US Department of Energy 2025)

	Electricity demand (kWh/kg H_2)	Lifetime stack (h)	Critical material reduction (platinum and titanium) (%)
PEM 2030	52.3	80,000	87.50
PEM 2050	47.3	80,000	96.25

both efficiency and critical material reduction, following the EU (Clean Hydrogen Partnership 2025a) and US targets (US Department of Energy 2025).

Supplementary Table 1 defines the capacity and lifetime of each analyzed technology. They reflect the different characteristics of the systems. NTP MS and PEMEL use a modular concept that can be adapted to different industrial requirements, whereas reforming requires more extensive industrial infrastructure and imposes higher capacity requirements (Espitalier-Noël et al. 2024). The process's technical characteristics are summarized in Table 2 (reforming processes), and Table 3 (PEMEL); for the complete LCI, refer to Supplementary Tables 2–5.

Foreground LCI non-thermal plasma Methane Splitting

The NTP MS technical performance process was extracted from the ASPEN HYSYS simulation using experimental data from the ColdSpark® project. The simulations are described in the Supplementary Note 5. The model uses experimental data showing 8.2% methane conversion efficiency to simulate optimized systems with 20% and 40% methane conversion efficiencies. At the laboratory scale, the splitting reactor and carbon separation system are tested, and no gas recirculation is observed. In the HYSYS model, the system has been upgraded to introduce recirculation of the residual gas, separate acetylene from the rest of the gas, purify the gas with a Pressure Swing Adsorption system, and compress the purified hydrogen. All the steps are included in the energy system model. For LCA purposes, cooling energy has been excluded; in the experimental data, this heating may occur via natural heat exchange with the surroundings and is therefore excluded from the energy calculations at this stage.

In 2030 scenarios, the reactor power demand is derived from the HYSYS simulation of a 20% methane conversion efficiency. In the 2050 scenario, the reactor power demand is set at 15 kWh/H_2 to indicate process optimization. This value aligns with the objectives outlined by the EU research call (Clean Hydrogen Partnership 2025a).

The technical inputs adopted for the LCI modeling are defined in Table 4, while the full LCIs are reported in the Supplementary Tables 10–11. For detailed information on the foreground data modeling of NTP MS, refer to Supplementary Note 6.

Table 4 NTP MS technical assumptions

	NTP MS 2030	NTP MS 2050
Methane conversion efficiency	20.00%	40.00%
Reactor energy requirement	Simulation	EU target (Clean Hydrogen JU 2025)
Input		
Methane feedstock (m^3/kgH_2)	6.15	6.03
Electricity demand (kWh/kgH_2)	39.31	19.50
Output (co-products)		
Carbon (kg/kgH_2)	1.87	2.01
Acetylene (kg/kgH_2)	1.65	1.43

Background LCI

The background data identified in this study are electricity, NG, petroleum, water, and all the materials included in the BoP.

The electricity mix is modeled with a prospective approach in 2030 and 2050 for each of the countries selected (NO, DE, ES, FR); the complete LCIs are reported in Supplementary Tables 12–15.

The background electricity data were defined using the model developed by The Institute of Climate and Energy Systems—(Juelich Systems Analysis (ICE-2) 2025), Forschungszentrum Jülich, and were based on production cost optimization in alignment with the EU GHG emissions reduction target. The electricity mix includes electricity imports and domestic electricity production, with no distinction between electricity exported and electricity supplied to the domestic market (Itten and Frischknecht 2012), in line with the ecoinvent approach (Wernet et al. 2016). The countries involved in the electricity import mix of NO, DE, ES, and FR were identified in the model, and their electricity supply was subsequently modeled.

For fuel-based technologies, the NG supply was included as regional market dataset from ecoinvent v3.11. It includes the extraction of NG in various countries and its subsequent supply using high-pressure pipeline distribution networks. Country-specific data were characterized by the shares of domestic extraction and import demand from various places of origin, yielding average transport distances. CO_2 transport and storage were modeled for a country-specific context, varying the electricity mixed input. The BoP LCI for each technology was defined, selecting, when available, data from the European market region. Deionized water data reflect the European market. For petroleum in Germany and Norway, the regional dataset was selected, while for Spain and France, in the absence of the country-level data, the European one is applied.

LCIA

This study prioritizes climate change impacts, as the sustainable production of hydrogen and its deployment in energy-intensive sectors are primarily driven by the need to reduce GHG emissions. However, climate-oriented mitigation strategies may induce unintended environmental trade-offs along supply and production chains. Therefore, a broader set of environmental impact categories is included in the assessment. The adopted calculation method is the environmental footprint 3.1, as recommended by the SH2E guideline (Bargiacchi et al. 2022). Table 5 lists the selected environmental indicators. The impact indicators with Robustness I and II, elaborated by the Joint Research Center (JRC) were adopted (Fazio et al. 2018). The selection encompasses

Table 5 Selected impact categories

No	Impact category	Indicator	Abbreviation	Unit	LoR
1	Climate change	Radiative forcing as Global Warming Potential (GWP100)	GWP 100	kg CO_2-eq	I
2	Ozone depletion	Ozone Depletion Potential (ODP)	ODP	kg CFC-11 eq	I
3	Particulate matter	Human health effects associated with exposure to $PM_{2.5}$	PM-ihh	Disease incidences	I
4	Acidification	Accumulated Exceedance (AE)	A-ae	mol H^+-eq	II
5	Eutrophication, freshwater	Fraction of nutrients reaching freshwater end compartment (P)	EP-fw-P	kg P-eq	II
6	Eutrophication, terrestrial	Accumulated Exceedance (AE)	ET-ter-ae	mol N-eq	II
7	Eutrophication, marine	Fraction of nutrients reaching marine end compartment (N)	EP-mar-N	kg N-eq	II
8	Ionizing radiation, human health	Human exposure efficiency relative to U^{235}	IR-hee	kBq U^{235}	II
9	Photochemical ozone formation	Tropospheric ozone concentration increase	POF-toci	kg NMVOC-eq	II
10	Land use	Soil quality index	LU-sqi	Aggregated index	III
11	Water scarcity	User deprivation potential	UDP-dwwc	kg world-eq deprived	III
12	Resource use, minerals and metals	Abiotic resource depletion (ADP ultimate reserves)	ADP	kg SB-eq	III

indicators related to water scarcity, land use, and resource utilization, despite their relatively lower robustness. This choice is driven by the significant interest in the sustainable challenges identified within these categories (Clean Hydrogen JU 2025).

Results and discussion

The results for each environmental indicator are reported in Supplementary Tables 16–24. Given the central role of GHG in the evaluation of low-carbon hydrogen pathways, the discussion first focuses on climate change impacts. Figure 2 presents the GHG emissions associated with the analyzed hydrogen production routes for the 2030 and 2050 scenarios, disaggregated by input contribution, for each country.

2030 Scenario

In Norway by 2030, the NTP MS has the lowest emissions (0.92 $kgCO_2eq/kgH_2$), followed by MM MS, PEMEL, and ATR CCS.

In France and Spain, the best options are represented by electricity-based processes: PEMEL (1.65 $kgCO_2eq/kgH_2$ FR, 2.79 $kgCO_2eq/kgH_2$ ES), followed by NTP MS. The reforming with CCS and MM MS CCS overcome the EU emissions threshold of 3.4 $kgCO_2eq/kgH_2$ for low-carbon hydrogen (The European Parliament and the Council of the European Union 2018; European Commission 2025). In Norway, the NG is extracted domestically, while Spain and France depend on imports, mainly from North African countries, where higher upstream emissions are recorded during extraction and transport. The impact of NG is reflected in the processes with higher NG consumption. In NTP MS, the NG contribution increases from 45% (NO) to 69% and 74% in Spain and France, respectively.

Looking at Germany, it is the only country among those evaluated where electricity-based technologies have higher (PEMEL 21.13 $kgCO_2eq/kgH_2$) or similar (NTP MS 8.42 $kgCO_2eq/kgH_2$) GHG emissions than traditional SMR. In 2030, Germany's electricity mix is still expected to have a higher share of fossil fuels than those of the other countries analyzed. In this scenario, in Germany, MM MS and ATR CCS emerge as the technologies with the lowest carbon emissions.

2050 scenario

In Norway and Germany, the NTP MS registers the lowest GHG emissions, followed by MM MS, ATR CCS, and PEMEL; for all of these, emissions are below the 3.4 $kgCO_2eq/kgH_2$ threshold. In the Norwegian context, the NTP emissions register a reduction due to technological development, while a slight increase in PEMEL impact is observed as a result of the shift from hydroelectric to photovoltaic power.

In Germany, GHG emissions are expected to reduce from 2030 to 2050 as a consequence of the phase-out of fossil fuels from the electricity mix.

In Spain and France, the electricity-based processes (PEMEL and NTP MS) are the best options, while the GHG emissions of ATR CCS reach 3.32 and 3.97 $kgCO_2eq/kgH_2$, respectively.

The results confirm the relevance of the geographical location to the process's GHG emissions, even when a renewable-based mix is modeled, shifting the hotspot from electricity to the NG mix.

A technical barrier is observed only for the SMR CCS, where a maximum of total capture efficiency of 68.8% is predicted when the precombustion capture system is installed. For this technology, even in a favorable location such as Norway, the GHG emissions do not decrease below 3.30 $kgCO_2eq/kgH_2$, while reaching the maximum of 5.91 $kgCO_2eq/kgH_2$ in Spain.

Focusing on MM MS, this study designs the process with internal hydrogen combustion. This sysstem is selected, among several alternatives (carbon combustion, natural gas combustion, and electric arc furnaces), to represent the range of energy supply options for hydrogen production technologies: electricity for PEMEL and NTP MS, NG for reforming processes with CCS, and hydrogen for MM MS. Part of the hydrogen produced by the system is internally combusted to cover the heat required by the reaction, implying higher NG consumption than in NTP MS. This is negatively reflected in Spain and France, where GHG emissions of 3.14 $kgCO_2eq/kgH_2$ and 3.80 $kgCO_2eq/kgH_2$ are calculated, respectively.

Carbon process comparison

Today, carbon is the main product of the MS process, produced at an industrial scale, with hydrogen mentioned as a byproduct (Levidian 2025). The strong interest in carbon is driven by elevated demand across sectors (cement, asphalt additives, links, water purification, tires) and the reduced market volume of hydrogen (Bulfaro et al. 2025).

Coldspark® NTP MS produces carbon in the carbon-black allotropic form in the highest percentage. For this reason, the environmental impact analysis of the NTP MS process is extended to include a comparison with the traditional FB for carbon black production.

In Fig. 3 the NTP MS shows the lowest contribution to climate change in both the 2030 and 2050 scenarios in Norway, Spain and France. The only exception is Germany, where it is necessary to wait until.

The 2050 scenario for a sufficient decrease in the electricity mix.

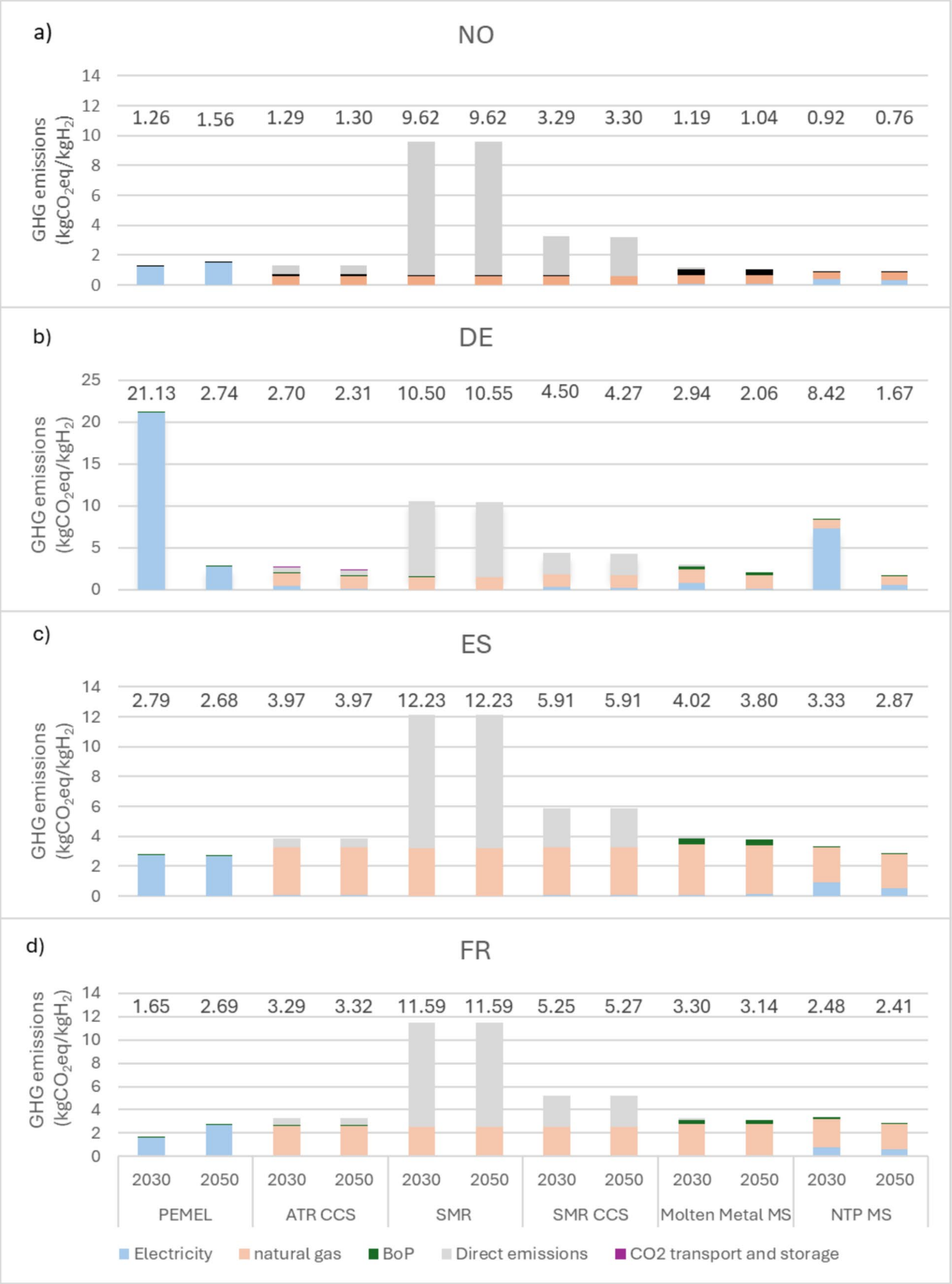


Fig. 2 GHG emissions ($kgCO_2eq/kgH_2$) of hydrogen production processes in **a** NO, **b** DE, **c** ES, **d** FR

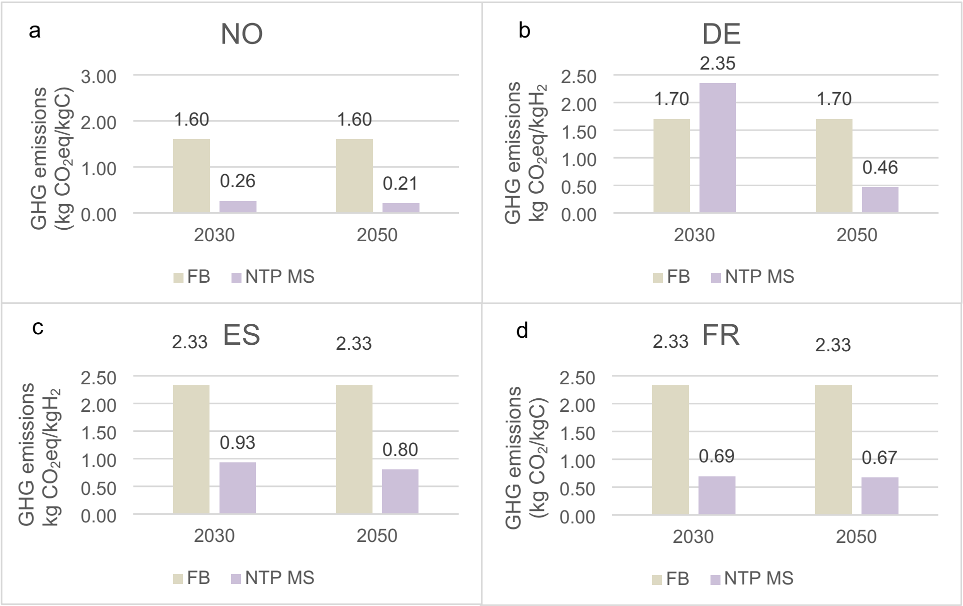


Fig. 3 GHG emissions (kgCO_2eq/kgC) of FB and NTP MS carbon production processes in **a** NO, **b** DE, **c** ES, **d** FR

The NTP MS emerges as a lower emitting carbon black production pathway than the benchmark, confirming good performance on climate change impact for both hydrogen and carbon production. During the NTP splitting reaction, other carbon allotropic forms, along with carbon black, are produced in minor quantities (Yuan et al. 2024). In the future, studies could further focus on comparative analysis of pLCA across different carbon allotropic forms and their respective production processes.

Analysis of others' environmental indicators

The low-carbon hydrogen emerges as one of the pillars of the decarbonized energy and heavy industry transition. For this reason, the policy and scientific community's interest is mainly focused on the GHG emissions. However, the transition to a net zero carbon future must consider other environmental aspects beyond climate change, avoiding the shift of environmental issues, such as loss of soil quality, biodiversity, and water scarcity. The "LCIA" section reports the environmental categories and indicators selected for this analysis. The results are presented for the Norwegian 2050 scenario (Fig. 4), reporting the percentage difference compared to the traditional SMR. The absolute values of the 2030 and 2050 scenarios are shown in the Supplementary Tables 16–24, while the percentage comparison of Germany, Spain, and France graphics are reported in Supplementary Figs. 2–4.

The percentage differences show a consistent trend. As yet observed by (Hermesmann and Müller 2022), the low-carbon pathways reduce the GHG emissions, while an increase is detected for the other impact categories. PEMEL has the highest impact across the indicators due to the critical materials within the electrolyzer and high electricity demand, with the only exceptions being ozone depletion (NO, DE, FR) and particulate matter formation (FR and ES). Future material recyclability could mitigate these impacts; however, this study will not discuss this further. The NTP MS is the only technology showing reductions in impact categories other than climate change and ozone depletion, specifically in particulate matter formation (DE, ES, FR), marine eutrophication (NO, ES, FR), terrestrial eutrophication (ES, FR), and acidification (ES). Comparing the two MS processes, the NTP MS performs better than MM MS, except for land use and water consumption, which are indicators related to electricity consumption. The presence of catalysts inside the MM reactor increases the technology's environmental impact. Finally, NTP MS demonstrates competitive environmental performance relative to reforming processes with CCS, even under higher electricity and natural gas demand, highlighting the importance of accounting for system multifunctionality through impact allocation.

The major differences across countries identified in the percentage comparison are in ionizing radiation and water deprivation. France's high share of nuclear power increases ionizing radiation compared to other countries. The same concept repeats in Norway, with water deprivation due to the role of hydropower in the electricity mix. In Spain and France, PEMEL demonstrates an improved reduction in impacts related to matter formation and terrestrial and marine eutrophication than in Germany and Norway. This difference is attributed to the higher upstream emissions of natural gas in these regions.

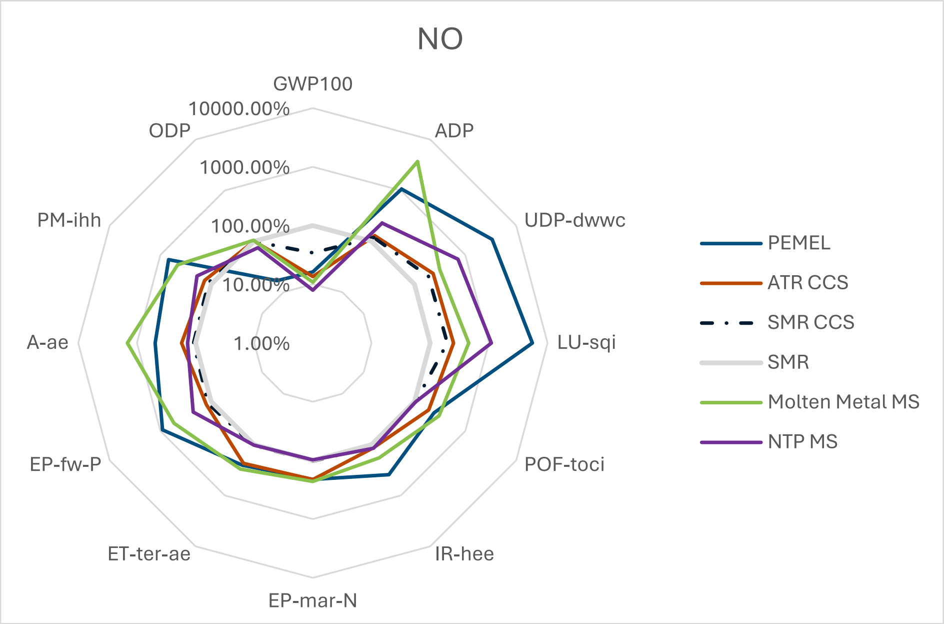


Fig. 4 Percentage comparison of PEMEL, ATR CCS, SMR CCS, MM MS, and NTP MS with SMR in Norway for 2050. The comparison is adopted among the impact categories defined in the LCIA subsection. For indicators, abbreviations refer to Table 5

Sensitivity analysis

The analysis proposed in this study aims to assess the environmental impacts of hydrogen and carbon production technologies projected into future scenarios. As such, the results rely on process simulations and assumptions regarding technological improvements, particularly for emerging technologies such as NTP MS and PEMEL electrolysis. While the input parameters for benchmarking technologies were derived from established scientific literature, the NTP MS assessment represents original work, and the assumed process parameters are therefore subject to higher uncertainty. For this reason, a sensitivity analysis was conducted for the 2050 scenarios to evaluate the robustness of the pLCA results. The analysis was performed at two levels: (i) key technical assumptions of the process, and (ii) methodological choices related to carbon byproducts and multifunctionality.

Key technical assumptions

In the first analysis, the CH_4 conversion efficiency ranges from 8.2% (laboratory experimental data) to 20,40,60,80 and 100%. The process technical parameters for each efficiency are reported in Supplementary Table 25.

In the results, presented in Fig. 5, the GHG emissions reach a minimum in the 40% scenario, with a slight increase (<2%) observed with further efficiency improvements. The reduction in energy demand in improved efficiency scenarios is offset by the higher H_2 allocation ratio. At higher methane conversion rates, the relative amount of acetylene decreases compared to that of hydrogen.

Looking at a lower conversion efficiency, achieving 40% compared to 8.2% reduces the GHG emissions by 25%, 13%, 7%, and 9% in NO, DE, ES, and FR, respectively.

Moving to the second sensitivity analysis parameter, the reactor electricity consumption varied from the optimized value of 10 kWh/kgH_2 (Kerscher et al. 2021) to 34.5 kWh/kgH_2, obtained from pyrolysis simulation (Fig. 5b). Across these values, the GHG emissions increase by a maximum of 56% in the Norwegian context and by a minimum of 24% in Spain, where the major contribution came from NG. However, in this case, emissions exceed 3.4 kg CO_2eq/kg H_2. Overall, the sensitivity analysis shows that the electricity demand assumptions can have a reduced impact on GHG emissions (<25%) in countries with higher NG emissions, such as France and Spain. However, this increase could exceed the GHG emission threshold due to the higher starting value. In Norway, the GHG emissions are relatively high, with a maximum value of 56%; however, process GHG emissions remain below the EU threshold thanks to reduced upstream GHG emissions from both NG and the electricity mix, minimizing the impact of the non-optimized reactor energy scenario.

The sensitivity analysis reveals the key role of electricity consumption in the NTP MS life cycle GHG emissions. To assess the process environmental impact and sustainability, electricity demand should be monitored over time to verify the prospective assumption defined in this study. The methane conversion efficiency has a minor role compared to the electricity demand. Its influence is negligible above 40% efficiency, while below 40% efficiency, its impact ranges from 25 to 7%. With this study approach, the 40% target should therefore be integrated to optimize environmental

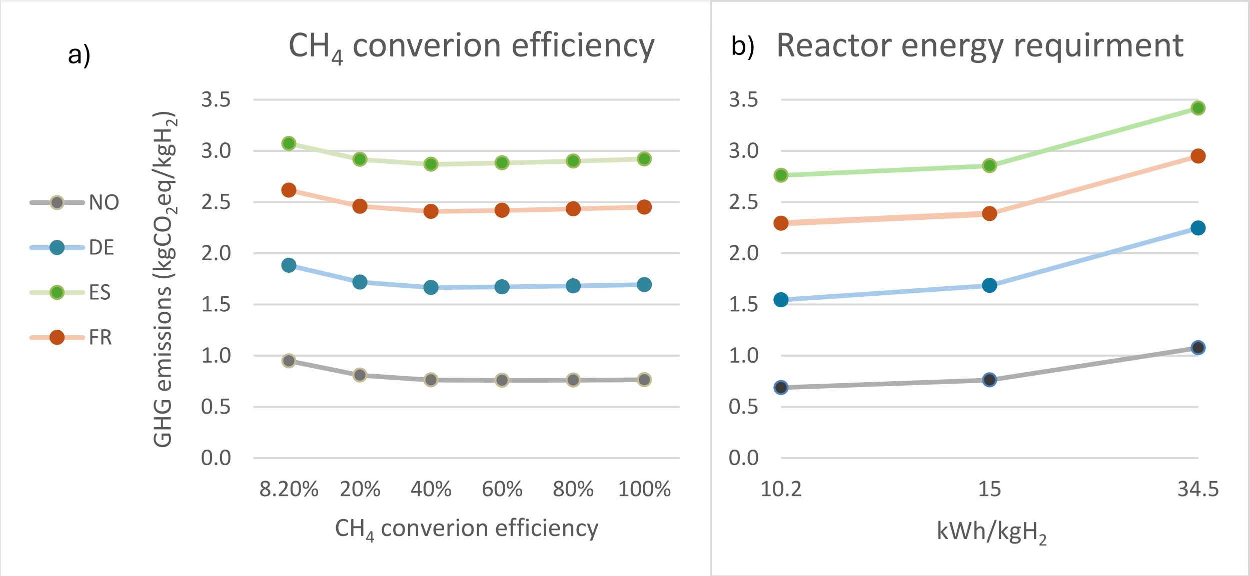


Fig. 5 GHG emissions ($kgCO_2eq/kgH_2$) of the NTP MS process varying the CH_4 conversion efficiency a) and reactor energy requirement b) for the 2050 scenario

performance, given that all process outputs (hydrogen, carbon, and acetylene) have monetary value and emissions can be allocated among them.

Carbon byproducts and multifunctional allocation approach

The NTP MS process is a multifunctional process producing hydrogen, carbon, and acetylene. The pLCA approaches to multifunctionality are systems expansion and allocation (ISO 2006a, b). The allocation can be based on the product's energy, mass, or economic value. In this study, the energy allocation was selected in alignment with the EU guidelines for low-carbon hydrogen (European Commission 2025).

The sensitivity of the results to the multifunctionality approach is analyzed by applying the economic allocation and system expansion. Table 6 presents the lower heating value (LHV) and price used to calculate the allocation factor. The economic value represents the EU market: the H_2 price is the EU SMR average, with SMR representing the lowest price option (Clean Hydrogen Partnership 2025b). For carbon black, the bottom price is selected from the range provided in the literature (Chikri and Wetzels 2017), while the acetylene represents the minimum price in the EU for the 2025s semester (Chemanalyst). The Norwegian 2050 scenario is the one selected for this sensitivity analysis. The authors consider the analysis of only one country sufficient, given that the same trend is replicable across different locations. Figure 6 shows the variation in the process's GHG emissions with the multifunctional approach in use.

Table 6 LHV and product price for the calculation of the energy and economic allocation

	Unit	Hydrogen	Carbon black	Acetylene
LHV	(MJ/kg)	120.0	33.5	48.5
Price	(€/kg)	3.3	0.5	1.9

A higher impact is observed with energy allocation, while economic allocation shows a slight 3% reduction. Despite both choices showing comparable results, economic allocation is recommended only when it is not possible to adopt a physical allocation, because it is more sensitive to market oscillation over time and geographical locations (European Commission 2025).

With system expansion, the GHG emissions reach a negative value of -8.02 $kgCO_2eq/kgH_2$. It is obtained by subtracting from the system the GHG emissions generated by producing the byproducts using the benchmark technologies. This first method is the most critical. The negative value could indeed be misinterpreted as the removal of CO_2 from the atmosphere and could also incentivize a rebound effect that is not conventionally accounted for in the LCA. With lower emissions, the market could be incentivized to produce more carbon than is produced today, not representing a real avoided emission, but rather incentivizing higher production that would not otherwise be observed. To limit this effect, system expansion is recommended only for consequential LCA, not for attributional LCA, as in this study (Weidema 2003).

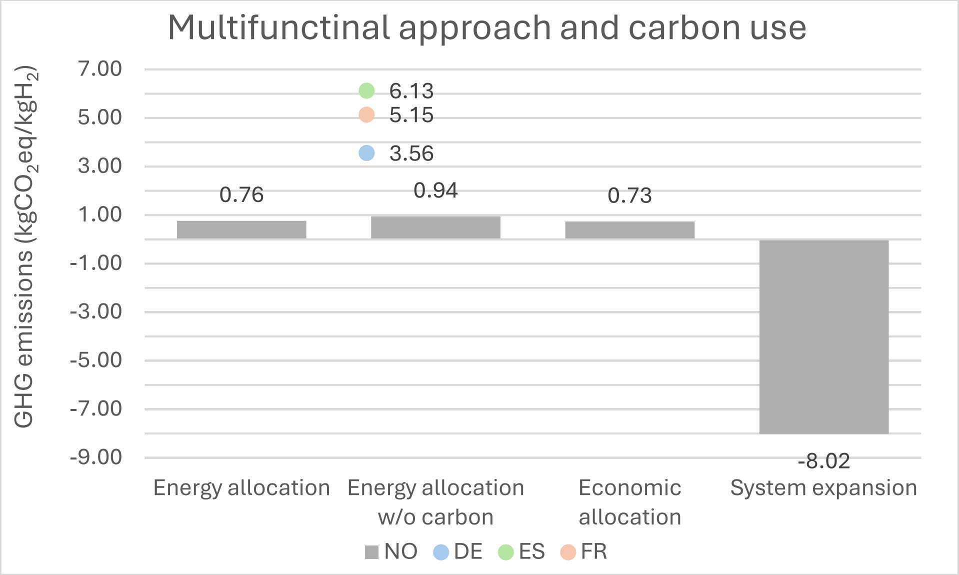


Fig. 6 GHG emissions ($kgCO_2eq/kgH_2$) of NTP MS process varying the multifunctional approach for the NO 2050 scenario. The energy allocation without carbon is presented for DE, ES and FR. In this case, carbon is not a byproduct, increasing the H_2 energy allocation factor and therefore the overall hydrogen GHG emissions

Finally, a third case study is analyzed by adopting energy allocation while excluding carbon as an allocable byproduct. The carbon indeed could be stored, and therefore classified as waste, for two reasons: i) the carbon market volume is smaller compared to the hydrogen one, risking a rapid saturation if MS is implemented on a large scale for hydrogen production; ii) to be classified as low-carbon hydrogen following the EU directive (European Commission 2025), the carbon from the MS must be stored or mineralized; in this case, indeed, the carbon end-of-life combustion can be omitted from the total calculation, and the total emissions will be below the threshold of 3.4 $kgCO_2eq/kgH_2$ (Bulfaro et al. submitted).

The carbon storage scenario is calculated by considering the hydrogen allocation factor, while the impact of carbon transport to the storage site is excluded. The scope of this sensitivity analysis does not yield an exact value; rather, it serves to demonstrate differences in the methodological approach.

When carbon is not a byproduct, in Spain, France, and Germany, the GHG emissions reach 6.13, 5.15, and 3.56 $kgCO_2eq/kgH_2$, respectively, while in Norway, they are still below 3.4 $kgCO_2eq/kgH_2$, at 0.94 $kgCO_2eq/kgH_2$. The observed increase in the storage scenario conflicts with the EU GHG emissions assessment guideline, which prioritizes the environmental benefits of storage. This analysis adopts a cradle-to-gate scope, excluding the use and end-of-life stages. In this case, the carbon use scenario shows a lower environmental impact due to a decrease in the hydrogen allocation factor. It favors process circularity and discourages storing products with market value that would otherwise be produced. On the other hand, it excludes the end-of-life emissions of all byproducts, representing a limitation of the cradle-to-gate scope. This conflict has yet to be observed in the EU and UK guidelines for low-carbon GHG emissions. Following the UK approach, as in this case study, the solid carbon use and end-of-life stages are not included (UK Department for Energy Security and Net Zero 2023). In the EU, the specific carbon end-of-life emissions, intended as combusted, are included. However, carbon can serve for different uses, and its combustion is only one of the possible end-of-life. This approach penalizes the carbon use, and does not distinguish its different applications, other than mineralization. An extension of the system boundaries can be evaluated for future analysis, including the use and end-of-life stages, and evaluating different carbon use and end-of-life options and their impact on the overall emissions.

Acetylene is the third largest byproduct by mass. Its sensitivity analysis is not performed at this stage of the study. The technology developers' interest in acetylene is focused on both the separation and sale, as simulated in this study, or on reintegration into the system and splitting. However, experimental data on acetylene cracking are not available at this stage of the technology.

Future work should focus on large-scale experimental validation and refined process simulations, particularly addressing acetylene separation or recycling and thermal management aspects.

From a systems perspective, NTP MS emerges as a robust and potentially complementary option for future hydrogen portfolios, whose sustainability performance depends more on location-specific energy system characteristics and carbon management strategies than on reactor optimization alone. The 40% methane conversion efficiency optimization target, observed in the technical key assumptions section, depends on the allocation approach and the study system boundaries and should not be understood as an absolute value.

Conclusion

This paper presents a pLCA of the Non-Thermal Plasma Methane Splitting (NTP MS) process and its comparison with hydrogen benchmarking technologies: Steam Methane Reforming (SMR), Steam Methane Reforming with Carbon Capture and Storage (SMR CCS), Autothermal Reforming with CCS (ATR CCS), Molten Metal Methane Splitting (MM MS), Proton Exchange Membrane Water Electrolysis (PEMEL), and carbon production with furnace black (FB). The analysis is conducted for two scenarios in 2030 and 2050 in four countries: Norway, Germany, Spain, and France.

The NTP MS, even with unoptimized reactor electricity consumption and a methane conversion efficiency of 20%, shows GHG emissions below the EU GHG emissions threshold of 3.4 $kgCO_2eq/kgH_2$ in both the 2030 and 2050 scenarios. The only exception here is Germany, where it is necessary to wait until the 2050 scenario to observe an emissions reduction, due to the high upstream emissions of the electricity mix.

Widening the analysis to other environmental indicators, it is observed that alternative processes to SMR can produce hydrogen with lower carbon emissions; however, this reduction is offset by increases in other environmental indicators. The NTP MS exhibits different behavior: despite having higher NG and electricity demand than SMR, it shows lower values for several environmental indicators. This is explicable with the absence of catalysts inside the reactor and the multifunctional nature of the process.

The NTP MS GHG emissions are further explored by applying a sensitivity analysis for two technical parameters and the pLCA approach to multifunctionality and carbon application. Reactor energy optimization and carbon application emerge as two critical factors. The use of carbon reduces GHG emissions by lowering the allocation factor. However, it contrasts with EU policy, where the carbon end-of-life is included and storage is more environmentally favorable. This paper raises further questions about the role of carbon: whether carbon use or storage is the best environmental option.

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Authors contributions Isabella Bulfaro: Conceptualization, investigation, formal analysis, methodology, writing-original draft Anna Sanchez: Writing- review and editing Mikel Fadul: Writing- review and editing Gabriela Benveniste: Supervision Torbjørn Vevle Grønn: investigation, writing-original draft Christina Wulf: methodology, writing- review and editing, supervision Beatriz Amante: Writing- review and editing, supervision Víctor José Ferreira: Supervision, Writing- review and editing, Funding acquisition, Project administration.

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Data availability All data supporting the findings of this study are available within the paper and its Supplementary Information.

Declarations

Competing interests The authors declare no competing interests.

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