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From grey to "Green": Modelling the non-energy uses of hydrogen for the EU energy transition☆

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HIGHLIGHTS

- A comprehensive assessment of non-energy uses of hydrogen is conducted.
- A dynamic, recursive model of the hydrogen sector is built and applied to the EU.
- Green hydrogen could require up to 42 % of EU's current electricity output by 2050.
- Aligning electrolyser deployment with renewable growth is key for decarbonisation.
- Hydrogen shows significant potential to decarbonise the steel industry.

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ABSTRACT

Hydrogen (H_2) used as feedstock (i.e., as raw material) in chemicals, refineries, and steel is currently produced from fossil fuels, thus leading to significant carbon dioxide (CO_2) emissions. As these hard-to-abate sectors have limited electrification alternatives, H_2 produced by electrolysis offers a potential option for decarbonising them. Existing modelling analyses to date provide limited insights due to their predominant use of sector-specific, static, non-recursive, and non-open models. This paper advances research by presenting a dynamic, recursive, open-access energy model using System Dynamics to study long-term systemic and environmental impacts of transitioning from fossil-based methods to electrolytic H_2 production for industrial feedstock. The regional model adopts a bottom-up approach and is applied to the EU across five innovative decarbonisation scenarios, including varying technological transition speeds and a paradigm-shift scenario (Degrowth). Our results indicate that, assuming continued H_2 demand trends and large-scale electrolytic H_2 deployment by 2030, grid decarbonisation in the EU must accelerate to ensure green H_2 for industrial feedstock emits less CO_2 than fossil fuel methods, doubling the current pace. Otherwise, electrolytic H_2 won't offer clear CO_2 reduction benefits until 2040. The most effective CO_2 emission mitigation occurs in growth-oriented ambitious decarbonisation (−91 %) and Degrowth (−97 %) scenarios. From a sectoral perspective, H_2 use in steel industry achieves significantly greater decarbonisation (−97 %). However, meeting electricity demand for electrolytic H_2 (700–1180 TWh in 2050 for 14–22.5 Mtons) in growth-oriented scenarios would require 25 %–42 % of the EU's current electricity generation, exceeding current renewable capacity and placing significant pressure on future power system development.

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Nomenclature

AEL	Alkaline Electrolysis
AEM	Anion Exchange Membrane Electrolysis
ATR	Autothermal Reforming
BF-BOF	Blast Furnace - Basic Oxygen Furnace
CCUS	Carbon Capture, Utilisation, and Storage
CH_3OH	Methanol
CO_2	Carbon Dioxide
Dmnl	Dimensionless
DRI	Direct reduction of Iron
EAF	Electric Arc Furnace
EROI	Energy Return on Investment
EU	European Union
FCHO	Fuel Cells and Hydrogen Observatory
H_2	Hydrogen
HDRI	Hydrogen-based Direct Reduction of Iron
HHV	Higher Heating Value
HVO	Hydrotreated Vegetable Oil
IAM	Integrated Assessment Model
IEA	International Energy Agency
IESA-Opt	Integrated Energy System Analysis Optimisation
IRENA	International Renewable Energy Agency
LHV	Lower Heating Value
NG	Natural Gas
NH_3	Ammonia
Mt	Million tons
PEM	Polymer Exchange Membrane Electrolysis
POX	Partial Oxidation
RES	Renewable Energy Sources
SMR	Steam Methane Reforming
SOEC	Solid Oxide Electrolyser Cell

1. Introduction

There is an increasing interest on hydrogen (H_2) as a key energy carrier in the future decarbonised energy system. Two main arguments drive the support for hydrogen. First, the depletion of high-quality non-renewable resources [1–4] demands new products to replace fossil fuels in sectors that are unfeasible to electrify at large-scale such as freight transport [5], high-temperature industrial processes [6], and certain non-energy uses (oil refining, methanol production, ammonia synthesis, and steel industry) [7]. Second, the urgency to combat climate change and environmental impacts [8], caused by fossil fuel use, industrial activity, and carbon sinks degradation [9–11]. In this context, hydrogen presents a potential partial solution [12,13], as it can be produced from renewable energy sources (RES) such as solar, biomass and wind, resulting in what is known as "green" hydrogen. In addition, its capacity to store surplus energy may enhance system flexibility and resilience [14].

Currently, hydrogen's role is limited to being a feedstock (i.e., non-energy uses) for specific processes such as oil refining, ammonia, and methanol production, with global demand at 97 million tons of hydrogen (Mt H_2/yr) in 2023 [15]. However, its current production is almost entirely met by fossil fuels [16], contributing to carbon dioxide (CO_2) emissions of around 920 million tons per year (Mt CO_2/yr), nearly four times the total CO_2 emissions in Spain [17]. Hence, these processes are typically identified as a high priority for green hydrogen production [18]. Among green hydrogen production technologies, electrolysis is the most mature [19]. However, this technology faces significant challenges such as the inefficiency and high cost [20], its water-intensive nature [21], and operational issues in intermittent systems [20]. These barriers highlight the complexity of scaling green hydrogen production, highlighting the need for comprehensive quantitative analyses within the broader context of the energy transition.

While numerous studies have explored the potential applications of hydrogen for energy-uses from a regional perspective in challenging sectors to decarbonise, such as transportation [22–24] or residential/commercial [25,26], much less attention has been devoted to the non-energy uses of hydrogen, despite its accounting for all current hydrogen use today in chemicals, refineries and steel. In this context, a selection of relevant modelling studies analysing the energy system implications of green hydrogen deployment as feedstock in industry was reviewed. Table 1 presents a synthesised summary of the literature review, organized according to the following criteria: sectors coverage, the time horizon, including whether it is dynamic (modelling continuous changes over time) or static (focusing on single years), simulation recursivity (involving feedback loops and cumulative effects), the scenarios analysed, and the model's public availability. See Appendix A for details on the literature review.

The literature review (cf. Table 1 and Appendix A) reveals relevant knowledge gaps. While specific sectors are individually well-explored, a comprehensive understanding of the integration of hydrogen as a feedstock across the broader industrial[1] landscape is lacking. Rixhon et al. [41], and Quarton et al. [42] also emphasize the limited attention of hydrogen's non-energy uses in bottom-up energy system models, despite their critical role in industrial decarbonisation [43]. Many studies rely on static modelling approaches, focusing solely on a single year (e.g., 2050) in which they project green hydrogen deployment. This approach fails to capture the transitional effects that may lead to non-linear outcomes and unforeseen dynamics, such as rebound-related increases in CO_2 emissions due to a misalignment between electrolyser and RES deployment. Furthermore, these studies often employ non-recursive models, known for their inability to capture path-dependency and endogenous learning effects over time, which hamper the realistic modelling of transitions and technology evolution. In terms of scenario-methodology, transitional pathways with varying speeds of transition towards green hydrogen (e.g., 100 % green H_2 by 2030, 2050 or 2070) have not been explored. Furthermore, industry transformation for high service provisioning with low-energy and material demand paradigms not based on growth such as those based on sufficiency or Decent Living Standards aligned with Degrowth principles [44–46] receive overall a minimal attention; although they are on the rise [47]. However, specific attention to hydrogen as feedstock in this field is rare. A notable exception explicitly addressing non-energy uses in general and hydrogen feedstocks in particular in the context of a sufficiency scenario for Europe is the CLEVER scenario [40]. Lastly, issues with model transparency are highlighted in the literature review, in line with Quarton et al. [42]. They note that the few energy system models incorporating non-energy uses of hydrogen lack transparency, as they do not disclose their undelaying data assumptions. These limitations underscore the need for more integrated, dynamic, and transparent frameworks, as well as a greater plurality of scenarios, to comprehensively evaluate hydrogen's potential for industrial decarbonisation.

This paper aims to fill the identified knowledge gaps through the following innovative contributions:

1) Comprehensive focus on non-energy uses of hydrogen (that is, applications where hydrogen serves as a raw material input rather than as an energy carrier) with detailed (i.e., bottom-up) modelling of

[1] In this work, the term "industry" refers to the broad manufacturing sector, encompassing typical manufacturing sub-sectors (e.g., chemical, metals, etc.) as well as oil refining.

Table 1
Selection of relevant modelling studies analysing the energy system implications of green hydrogen production deployment as feedstock in industry. Own compilation. (*): indicates a qualitative study.

Study	Sectors coverage (related to H_2 uses as feedstock)	Time horizon of the analysis	Recursive simulation	Scenarios (related to H_2 uses as feedstock)	Freely available model
Koivunen et al. [27]	Industrial uses (top-down approach)	2040 (single year)	No	Constant H_2 Flexible H_2	No
Chisalita et al. [28]	Ammonia	N/A	N/A	No	No
Marzouk [29]	Industrial uses (top-down approach)	2030, 2040 and 2050 (single years)	N/A (*)	IEA-WEO NZE IRENA-1.5 °C	N/A (*)
Contreras Fregoso et al. [30]	Refining (oil)	2020 to 2050 (single years)	Yes	National Energy System Development Roadmap	No
Mathiesen et al. [31]	Steel and chemicals	2030 and 2050 (single years)	No	Maximum energy efficiency +100% RES Best available technology + H_2 (high recycling)	Yes
Lopez et al. [32]	Steel	2020 to 2100 (single years)	No	High HDRI penetration	No
Rechberger et al. [33]	Steel	N/A	N/A	No	No
Trollip et al. [34]	Steel	2030 (single year)	No	H_2 for primary steel	No
Nurdiawati and Urban [35]	Refining (oil)	Future decarbonisation (unspecified year)	N/A (*)	No	N/A (*)
Egerer et al. [36]	Steel and chemicals	Future decarbonisation (unspecified year)	No	Low H_2 (feedstock) High H_2 (feedstock + energy uses)	No
Manuel [37]	Steel, chemicals and refining (oil)	2050 (single year)	No	HYD (extreme H_2-economy)	No
Plazas-Niño et al. [38]	Refining, chemicals and others (top-down perspective)	2021 to 2050 (single year)	No	Baseline	Yes
Oshiro et al. [39]	Steel	2020 to 2050 continuously	No	Target 1.5 °C Target 2 °C	Yes
Wiese et al. [40] (CLEVER)	Steel, ammonia, methanol and refining (oil+bio)	2019 to 2050 continuously	Not specified	Sufficiency	Yes
This study	Steel, ammonia, methanol and refining (oil+bio)	2020 to 2070 continuously	Yes	H_2-expansion H_2-high-expansion H_2-delayed-expansion EU-H_2-roadmap Degrowth	Yes

ammonia, methanol, refining (including both oil and bio) and steel production sectors.

2) Dynamic and recursive model that captures nuances and transitional effects that may lead to non-linear outcomes and unforeseen dynamics in energy transitions, which typical static models in literature miss.
3) Scenario plurality: It examines five novel long-term decarbonisation scenarios with varying transition speeds, which have not been explored in the current literature on non-energy uses of hydrogen. It also presents a Degrowth scenario, offering an alternative to the dominant growth-oriented paradigms in existing research on industrial hydrogen integration. These alternative pathways provide valuable insights for planning an energy transition that incorporates green hydrogen.
4) Integration of an extensive and detailed literature review with the development of a transparent and freely available model and associated technical database.

The final goal of this work is to offer a set of policy recommendations to support decision-making regarding the transition to green hydrogen feedstock within the industrial sector. We focus on the specific dynamics of the hydrogen demand and supply, while other aspects of energy systems and broad energy transition, such as energy variability, Energy Return on Investment (EROI) [48], mineral requirements, other structural transformations, etc. are left out of scope.

Although the model is general and extensible to any region, all scenarios are applied to the European Union (EU-27). The EU serves as an appropriate region for this study due to its ambitious green transition goals [49], its interest in promoting the development and adoption of green hydrogen [50], its diverse industrial sectors that could benefit from hydrogen use, its supportive regulatory framework [51,52], and substantial investments in hydrogen infrastructure [53]. Moreover, the region's current hydrogen landscape is analogous to the global situation: its role is limited as feedstock in oil refining, ammonia, and methanol production, with 99 % of its current production capacity relying on fossil fuels [54]. In this case, the demand stands at 7.9 Mt H_2/yr in 2023 [54], and contributes to emissions of between 70 and 100 Mt CO_2/yr [50]. The conclusions drawn are applicable beyond this case study. Furthermore, the model is intended to contribute to the development of similar application models, and to complement multidisciplinary frameworks, such as Integrated Assessment Models (IAMs).

Next Section 2 provides an overview of the current and future landscape of hydrogen use across various sectors; Section 3 outlines the methodology used to build the model; the scenarios simulated are covered in Section 4; the results obtained are presented and discussed in Section 5; and Section 6 offers the conclusion.

2. Overview of hydrogen use today and future prospects

This section reviews the current landscape of hydrogen use and its future prospects. It examines hydrogen's role across various sectors, identifies the challenges and opportunities related to its production and demand, with a particular focus on the EU.

2.1. Hydrogen end-use

Hydrogen demand. In this study, hydrogen demand encompasses both pure hydrogen and hydrogen used within gas mixtures (e.g., synthesis gas), provided it is intentionally produced (i.e., produced ex professo) and chemically consumed in the process [55]. It excludes hydrogen merely rearranged during hydrocarbon transformations or present in industrial waste gases reused on-site.

Present and future hydrogen consuming sectors in the industry. As of 2023, global hydrogen demand is estimated at 97 Mt H_2/yr, almost entirely from the industrial sector [15]. Key applications include oil refining (43 Mt H_2/yr), chemicals (48.6 Mt H_2/yr) and steel (5.4 Mt H_2/

yr), with minimal contributions from transport and energy sectors [15].

In oil refining, hydrogen serves as a feedstock, reagent, or energy source. At the EU level, the sector accounts for 57 % (4.5 Mt H_2/yr) of regional demand, led by Germany, Italy, the Netherlands and Spain [54]. Since refinery activity is currently closely tied to transport fuel demand, it is expected to decline in the future due to climate targets, resulting in a corresponding decrease in hydrogen demand. Nevertheless shifts in refinery product slates may create new roles for hydrogen, particularly as a purifying agent in low-carbon synthetic hydrocarbon fuel production, like biofuels, which could replace petroleum-based fuels in hard-to-electrify transport modes, thus creating a new demand for hydrogen in the sector [16,56]. Among these, refined Hydrotreated Vegetable Oil (HVO) biodiesel stands out, which can be used directly in existing diesel engines and infrastructure without the need for blending with conventional diesel or technical modifications, unlike conventional FAME biodiesel [57].

In the chemical sector, hydrogen is used for methanol (16.2 Mt H_2/yr globally in 2023) production, which is employed in a wide range of industrial applications (e.g., the manufacture of formaldehyde, methyl methacrylate, etc.), and ammonia (32.4 Mt H_2/yr globally in 2023), around 70 % of which is used to produce fertilisers, with the remainder allocated to various industrial applications [6,58]. Beyond its current applications, methanol also offers a decarbonised route to produce high-value chemicals (e.g., olefins and aromatics), essential for plastics manufacturing. At the EU level, ammonia production consumes 2.0 Mt H_2/yr (25 % of regional total hydrogen), with another 0.9 Mt H_2/yr for methanol and other chemicals. In this field, Germany, the Netherlands and Poland are leading producers [54]. While no disaggregated data for EU ammonia end-use is available, it is noteworthy that the EU is a net importer of ammonia, having accounted for 24 % of global ammonia trade in 2019 (4.8 Mt out of 20 Mt) [58]. In the future, economic and population growth will drive increased global production of ammonia and methanol, thereby raising hydrogen demand in the chemical sector, according to the IEA [16].

The steel sector accounts for 5.5 % of global hydrogen demand, through the direct reduction of iron with electric arc furnace (DRI-EAF) processes where hydrogen, contained in the synthesis gas produced from natural gas (NG), acts as a reducing agent [15]. DRI accounts for only 9 % of global iron production [59], while the remaining 91 % predominantly relies on traditional blast furnace route, typically followed by basic oxygen furnace (BF-BOF) steelmaking. This route is very intense in CO_2 emissions due to coking coal usage. Hence, decarbonising the steel sector is crucial, with hydrogen playing a significant potential role as a reducing agent [60]. The direct reduction of iron with the exclusive use of pure hydrogen produced from RES, followed by steelmaking in an electric arc furnace (HDRI-EAF), represents the main way to carry out decarbonisation; however, its commercial deployment is not expected before the early 2030s due to remaining technical and supply challenges [61]. Interim strategies include replacing the traditional BF-BOF method with direct abatement with natural gas [6], or introducing green hydrogen into existing processes [62]. In any case, all these alternatives foresee a considerable increase in hydrogen demand within the sector.

2.2. Hydrogen production

Hydrogen generation processes. Presently, the most widespread method to produce hydrogen is reforming, which results in CO_2 emissions due to fossil fuels use. There are three reforming processes [6,63]:

- Steam reforming. This process involves reacting hydrocarbons with steam, to produce synthesis gas (a mixture of carbon monoxide and hydrogen). A subsequent water-gas shift reaction increases hydrogen concentration, while producing CO_2. Hydrocarbons typically include natural gas, in which case the process is known as "steam reforming of natural gas" (SMR).
- Partial oxidation (POX). In this process, an exothermic reaction between air and hydrocarbons produce synthesis gas, latter processed similarly to reforming. When coal is used, the process is termed coal gasification.
- Autothermal reforming (ATR). ATR combines elements of both SMR and POX, typically using natural gas as hydrocarbon.

If CO_2 from these pathways is captured and stored or utilised (CCUS), the produced hydrogen is considered "blue"; otherwise it is called "grey" [64].

As for production from water, electrolysis is key to decarbonising hydrogen production by utilising electricity to split water into hydrogen and oxygen (O_2). The most mature commercial sub-technology is alkaline electrolysis (AEL), followed by polymer exchange membrane electrolysis (PEM). PEM uses more expensive materials than AEL, which is why it is costlier and less dominant in the market [65,66]. Other types, such as solid oxide electrolyser cell (SOEC) and anion exchange membrane electrolysis (AEM), are still in the development phase [67]. When the electricity utilised in hydrogen production is sourced from RES, the resulting hydrogen is considered "green".

Hydrogen can also be generated through biomass, via biochemical or thermochemical routes [67]. Although associated CO_2 emissions are offset by prior atmospheric absorption during biomass growth [68], these processes face competitiveness challenges due to the complexity of biomass treatment and limitations of sustainable biomass potentials.

In addition to the aforementioned production processes, hydrogen can be found naturally in geological deposits, but its quantity is highly uncertain [69].

For the purposes of this study applied to EU, the focus is on hydrogen produced through SMR and electrolysis.

Global and EU hydrogen production. In 2023, the global demand for hydrogen (97 Mt H_2/yr) was met almost entirely through fossil fuel-based processes. Approximately 85 % of hydrogen is produced in dedicated hydrogen production plants, with the remaining 15 % as industrial by-products [15]. Natural gas, primarily via SMR, accounts for around two-thirds of total production, and is expected to remain dominant due to its widespread operational presence and economic viability [70,71]. Coal gasification accounts for 20 % of hydrogen production [15], primarily in China due to ample access to coal resource [72]. Fossil fuel predominance in the hydrogen production stage, results in 2.5 % of global energy-related CO_2 emissions [15,73]. In line with the energy transition goals, mitigating associated CO_2 emissions is imperative. Presently, global electrolytic hydrogen (i.e., H_2 generated via electrolysis) accounts for less than 0.1 Mt H_2/yr (<0.1 % of total production), while only 15 CCUS-equipped generate 0.6 Mt blue H_2 per year (0.6 % of total production) [15]. Electrolyser deployment is accelerating, particularly in China, Europe and the United States. Among electrolyser sub-technologies, AEL is the most widespread (60 % of installed capacity) due to its maturity and development compared to PEM.

Regarding hydrogen production, European level literature identifies the facilities in three categories [74,75]: captive (on-site consumption), commercial (commercial purposes) and by-product (from other industrial processes). This study focuses on captive and commercial facilities, as they produce hydrogen ex professo to satisfy demand. In 2023, Europe's hydrogen production capacity amounted to 11.23 Mt H_2/yr, with 88 % (9.85 Mt H_2/yr) from captive and 12 % (1.38 Mt H_2/yr) from commercial facilities [54]. Virtually all production relies on fossil fuel-based processes, primarily SMR [54,76]. Blue hydrogen production is minimal, with a total installed capacity of 56.15 kt H_2/yr (0.5 % of total capacity in Europe) [54]. Electrolysis, highlighted in the EU H_2 Roadmap as the leading pathway for hydrogen-based decarbonisation (with a 2030 target of 40 GW) [50], currently accounts for an installed capacity of 258.39 MW (0.05 Mt H_2/yr; 0.45 % of total capacity in Europe).

3. Methods

This section outlines the process employed to model the role of hydrogen as a feedstock, encompassing both its production and end-uses. The steps of this process are as follows: 1) Hypothesis formulation and conceptualization of the model based on the review reported in Section 2; 2) Elaboration of causal loop diagrams; 3) Parametrisation 4) Programming.

3.1. Modelling methodology: System dynamics

System Dynamics, implemented through the simulation software Vensim DSS [77], served as the analytical tool for this study. System Dynamics facilitates modelling the interactions among independent elements constituting a system, enabling a comprehensive understanding of the underlying structural causes governing its behaviour over time. It functions as a management tool aimed at evaluating system trends resulting from different scenarios [78].

3.2. Model archetype and modelling assumptions

Within the System Dynamics approach, a regional energy model has been developed to represent the hydrogen sector in the industrial context, with a particular focus on its role as a feedstock, aiming to facilitate the dynamic evaluation of long-term decarbonisation scenarios. The model adopts a bottom-up framework, which emphasizes a detailed, technology-oriented representation of the hydrogen industrial sector (covering both demand and supply). It functions primarily as a simulation-based tool, equipped to forecast plausible future trends based on predefined inputs and assumptions. Furthermore, the model can operate in a hybrid optimisation mode (i.e., combining predefined future trends for certain variables while optimising others), aiming to minimise CO_2 emissions over time under specified constraints. Its temporal scope extends over the long term, encompassing the period from 2020 to 2050–2070, with results presented as a continuous projection. To aid in understanding the structure of the model and the interconnections between its components, including the different inputs and outputs, an accompanying diagram (Fig. 1) is provided. Furthermore, since the primary endogenous dynamics occur within the H_2 production capacity sub-module (whose inputs and outputs are outlined in Fig. 1), the corresponding causal loop diagram is also included (Fig. 2). The complete Vensim DSS code, including the full model equations, is available at [79].

The scope of the model is restricted to the industrial scope of the EU as a whole. The sectors identified as hydrogen consumers within the region include those utilising hydrogen as a feedstock (i.e., for non-energy uses). These sectors are: the oil industry for the refining of crude oil and HVO biodiesel (hereafter, biodiesel), the chemical sector for the production of ammonia and methanol, and the steel sector, comprising the production of primary steel via HDRI-EAF, DRI-EAF and BF-BOF (the latter being posed in opposition to the first two in order to assess the decarbonisation of the steel sector) and secondary steel with EAF. The selection of these sectors and technologies aligns with findings from the literature (cf. Section 2). It is important to point out that this study focuses on the production of ammonia, methanol, steel, crude oil, and biodiesel, rather than their demand. This emphasis is due to the fact that these industrial sectors are the consumers of hydrogen as feedstock in the EU. Regarding hydrogen production, the SMR route with natural gas is considered as it is the only H_2 generation route currently employed in the EU (cf. Section 2). Likewise, electrolysis is contemplated as an alternative technology to current production since it is the most performant to carry out the decarbonisation of the system according to the literature (cf. Section 2). As for the production of hydrogen in the form of by-product, it is not considered since this hydrogen is recirculated in those processes where it is generated; it does not imply an ex professo requirement by the industry.

For simplicity it is assumed that hydrogen production is consumed on-site in each of the sectors, implying no storage or distribution involved (i.e., zero losses) and all production in captive form. This assumption reflects the current situation of on-site hydrogen production and consumption (cf. Section 2). However, it is important to acknowledge that, regardless of the model, 12 % of hydrogen in the EU is currently commercialized, which constitutes a limitation of this study (cf. Section 5.5). In addition, international trade of hydrogen and

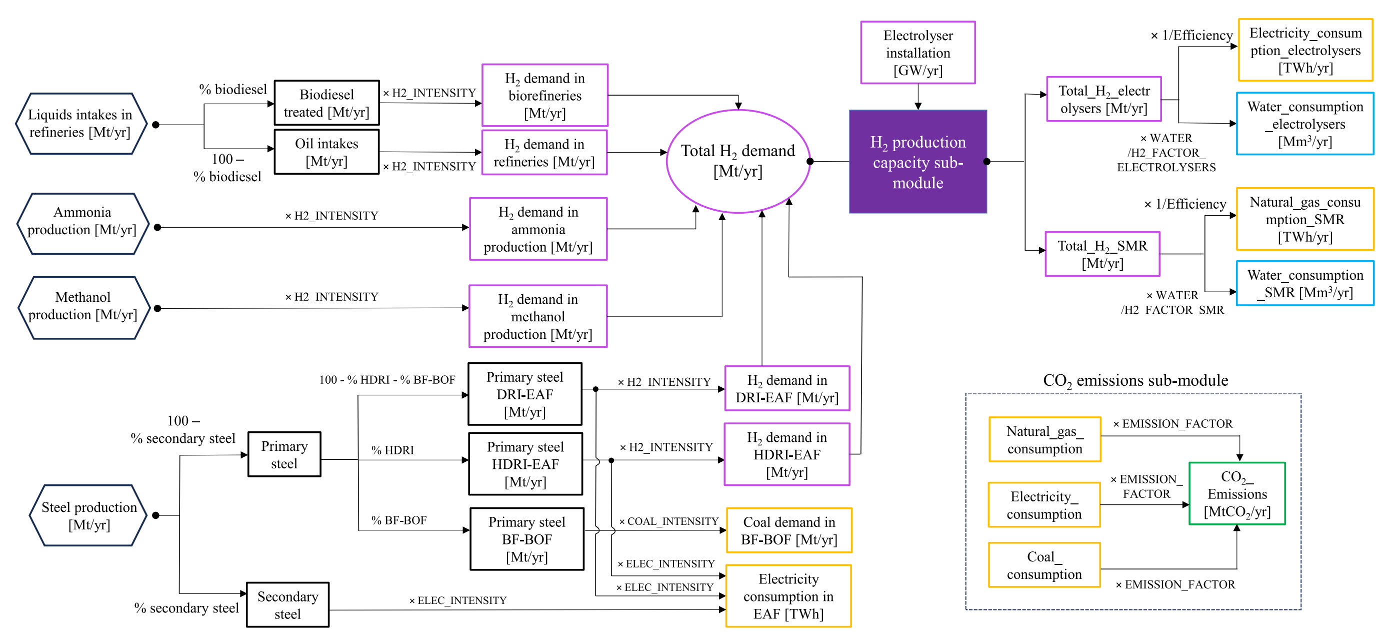

Fig. 1. Structure of the model for on-site hydrogen supply and its use as a feedstock in industry. Purple boxes denote sections associated with hydrogen production and demand. Yellow boxes indicate various energy flows, including electricity, natural gas, and coal. Blue boxes represent water consumption, while the green box highlights CO_2 emissions. For an overview of the H_2 production capacity sub-module, see Fig. 2. Note: minor auxiliary electricity uses (e.g., lighting, control systems) are excluded from the model due to their negligible influence and invariance across scenarios. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

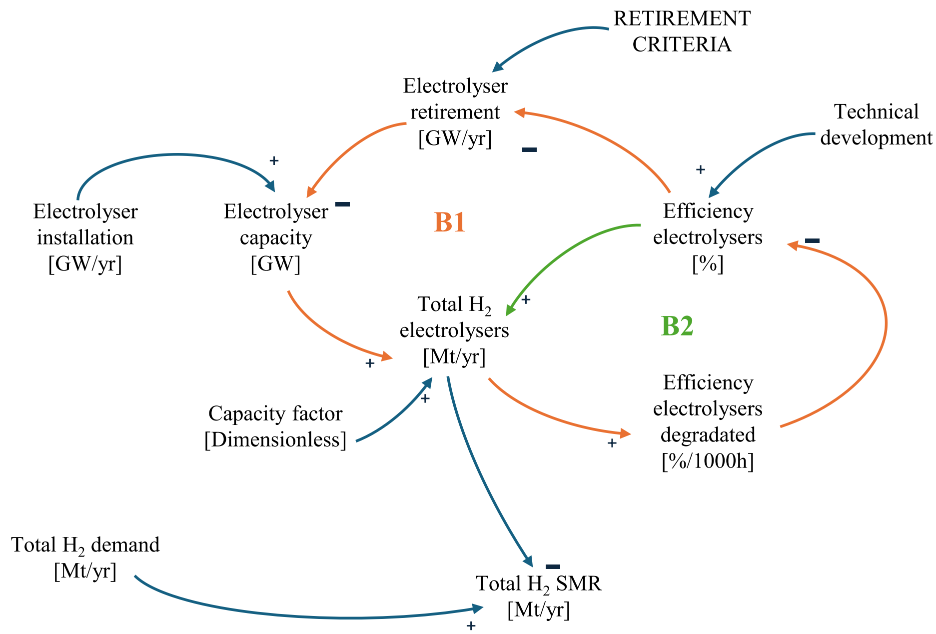

Fig. 2. Causal loop diagram of the hydrogen production sub-module. The figure shows two balancing loops: B1 (electrolyser retirement loop), where increasing electrolyser capacity leads to higher electrolyser retirement (in absolute terms), stabilising capacity over time, and B2 (efficiency degradation loop), where greater use of electrolysers (i.e., higher H_2 production) accelerates efficiency degradation, reducing H_2 output and stabilising production, though partially mitigated by technical development. Although not explicitly shown in the diagram, the share of total H_2 demand associated with the DRI-EAF process is exclusively met through the SMR process.

hydrogen-requiring products, as well as the relocation of production, is not considered, as it is out of the scope of the study.

In terms of modelling, most of the assumptions considered are the usual ones for energy models integrated in IAMs [80–83] namely; calculation of energy and water requirements from process intensities and efficiencies, CO_2 emissions determined according to emission factors, application of the concepts of capacity factor and installed power, addition of installed power based on policies (in simulation mode) or optimisation (in hybrid mode), retirement based on the degradation of its efficiency, and excluding short-term transitional dynamics (e.g., ramp-ups) as well as fine-grained spatial resolution, among others.

Other modelling assumptions are described as follows:

- The electrolysis production model assumes an equal market share (50/50) between AEL and PEM sub-technologies, reflecting the expected growth of PEM alongside the well-established AEL sub-technology. Consequently, the model incorporates average values from both AEL and PEM. While market shares between sub-technologies remain static, technical parameters may evolve dynamically to reflect technological progress over time. The use of electrolysers for balancing out electricity supply and demand is not considered in the model. A mean efficiency of electrolysers is assumed, considering efficiency losses over time, and it is assumed that the electrolysers always operate at full capacity. Additionally, the degradation of electrolysers' efficiency influences their removal and once a certain threshold is reached, they are removed from the system; in this case, when the efficiency decreases by 10 % from its original value, the electrolyser is assumed to have reached the end of its useful life, adopting the same criterion as in [84,85]. Finally, it is assumed that the electrolysers use air cooled systems (meaning water is required only as feedstock), as these systems are well-suited to the European climate and are therefore commonly used across the region [86].
- Electrolyser installation (GW/yr) can be specified either exogenously or endogenously, depending on the selected function mode of the model. In simulation mode, electrolyser installation is predefined by the user, allowing for the exploration of specific deployment trajectories (e.g., those aligned with national hydrogen strategies or policy targets). Alternatively, in hybrid optimisation mode, electrolyser capacity installation is determined endogenously according to the optimal installation pathway that minimises CO_2 emissions over time, given the constraints and input parameters. This dual functionality enables the analysis of both policy-driven scenarios and cost-/impact-optimal trajectories, supporting a comprehensive assessment of hydrogen deployment strategies.
- SMR production is assumed to have infinite production capacity, so that the unmet hydrogen production via electrolysers is covered by the unlimited capacity of SMR technologies. This hypothesis is used for the sake of simplicity, arguing that the current installed capacity in the EU is sufficient to cover the demand and that the purpose of the model is to consider the progressive replacement of the SMR facilities present in the industrial sector by electrolysers.
- The allocation of steel production across the BF-BOF, DRI-EAF and HDRI-EAF routes is defined exogenously, based on scenario assumptions. However, the model does not explicitly simulate the associated physical infrastructure or intra-plant flexibility between DRI and HDRI. Instead, it focuses on representing the energy requirements of each production route to capture long-term structural shifts in technology adoption and energy use at the system level.
- The hydrogen demand associated with the traditional DRI-EAF process must be covered via SMR because this process requires synthesis gas produced through a reforming process.
- The hydrogen demand covered by electrolysis and SMR is distributed homogeneously by sector. This means that at any given time, the share of hydrogen production met through methane reforming is consistent across all sectors (excluding DRI-EAF). This hypothesis aligns with the progressive replacement of SMR installations in the industry by electrolysers.
- Since steel production via BF-BOF is considered solely for the purpose of evaluating its replacement within the context of steel decarbonisation, only the CO_2 emissions associated with this process are modelled.

The historical values for the various model inputs were obtained

Table 2
Historical input parameters included in the model. Corresponding values are provided in S2 of the Supplementary material.

Parameter	Units	References
Liquid intakes in refineries	Mt/year	[87]
Ammonia production	Mt/year	[75,88]
Methanol production	Mt/year	[75,89]
Steel production (primary + secondary)	Mt/year	[90]
Share of secondary steel	%	[90]
CO_2 intensity of the electricity mix	kg CO_2 / MWh	[91]

from the following references (cf. Table 2): Eurostat [87] for crude oil refining (i.e., liquids intakes in refineries), Pawelec et al. [75] and IndexMundi [88] for ammonia production, Pawelec et al. [75] and Pérez-Fortes et al. [89] for methanol production, The European Steel Association [90] for primary and secondary steel production, and European Environment Agency [91] for the intensity of CO_2 emissions in the electricity mix. For a more detailed examination of the historical evolution of these variables, please consult S2 of the Supplementary material.

3.3. Parametrisation of the model

Numerical values for various technical parameters were collected, including process intensities, efficiencies, CO_2 emission factors, and physical constants, again from literature. Table 3 provides the range of values for each parameter found in the literature, along with the chosen values for the model. Detailed information regarding the selection process for these values, along with both the definition of the technical parameters and the single values from each reference, is provided in S1 of the Supplementary material.

Given the technological immaturity of emerging hydrogen-based technologies and the limited availability of comprehensive datasets in the field [55], a rigorous approach was used to select references and evaluate data quality for parametrisation. References were identified through an extensive review of academic and technical databases, including Scopus, Web of Science, and specialised platforms within the energy and hydrogen sectors, such as the IEA, the Fuel Cells and Hydrogen Observatory (FCHO), among others. To maintain data relevance and robustness, priority was given to sources published within the last six years. Source reliability was ensured by selecting studies with transparent, traceable, and well-justified methodologies, and consistent in assumptions and findings across multiple independent references. To enhance robustness, parameters were cross verified with multiple sources to obtain a representative dataset. The search also considered the representativeness of typical technology sizes in industrial contexts to ensure accurate scaling factors, which are essential for robust parametrisation. For instance, a representative size of 1 MW was assumed for electrolyser technologies, as it aligns with current industry standards and near-term deployment expectations [92,93]. Additionally, due to the immaturity of some hydrogen-related technologies, we prioritised data representative of current industrial performance, avoiding overly optimistic from laboratory or pilot-scale conditions which are often under highly controlled or ideal scenarios. For these less mature technologies, such as electrolysers, the reported values reflect the current state of the art. The model, however, is flexible enough to implement future projections for such parameters as part of the scenario hypotheses (cf. Section 4.1) to account for technological advancements over time, ensuring both realistic baseline assessments and dynamic scenario modelling.

Despite the methodological rigor applied in the model's parametrisation, certain inherent uncertainties must be acknowledged due to the current state of knowledge in the hydrogen technology sector. First, the lack of comprehensive datasets for hydrogen-based technologies limits the accuracy of the parametrisation, particularly for newer technologies. This has necessitated gathering data from multiple sources, and although efforts were made to prioritise sources with transparent and well-justified methodologies, discrepancies between studies, especially those from different regions, time periods, and technological specifications, may still introduce some uncertainty. Second, the variability in reported values for many technical parameters reflects the inherent differences in industrial practices, feedstock compositions, and process conditions across the reviewed sources. The model cannot fully capture this granularity, as it is designed for a regional analysis of future trends within the EU as a whole. Finally, the technological immaturity of certain hydrogen-based technologies introduces additional uncertainty since estimating their future performance is difficult. Although current state-of-the-art values were provided, these technologies are still evolving, and their future technical parameters are uncertain. As the model analyses long-term trends, assumptions about future advancements in hydrogen production are highly uncertain.

4. Scenarios

The results of this study stem from simulating various scenarios using the model developed as described in section 3. Six explorative scenarios have been designed to analyse the broad space arising from the interaction between technological, socio-economic, and policy dimensions necessary for the transition from grey to green hydrogen as feedstock. Each scenario reflects distinct assumptions regarding hydrogen demand, hydrogen production for the various industrial commodities, and the speed at which new capacities both of RES and the new technologies (electrolysers, biomass refinery and steel production via HDRI coupled with EAF route) can be installed. These scenarios—Baseline scenario (Baseline), Hydrogen deployment scenario (H_2-expansion), Ambitious decarbonisation scenario (H_2-high-expansion), Degrowth scenario (Degrowth), Delayed deployment of hydrogen scenario (H_2-delayed-expansion) and European Union Hydrogen Roadmap scenario (EU-H_2-roadmap)— enable a comprehensive exploration of potential trajectories and their implications on EU energy systems, CO_2 emissions, and industrial sustainability.

4.1. Common hypotheses

All scenarios share certain assumptions:

- The base year is 2020, with the simulation period extending to 2050, except for H_2-delayed-expansion and EU-H_2-roadmap scenarios, which extend to 2070 and 2030, respectively.
- The model prioritises hydrogen production through electrolysis over conventional fossil-based technologies, and the capacity installed in the year 2020 is set to zero. Even though there already exist EU electrolytic installations (99 MW in 2020) [74], this capacity is negligible compared to the target for 2030 proposed by the European Commission (40 GW) [50], which to be met require a 400-fold increase.
- The initial efficiency (at purchase) of each new installed electrolyser is expected to improve linearly from 57.5 % reaching 68 % by 2050 [6] due to expected technological developments.
- In all scenarios (except the baseline), the rate of capacity expansion for new technologies (electrolysers, biomass refinery and HDRI-EAF route in steel making) varies. It is assumed that these technologies

Table 3
Quantification of the technical model parameters. See Table S2 of the Supplementary material for the data reported by individual studies.

Parameters	Units	Range of values	Considered value	References
H_2 intensity Ammonia Production	kg H_2/ton NH_3	170–190	178.8	[16,56,62,74,76,94–96]
H_2 intensity Methanol Production	kg H_2/ton CH_3OH	114.8–118.5	117.3	[62,74,94]
H_2 Intensity Oil Refining	kg H_2/ton oil	6.37–8.99	7.91	[74,76,87,96–98]
H_2 Intensity Biodiesel Treating	kg H_2/ton biodiesel	38–53	45.5	[6,56]
H_2 Intensity DRI EAF NG	kg H_2/ton steel	37.8–43	40.2	[6,16,98]
H_2 Intensity DRI EAF H2	kg H_2/ton steel	47–68	56.5	[6,56,62,98–107]
Electricity Intensity EAF	MWh/ton steel	0.31–0.88	0.565	[33,99,100,103–105,108–110]
Maximum Capacity Factor Electrolysers	Dimensionless (Dmnl)	0.97–0.98	0.975	[111,112]
Lower Heating Value (LHV) H_2	MJ H_2/kg H_2	–	119.9	[67]
Water/H_2 Factor Electrolysers	L of water/kg H_2	8.8–9	9	[6,113]
Efficiency Electrolysers	% LHV	41–69	57.5	[114–119]
Efficiency Degradation Electrolysers	% / 1000 h	0.01–0.29	0.15	[114,116,118,119]
Footprint Intensity Electrolysers	m^2/MW	48–107	75.5	[6,119]
Efficiency SMR	% HHV	70–85	78.2	[63,67,118]
Higher Heating Value (HHV) H_2	MJ H_2/kg H_2	–	141.9	[67]
Higher Heating Value (HHV) NG	MJ NG/kg NG	–	53.9	[120]
Water/H_2 Factor SMR	L of water/kg H_2	4.5–7	7	[6,121,122]
NG Emission Factor	kg CO_2/GJ NG (HHV)	49.11–50	49.56	[123,124]
BF Emission Factor	ton CO_2/ton steel	1.6–2.2	1.87	[33,62,99–101,106]

develop following an S- or sigmoidal shaped learning curve, which have typically been observed for the development of new technologies [125]. The parameters of these curves are partially predefined: deployment begins in the base year (2020) with zero installed capacity, and the climax point (i.e., final year) is scenario-specific year. The final value of the curves is also fixed. However, for electrolysers, the final capacity value is endogenously optimised to minimise the use of resources and CO_2 emissions over time (hybrid optimisation mode), except in the EU-H_2-roadmap scenario, whose deployment follows an exogenous predefined path to meet the targets outlined in the roadmap (simulation mode).

- The projected growth of RES generation is based on assumptions about the CO_2 emissions intensity in the electricity mix, with trajectories aligned to the specific scenario narratives that reflect varying levels of ambition throughout the energy transition.

4.2. Scenario definition & parametrisation

Baseline scenario (Baseline). The baseline scenario was parametrised using historical data on crude oil refining [87] (1990–2019), ammonia production [75,88] (2003–2019), methanol production [75,89] (2010–2019), primary and secondary steel production [90] (2010–2019), as well as the intensity of CO_2 emissions in the electricity mix [91] (1990–2019). For a more detailed examination of the future projections under the baseline scenario, refer to S2 of the Supplementary material. The baseline scenario assumes that current consumption and production trends continue into the future. It forecasts a 42 % increase in ammonia production, a 122 % increase in methanol production, and a 26 % decrease in steel production by 2050 compared to 2020, with crude oil refining remaining constant (cf. S2 of the Supplementary material). The share of secondary steel over the overall steel production is maintained, while the remaining is produced by the conventional and CO_2-intensive BF-BOF process. Given the low (almost zero) production of hydrogen via electrolysis in the past, this scenario assumes zero installed capacity for electrolysers, with 100 % of hydrogen produced through the SMR process. In the following evaluation scenarios, unless stated otherwise, the characteristics of the baseline scenario remain unchanged.

Hydrogen deployment scenario (H_2-expansion). The scenario assumes that electrolyser deployment starts in 2020 and peaks in 2050, supplying over 90 % of hydrogen production by that year (transitioning from SMR to electrolysis). The production of ammonia, methanol, steel, and oil refining follows historical trends, as in the Baseline scenario. Given the foreseeable growth in the recycling rates of steel [56], the share of secondary steel in the overall steel production increases linearly from 41 % in 2020 to 60 % in 2050, while the BF-BOF method gradually declines and is replaced by the HDRI-EAF process for carbon-free steel production starting in 2030 and peaking in 2050 (covering over 95 % of the steel production in 2050 with this route). Additionally, renewable energy in the electricity mix is considered to increase in line with current trends, reducing the EU's CO_2 emissions factor by 83 % in 2050 compared to 2020 (cf. S2 of the Supplementary material) (i.e., the percentage of RES in the electricity system increases from 37.5 % in 2020 to 54 % in 2030 to 90 % in 2050).[2]

Ambitious decarbonisation scenario (H_2-high-expansion). This scenario maintains current trends in ammonia, methanol, steel and liquids intakes in refineries, as in Baseline and H_2-expansion scenarios. Electrolyser and HDRI route deployment evolve reaching their peak in 2050, as in the H_2-expansion scenario. In contrast to the previous scenarios, H_2-high-expansion scenario sets more ambitious decarbonisation targets, leading to significantly higher hydrogen use and a larger share of renewables in the electricity mix (the CO_2 emissions factor of the electricity mix declines exponentially, increasing RES share from 37.5 % in 2020 to 77 % in 2030 to 97 % in 2050). Additionally, biodiesel production rises, substituting oil refined products. Given the potential of HVO biodiesel to utilise existing diesel infrastructure and the interest in its deployment over conventional FAME biodiesel [57], it is assumed that by 2050 HVO will fully replace the conventional diesel currently produced in the EU, which currently accounts for nearly 40 % of refined liquid fuels [128]. Contrary to H_2-expansion scenario, secondary steel production remains constant to enable higher hydrogen scenario.

Degrowth scenario (Degrowth). This scenario envisions a future shaped by deliberate and coordinated actions to shift the current growth-focused economy towards a sustainability paradigm that promotes technical and socio-cultural changes without relying on continuous growth [44–46]. By reducing resource and energy consumption and prioritising structural changes to enhance well-being, this approach would lead to decreased industrial production. This reduction may result from both the expected depletion of resources and shifts in consumption patterns. Here, we conduct a target policy analysis to examine the implications of meeting a set of sectoral targets, while acknowledging that a comprehensive Degrowth assessment would encompass

[2] Although the model uses CO_2 emissions intensities in the electricity mix, for clarity and scenario exposition, equivalent RES shares are reported based on historical data from Eurostat [126] and the European Environment Agency [91], in line with the hypotheses outlined in Álvarez-Antelo et al. [127]. For details, refer to S3 of the Supplementary material, where numerical and analytical definitions are provided.

the entire society cf. Fitzpatrick et al. [129]. Additionally, as degrowth paradigm implies a relocalisation of production, in this scenario we take a consumption-based approach.

In terms of parametrization: ammonia is today mainly dedicated to fertilizers. By 2050, we assume then that the agricultural system would have undergone a complete transformation towards the use of organic fertilisers, alongside a dietary shift towards predominantly plant-based diets [130,131]. For the remaining uses of ammonia (~30 % taking the global average), we assume that they will be largely either eliminated or replaced by biomass substitutes, hence we assume that only 15 % of the 2020 ammonia EU level is maintained in 2050. For steel, we take as reference the Reference scenario from Vélez-Henao and Pauliuk [132] who estimate material per capita requirements compatible with Decent Living: 129 kg/cap/yr. Moreover, since the EU is already close to covering basic needs (on average) [133,134], it is not necessary to model significant additional infrastructure. As first approximation, we consider by 2050 the same population as today [135], which translates into 58 Mt steel/year, a reduction of 64 % compared to current values. Lower demand enables more recycled steel use, but impurities build up and are hard to remove [136]. We thus cap recycled steel at 75 % to secure enough high-purity primary steel for critical uses. For methanol and biofuel, the picture is more complex. On the one hand, sufficiency measures would tend to reduce its use, on the other hand, substitutions of current fossil fuels would tend to increase its use. For biodiesel we take the estimate from Wiese et al. [40], which reports 205 TWh (16.9 Mt) of biodiesel use in 2050 in a "sufficiency" scenario, corresponding to 0.77 Mt H_2 (HVO). For methanol, we take the estimate reported by négaWatt in the CLEVER scenario (cf. the related industrial sector report [137]), corresponding to 13.4 Mt methanol[3] in 2050 for the production of high-value-chemicals, essential for plastic manufacturing. Finally, a residual demand for fossil oil (5 %, i.e., 28.4 Mt) is maintained by 2050, in line with négaWatt [138], to facilitate the production of high-value chemicals. The majority of current oil uses is assumed to be replaced through a combination of sufficiency measures, such as modal shifts, reduced transport activity (notably in air travel and private road transport), production relocalisation, and shifting freight transport to railways [139].

Since degrowth theories support environmental conservation, decarbonisation policies can remain ambitious, enabling the deployment of electrolysers (reaching the peak in 2050), the development of the HDRI route (beginning in 2030 and peaking in 2050) and the decarbonisation of the electricity production through a faster deployment of renewables (growing exponentially, as in scenario H_2-high-expansion scenario, achieving a RES percentage of 97 % by 2050).

Delayed deployment of hydrogen scenario (H_2-delayed-expansion). The scenario is identical to H_2-expansion, but with a slower deployment of the new technologies (electrolysers, biomass refinery and HDRI-EAF), resulting in the peak deployment of electrolysers occurring in 2070 instead of 2050. This scenario enables the evaluation of two critical aspects: the impact of practical barriers, such as financial or technological constraints (e.g., slower-than-expected technological progress)[4] or policy-induced delays in the adoption of hydrogen-based technologies; and the analysis of delayed electrolyser deployment to ensure that hydrogen production benefits from a higher share of renewables in the electricity mix, with the trade-off that in the former years a greater proportion of hydrogen would be produced via the SMR process.

European Union Hydrogen Roadmap scenario (EU-H_2-roadmap). The aim of this scenario is to assess the short-term trends (year 2030) if the EU's green hydrogen production targets were achieved (in the context of the intended decarbonisation goals). An electrolytic production target of 10 Mt of hydrogen per year by 2030 has been established in the model, consistent with the objective of reaching up to 10 Mt by that year [50]; therefore, the deployment of electrolysers follows a predefined pathway, hence the model operates in simulation mode, unlike previous scenarios. Regarding the share of RES in the electricity mix, it should be noted that the EU only sets RES percentage targets for the final energy mix, not specifically for the electricity mix. While the %RES targets for final energy use in 2030 are expected to double compared to current values, the %RES of the electricity mix is assumed an increase by +50 % (from 37.5 % in 2020 to 56.3 % in 2030). This assumption accounts for the growing challenges of increasing the RES share when it is approaching the 100 %. The projected 56.3 % is consistent with the level forecasted for Europe by the IEA in its Renewables 2022 report [140]. Regarding the production of ammonia, methanol, steel, and oil refining production, these sectors are expanding in line with historical trends. For secondary steel, a linear growth model is assumed, as in H_2-expansion scenario. All these assumptions are based on the hydrogen roadmap for the EU [50] and the EU's 2030 energy targets. Overall, this roadmap is more ambitious than the H_2-expansion, H_2-high-expansion, Degrowth and H_2-delayed-expansion scenarios in terms of electrolytic hydrogen production. It envisages a large-scale near-term deployment, where almost all hydrogen production would come from electrolysers by 2030, unlike the previously explored scenarios, which aim for this goal by 2050 (or by 2070 for H_2-delayed-expansion). However, in terms of decarbonisation of the electricity mix, the roadmap is slightly less ambitious than scenarios H_2-high-expansion and Degrowth (ambitious decarbonisation) although more ambitious than scenarios H_2-expansion and H_2-delayed-expansion (current trends). This scenario is consistent with the core assumptions of this study, as the EU's short- to medium-term strategy (2020−2030) identifies industrial applications such as ammonia, methanol, oil refining, and steel production (those considered in this work) as immediate targets for electrolytic hydrogen deployment. Additionally, the limited development of an EU-wide hydrogen infrastructure foreseen up to 2030 supports the assumption of on-site production and consumption.

4.3. Summary of the scenarios

A summary of the six scenarios to be assessed with the model is provided in Table 4. For further details regarding the numerical and analytical definitions, please refer to S3 of the Supplementary material.

5. Results and discussion

The different scenarios generate different hydrogen consumption (green and grey) and, consequently, the consumption of electricity and water, and pace at which new technologies have to be deployed (electrolysers, biodiesel refinery and HDRI-EAF route to steel making) differs. Fig. 3 shows the hydrogen demand (equivalent to production, as it occurs on-site) disaggregated by non-energy use, while Fig. 4 presents a panel summarizing the key results generated by the model.

5.1. Hydrogen demand and production

Total hydrogen production (including both SMR and electrolysis route) varies across different scenarios (5.5–22.5 Mt H_2/Year), as shown in Fig. 3 and aggregated in Fig. 4A. In the baseline scenario, hydrogen production follows current trends, driven by its use in crude oil refining, ammonia, and methanol production (see Fig. 3A). Both the H_2-expansion and EU-H_2-roadmap scenarios show higher hydrogen production than the baseline, driven by the expanded use of hydrogen in the steel sector (see Fig. 3B, and Fig. 3F). The H_2-delayed-expansion scenario

[3] The production of high-value chemicals from biomass, as reported in the CLEVER documentation, has been incorporated under the methanol-based pathways, since biomass is beyond the scope of the present study.

[4] These barriers and constraints are not modelled explicitly. Instead, they are represented through aggregated parameter adjustments in the growth function used to simulate technology deployment. Specifically, the delayed expansion scenario reflects these challenges by shifting the target year for full deployment from 2050 to 2070, while maintaining the same final capacity value.

Table 4
Summary of the scenarios assessed with the model. Electrolyser deployment follows sigmoidal shaped learning curves, with climax values optimised to minimise resource usage and CO_2 emissions, except in the EU-H_2-roadmap scenario, where deployment follows a predefined exogenous path. The resulting share of hydrogen demand met by electrolysis is shown in the table (cf. Table S3 of the Supplementary Material for further details).

Scenario	NH_3 production	CH_3OH production	Liquids (oil+biodiesel) refining	Steel production	% secondary steel	% RES electricity	Electrolyser deployment
Baseline	Current trends	Current trends	Current trends (0% bio)	Current trends	41 % in 2050	Current trends	No
H_2-expansion	Current trends	Current trends	Current trends (0% bio)	H_2 route (2050 target)	60 % in 2050	Current trends	90 % target share in 2050
H_2-high-expansion	Current trends	Current trends	Current trends (40 % bio in 2050)	H_2 route (2050 target)	41 % in 2050	Exponential growth	97 % target share in 2050
Degrowth	−85 % by 2050	+241 % by 2050	−92 % by 2050 (37 % bio in 2050)	−64 % by 2050 H_2 route (2050 target)	75 % in 2050	Exponential growth	97 % target share in 2050
H_2-delayed-expansion	Current trends	Current trends	Current trends (0 % bio)	H_2 route (2070 target)	60 % in 2050	Current trends	90 % target share in 2070
EU-H_2-roadmap	Current trends	Current trends	Current trends (0 % bio)	Current trends	47 % in 2030	IEA Current trends	10 Mt H_2 target in 2030

results in slightly lower hydrogen production than the H_2-expansion scenario, due to a delay in deploying hydrogen uses in the steel industry (see Fig. 3E). The H_2-high-expansion scenario shows a substantial increase in production, driven by unforeseen trade-offs related to the integration of biodiesel as a substitute for oil products (see Fig. 3C); as hydrogen demand for biodiesel production is nearly four times greater than for fossil oil, this leads to a major rise in overall hydrogen production. Lastly, in the Degrowth scenario, hydrogen production is much lower compared to the baseline scenario, due to a substantial reduction in the production of the various industrial products, despite the inclusion of hydrogen pathways in steel industry (see Fig. 3D).It is important to note that the model does not include all potential decarbonisation pathways that could compete with or complement hydrogen deployment, such as direct electrification, the use of CCUS or biomass, or enhanced circular economy strategies (e.g., in plastics). While these alternatives lie beyond the scope of the present analysis, their inclusion could influence both hydrogen demand and production trajectories.

Not all hydrogen depicted in the graph is derived from electrolysis. In this sense, to fulfil the hydrogen production requirements in each scenario, electrolytic hydrogen is utilised in varying proportions; by 2050 nearly 100 % of total hydrogen production is achieved via electrolysers in the H_2-expansion, H_2-high-expansion and Degrowth scenarios. In contrast, this milestone is reached by 2070 in the H_2-delayed-expansion scenario and by 2030 in the EU-H_2-roadmap scenario. Until these target years, hydrogen production is achieved through a mix of electrolysers and SMR. The hydrogen production capacity via electrolysis (which determines the amount of electrolytic hydrogen produced annually) is primarily driven by the annual installation rate of electrolysis facilities, the penetration of which has been optimised in each scenario to minimise the cumulative CO_2 emissions of the system (except for the EU-H_2-roadmap, which follows a predefined exogenous trajectory aligned with roadmap targets). This annual installation trajectory is presented in Fig. 4B. It is important to consider, however, that due to the degradation in efficiency over time, some of these facilities are gradually decommissioned, as accounted for in the hydrogen production sub-module. It is noteworthy that the EU-H_2-roadmap involves a substantially higher electrolyser deployment compared to other scenarios, despite similar hydrogen demand, as it achieves 100 % electrolytic supply by 2030, significantly earlier than the other scenarios. Furthermore, it is important to bear in mind that that SMR capacity is assumed to be unconstrained in the model (unlimited capacity). While this simplification facilitates the representation of electrolytic hydrogen supply during the transition, a more restrictive assumption (limited SMR capacity) could lead to a larger deployment of electrolysers in certain years, thus slightly increasing the capacity expansion shown in Fig. 4B. In addition, the model assumes that electrolysers operate at full capacity (with a capacity factor of up to 97.5 %), which is an optimistic assumption for on-site, grid-connected industrial applications. In practice, however, electrolysers may operate at lower capacity factors due to fluctuations in electricity prices or flexibility requirements. This would require higher installed capacity to meet the same hydrogen demand, increasing the capacity expansion shown in Fig. 4B.

5.2. Electricity and water consumption

The production of electrolytic hydrogen entails a significant increase in electricity consumption (see Fig. 4C). Under the various electrolyser deployment scenarios (namely, H_2-expansion, H_2-high-expansion, H_2-delayed-expansion, and EU-H_2-roadmap), the annual electricity requirements range between 700 and 1180 TWh/Year. This result aligns closely with the projection from Dolci, F. [62], who forecasts a demand of approximately 1000 TWh/Year by 2050 to supply green hydrogen for the industrial sector under a scenario comparable to H_2-expansion.

The findings highlight significant challenge for the integration of hydrogen production within the EU's energy system. With current renewable electricity generation capacity at approximately 1080 TWh/Year, within a total electricity production of 2824 TWh/Year [141], meeting the potential demand of hydrogen (5.5–22.5 Mt H_2/Year), could consume up to 42 % of the electricity generated in the EU today, while exceeding current renewable electricity production capacities. Such a substantial increase in electricity demand associated with hydrogen uses is also envisioned in other studies like [142,143]. Addressing this challenge requires ensuring the future expansion of renewable electricity generation capacity to meet the additional electricity demand for hydrogen production while safeguarding the energy supply for other sectors [76]. Furthermore, the literature identifies additional challenges associated with high renewable electrification, including a critical decline in the EROI of the energy system [48], risks related to the future availability of certain minerals [144,145], and the impracticality of meeting land use demands required for solar energy [146]. It is also important to note that this analysis is focused on non-energy uses of hydrogen, while not accounting for certain sectors (such as freight transport, high-temperature industrial processes, among others) which, according to projections by the European Hydrogen Backbone [56], could increase total hydrogen demand to as much as 40 Mt H_2 by 2050 (excluding non-energy uses). This would imply electricity requirements of approximately 3200 TWh/Year for total hydrogen production (assuming electrolytic route) alone far exceeding current electricity generation capacities and substantially intensifying the need for large-scale deployment of electrolysers.

The model also provides insights into total water consumption associated with hydrogen production through electrolysis and SMR, as illustrated in Fig. 4D. Total water usage varies based on the hydrogen production pathway, as both electrolysis and SMR rely on water but exhibit differing levels of intensity; electrolysis, for instance, requires 1.3 times more water than SMR. Consequently, the overall water

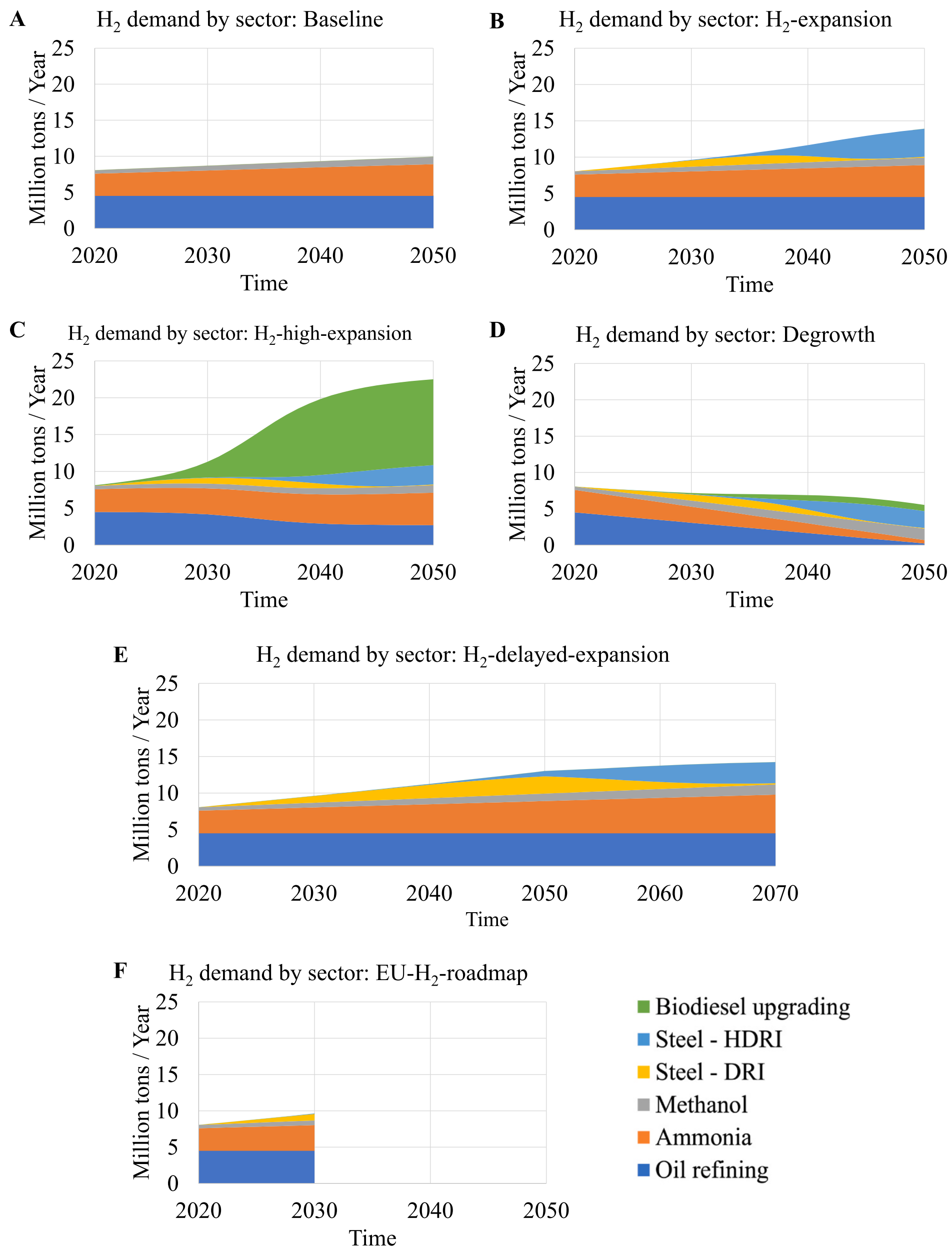

Fig. 3. Hydrogen demand by sector disaggregated by non-energy use. Given that the model assumes on-site production and consumption, demand is equal to production.

consumption is influenced by the share of hydrogen generated via electrolysis. The results of the model shows that, over time, due to the increased deployment of electrolysers and the greater hydrogen production, water consumption is expected to grow significantly by 2050, even duplicating (scenarios H_2-expansion and H_2-delayed-expansion) and even tripling (scenario H_2-high-expansion) with respect to the initial starting value (57.2 Million m^3 / Year), representing, in the most unfavourable case, about 0.1 % of the current annual industrial freshwater withdrawals of the EU.[5] This could pose challenges for local areas with limited water resources [149]. In contrast, only the Degrowth scenario maintains water consumption nearly constant with respect to the initial value. However, as the model assumes air cooled systems for the electrolysers, the adoption of evaporative cooling systems would likely increase water consumption across all scenarios involving electrolytic hydrogen, potentially exacerbating the challenges related to water resource availability [86,150].

5.3. CO_2 emissions

Fig. 4E shows the total annual CO_2 emission for the entire system under each scenario. In the model, CO_2 emissions are primarily influenced by the total hydrogen production, the proportion of hydrogen produced through electrolysis, the share of RES in the EU (i.e., the EU grid CO_2 emissions factor), and the method used for steel production. As shown in in Fig. 4E, except for the EU-H_2-roadmap scenario, CO_2 emissions decrease over time. By 2050, the CO_2 emissions from the H_2-expansion scenario decrease by 81 %, the H_2-high-expansion scenario by 91 %, the Degrowth scenario by 97 %, and the H_2-delayed expansion by 64 %). The Degrowth scenario, which assumes a more rapid

[5] Current industrial freshwater withdrawals of the EU amounts to 185,000 Mm^3 / Year. Data obtained from FAO AQUASTAT [147], accessed via the World Bank Group [148].

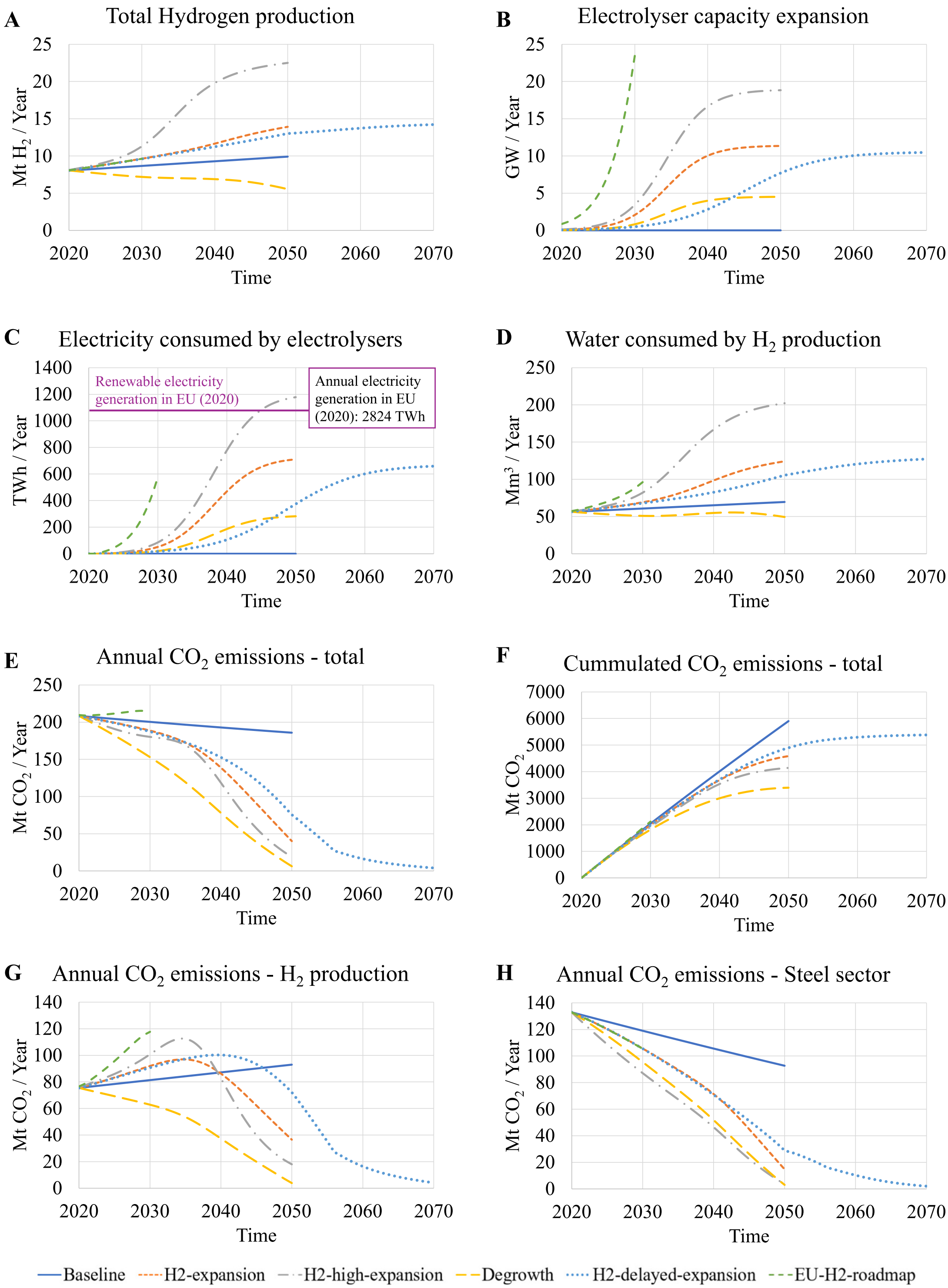

Fig. 4. Main results of the model for the EU. The electrolyser capacity expansion (B) is presented in terms of GW of power installed per year. Annual CO_2 emissions for H_2 production (G) considers both electrolysis and SMR pathways. Annual CO_2 emissions associated with steel manufacturing (H) account for BF-BOF, HDRI, DRI and EAF routes.

decarbonisation of electricity production through accelerated renewable deployment, combined with significant reductions in ammonia, liquids intakes in refineries and steel production, results in the lowest CO_2 emissions both annually (Fig. 4E) and cumulated over time (Fig. 4F). This scenario achieves full decarbonisation of industry the earliest.

It must be highlighted that the Degrowth scenario represent a rupture with the existing institutional, cultural and political framework in the EU (and globally, hence also geopolitical). Despite the growing body of degrowth research in recent years [151], key challenges remain regarding the consolidation, operationalisation, and feasibility of this narrative. As Lauer et al. [152] note, degrowth modelling is gaining traction and has improved our understanding of the interplay between consumption, well-being, and environmental impacts. However, such modelling efforts face multiple limitations, such as struggling to capture the complexity of a degrowth transition (such as diverse policy mixes, structural shifts) and unresolved debates around key concepts like geopolitical dynamics, the role of the Global South, and the issue of the (in)compatibility with capitalism [152]. This is partly due to the fact that degrowth is in fact very plural [44]. Also, systematic work relating energy technologies and degrowth is lacking [153], which could be done applying frameworks such as the Matrix of Convivial Technology [154]. In fact, hydrogen technologies are not typically part of the degrowth portfolio [129]. Edwards et al. [155] identify 4 main areas of improvement for IAMs: the energy-economy connection, spatial differentiation, sectoral differentiation, the inclusion of different provisioning systems and feasibility considerations.

In terms of CO_2 emissions, Degrowth scenario is followed by the H_2-high-expansion scenario, which drives CO_2 emissions down considerably despite high production levels. Both the H_2-expansion and H_2-delayed-expansion scenarios, which differ only in the speed at which electrolysers and H_2-based production routes will be deployed, contribute almost equally to the reduction of CO_2 cumulated between 2020 and 2050, as depicted in Fig. 4F. This is due to the rapid deployment of electrolysers in H_2-expansion scenario, which leads to increased electricity demand for hydrogen production. However, the expansion of electricity production capacity from RES cannot keep up with the additional demand in this scenario. Even though the required hydrogen in H_2-delayed-expansion scenario relies predominantly on natural gas (SMR route) in the first decade, the total cumulated CO_2 emissions in both scenarios are quite similar (in fact, up until 2035, CO_2 emissions in the H_2-expansion and H_2-delayed-expansion scenarios are virtually the same because the electricity mix is not sufficiently decarbonised to make electrolysis less carbon-intensive than the SMR process, as shown in Fig. 4G). This shows that, under certain conditions (such as an inadequately clean electricity mix), hydrogen produced via grid-bound electrolysis may not, in fact, be “green”, as also concluded in the Wood Mackenzie White Paper [156]. Given these conditions, the delay in the deployment of electrolysis, pending a cleaner electricity mix, warrants careful consideration. Without this delay, while cumulative CO_2 emissions would remain similar, the resulting level of electrification could impose unsustainable energy demands on the energy system.

The rise in total CO_2 emissions in the EU-H_2-roadmap scenario is justified by the very rapid deployment of electrolysers, which is not accompanied by a similar reduction in CO_2 emissions intensity of the electricity mix. In the first decade, the electrical grid remains too carbon-intensive, making hydrogen production via electrolysis more CO_2-intensive than production via SMR using natural gas, as illustrated in Fig. 4G. While the large-scale deployment of electrolysers (EU-H_2-roadmap scenario) could reduce the EU’s dependence on natural gas for hydrogen production, the power system does not appear adequately prepared to generate 10 million tonnes of “green” hydrogen by 2030 in a sustainable way (as shown in Fig. 4E). Furthermore, this could trigger a rebound, leading to an increase rather than a decrease in the consumption of fossil fuels, as fossil fuel-based power plants (present in the largely under-decarbonised electricity mix in the 2020–2030 scenario period) would need to supply significant amounts of electricity (53 % of current renewable electricity generation in the EU, according to Fig. 4E). However, it is important to consider the long-term strategic value of early electrolyser deployment. Even if such deployment leads to a temporary increase in CO_2 emissions, it may play a crucial role in establishing the necessary infrastructure and industrial readiness for a robust hydrogen economy. From this perspective, early investment in electrolysis technology could facilitate a faster and more scalable uptake of hydrogen demand once the electricity mix becomes sufficiently decarbonised, thereby enabling the sector to reach all hard-to-abate sectors [157].

Our simulations indicate that policies aligned with any of the alternative scenarios (H_2-expansion, H_2-high-expansion, Degrowth and H_2-delayed-expansion) are significantly more sustainable than the EU-H_2-roadmap scenario. Notably, none of these scenarios foresees that more than 50 % of hydrogen will be produced via electrolysis by 2030, while the EU-H_2-roadmap scenario assumes 100 % (hence the difference in CO_2 emissions). For the EU-H_2-roadmap scenario to avoid increasing CO_2 emissions, the electricity mix emission factor would need to reach nearly 133.8 kg CO_2/MWh by 2030 (a 50 % reduction compared to 2020). Given that the emissions factor in 2020 was 271.8 kg CO_2/MWh, this would require a reduction of 138.8 kg CO_2/MWh over the next 10 years (13.8 kg CO_2/MWh annually), substantially exceeding the 7.55 kg CO_2/MWh annual reduction achieved in the past decade [91]. In other words, achieving this would necessitate doubling the decarbonisation rate of the electricity grid, a significantly more challenging task as renewable capacity increase.

Finally, despite the aforementioned points, all five alternative scenarios (including the EU-H_2-roadmap scenario) result in a significant reduction of CO_2 emissions associated with steel manufacturing compared to the Baseline scenario (see Fig. 4H). This reduction is primarily driven by the replacement of the CO_2-intense BF-BOF process by less CO_2 emission-intensive processes, such as HDRI, or the increased production of secondary steel. This result aligns with the findings of Lopez et al. [32], who also observed a significant reduction in CO_2 emissions under a scenario dominated by the HDRI process in medium to long term. It is important to note that the model does not include cross-route configurations (e.g., BF-EAF or DRI-BOF), which are currently immature [158] and technically complex [159]. However, under advanced technological scenarios, these pathways could lower CO_2 emissions from remaining BF-BOF operations.

5.4. Policy recommendations

As a corollary to the discussion, a set of policy recommendations related to the uses of hydrogen as an industrial feedstock can be drawn:

- Coordinate electrolyser deployment with renewable energy expansion to effectively contribute to climate mitigation. For this purpose, it would be necessary to at least double the rate of reduction in the CO_2 emissions factor of the electricity mix; delaying the electrolyser target should be considered if the former cannot be ensured in time.
- Prioritise the CO_2 emissions reduction potential in the steel industry over other sectors. There is a big potential to drive down CO_2 emissions by replacing BF-BOF route to steel production with HDRI-EAF route. However, it is important to keep in mind that this steel production technology is still being developed, and its future commercial deployment remains uncertain.
- Evaluate more critically plans for the massive use of hydrogen. Our analysis indicates that replacing fossil fuels by electrolytic hydrogen as and industrial feedstock (for fertilizers, methanol, refineries and steel production) would require an additional 42 % of electricity generation in EU. The potential energy uses of hydrogen (e.g., for fuel transport, for synthetic fuels, etc.) would further increase this share. Therefore, the massive adoption of hydrogen poses significant technical, sustainability, environmental, and cost challenges, particularly in expanding renewable electricity generation to meet industrial needs.
- Prioritizing demand management and socio-technical changes to reduce energy demand facilitates the deployment of RES and lowers their impacts.
- Avoid locating new electrolytic hydrogen facilities on sites with risk of water scarcity. Since hydrogen production requires significant amounts of water, it could have a considerable impact on this vital seasonal resource, especially in those regions (e.g., southern European countries) where desertification is a potential threat.

5.5. Limitations and further work

First, the model assumes that 100 % of hydrogen demand is produced and consumed on-site, disregarding hydrogen transportation, distribution and storage, while in the EU, approximately 12 % of hydrogen is currently commercialized. We acknowledge that this simplification overlooks relevant infrastructure developments such as the European Hydrogen Backbone [160,161] and the REPowerEU Plan [162] targets, which envision extensive pipeline networks connecting supply and demand regions. Our model is designed to capture the production-side dynamics and their associated technical, energy and environmental implications, rather than to represent market structures or infrastructure planning. However, incorporating hydrogen distribution and storage into the model would be possible in energetic and environmental terms, and would likely increase total energy requirements and CO_2 emissions, due to additional steps and physical losses along the hydrogen value chain [163]. For instance, transporting gaseous hydrogen over 2500 km by pipeline requires electricity for recompression (around 4.56 TWh to deliver 1 Mt H_2 [164]), and is subject to hydrogen leakage, which not only implies energy loss (~1 % of the hydrogen delivered [164]) but also contributes to climate forcing due to hydrogen's high global warming potential [165]. Similarly, shipping liquid hydrogen over long distances (e.g., 5000 km) entails considerable energy uses for liquefaction (with an efficiency of 70–76 %) and results in boil-off emissions during transit (around 3–5 %) [163]. Including such effects would likely amplify the environmental and energy system challenges identified in our study. However, these negative effects are likely to be offset by systemic benefits stemming from enhanced market competition and economies of scale (which result in technological readiness) or spatial optimisation based on RES availability. For instance, hydrogen could be produced cheaply in regions with higher RES productivity (e.g., Southern Europe) and transported to major industrial consumers elsewhere (e.g., Central Europe) [166]. Capturing such dynamics, however, would require a multi-regional model with an economic structure capable of simulating trade flows and infrastructure investment, which goes beyond the scope of the current framework. Despite these limitations, we believe that our results remain relevant for several reasons. First, the focus on on-site hydrogen use provides a conservative scenario that can serve as a lower-bound estimate of system impacts. Second, many industrial hydrogen applications (especially in chemicals and refining) are centralised and would not require extensive distribution [163], making it reasonable to expect continued favouring of on-site in the short-to-medium term. Third, the key system-level insights from our analysis (such as the scale of RES required, the relative performance of alternative hydrogen pathways and their implications for CO_2 emissions) remain valid under both on-site and grid-based hydrogen supply models, albeit potentially mitigated through infrastructure-enabled scalability of the hydrogen sector.

Second, the model does not account for the import of hydrogen from regions outside the EU (negligible in practical terms), nor the importation of hydrogen-based products from outside the EU. To integrate such imports meaningfully, it would be necessary to extend the scope of the model to include the hydrogen sector of those external regions in a consistent manner, which is beyond the scope of the current work, as well as extending the framework beyond on-site restriction. If imports were incorporated, a key implication would be the partial displacement of RES generation and electrolysis capacity from within the EU to external regions, reducing total hydrogen production, electrolyser capacity expansion, as well as electricity and water consumption in EU. However, the environmental burden would not disappear, as the EU would remain accountable for the CO_2 emissions associated with imported hydrogen or hydrogen-based products. Nevertheless, in practice, this strategy would reproduce structural patterns of energy dependence [166]. However, analysing the role of such imports would be necessary to assess to what extent they are necessary, and whether the EU could feasibly meet its future hydrogen demand through domestic production alone [143].

Third, for simplicity, the energy and emissions associated with investments in new capacities are not considered; this limitation particularly affects the Degrowth scenario, which involves a higher level of system transformation. This issue is connected to the final noted limitation: this work focuses on a specific segment of the human system. Consequently, fully implementing sustainability transition scenarios would require a more comprehensive simulation tool that integrates all relevant dimensions of the problem.

Future research could address these limitations by implementing and extending this model into the new IAM WILIAM [167–169], particularly within the HYDRA project. This integration will enable a thorough analysis of the impacts of hydrogen deployment within a full energy module, including features of RES variability [170], impact on system EROI [48], its biophysical implications in terms of mineral requirements, the effects related to land-use [146], etc. Ongoing work in WILIAM will also consider a broader spectrum of potential hydrogen applications beyond its current role as a feedstock, such as in energy-intensive sectors such like freight transport, high-temperature industrial processes, the production of synthetic fuels, etc. These enhancements will tend to increase the potential demand of hydrogen thereby intensifying the challenge of supplying green hydrogen, and further intensifying the electrification of the system, as well as the expansion of electrolytic and renewable energy capacities. Additionally, advancements in hydrogen production technologies will be pursued. This will involve modelling other conventional hydrogen production methods that are more prevalent outside the EU (e.g., coal gasification in China), as well as the exploration of blue hydrogen production. The latter was excluded from the scope of the present study due to its current uncertainties [171–173], its incomplete full technological maturity [174], and its omission from the EU-H_2-roadmap. In addition, the multi-regional structure of the WILIAM model would facilitate a consistent analysis of the issues related to international trade in hydrogen and hydrogen-requiring products, as well as the relocation of production driven by "renewable pull" effects [175]. Finally, future work could provide a more in-depth assessment of the role of hydrogen in enabling low-carbon plastics production through methanol-based pathways for olefins and aromatics [40].

6. Conclusion

In this paper, a novel regional energy model to support decision-making regarding the transition to green hydrogen feedstock within the industrial sector was presented. The model, publicly available in a repository, covers the hydrogen transformation chain, from production (via fossil fuel-based conventional methods and electrolysis) to consumption in sectors such as ammonia and methanol production, steel manufacturing, and oil and biodiesel refining. It tracks energy flows, including electricity, natural gas, and coal use, alongside hydrogen production and consumption, and also calculates electrolyser capacities, water requirements, and associated CO_2 emissions by sector. Built within a dynamic framework, and adopting a bottom-up approach, the model can account for transitional and rebounds that common static and non-recursive models fail to address. The model is used to evaluate various innovative energy transition scenarios applied in the EU, including Degrowth, an EU H_2 Roadmap Scenario, and scenarios with varying transition speeds.

Simulation results show that a massive deployment of electrolysers for hydrogen production only contributes to climate change mitigation if, at the same time, there is sufficient capacity of renewable electricity installed. If the deployment of electrolysers (40 GWh by 2030 according to EU targets) is not bolstered by the expansion of renewable electricity generation capacity in a coordinated way, the cumulated CO_2 emissions will be neutral or may even increase. In case the reduction of CO_2 emissions from the electricity mix is not occurring at a rapid enough pace, delaying the electrolyser target could be considered (but at the expense of slower and less scalable hydrogen uptake and readiness). In the specific case of the objectives proposed by the EU [50], quantitatively, it would be necessary to at least double the current rate of decarbonisation of the electricity mix. In this sense, other scenarios with a slower deployment of electrolysers may unexpectedly become more sustainable in terms of CO_2 emissions.

We find a big potential to drive down CO_2 emissions in the steel industry by replacing the most CO_2-intense BF-BOF route to steel production with HDRI coupled with EAF route. However, this steel production technology is still under development and there are major uncertainties about its deployment in the future on a commercial scale.

Due to the relatively low efficiency of electrolysers (~60 %), to replace the non-energy use of fossil fuels with hydrogen as feedstock produced via electrolysis for fertilizers, methanol, refineries, and steel production, we estimate that electricity generation in the EU would need to increase by approximately 42 % in growth-oriented transition scenarios. Hence, meeting green hydrogen demand will pose a significant technical challenge for power systems. Since green hydrogen should be produced from RES, it also requires critical evaluation of its techno-sustainably and environmental impacts, as well as other systemic constraints left out of the scope of this research such as RES variability, material criticality or EROI. The simulation of a Degrowth scenario shows that the reduced demand of hydrogen helps to reach the targets with a lower pressure on the system. Moreover, potential energy applications of hydrogen not included in this analysis, such as fuel for transportation or the production of synthetic fuels, will tend to further raise this demand. The integration of all these elements will enhance the understanding of hydrogen's potential for the energy transition.

CRediT authorship contribution statement

Juan Manuel Campos-Rodríguez: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Íñigo Capellán-Pérez:** Writing – review & editing, Supervision, Project administration, Methodology, Conceptualization. **Gonzalo Parrado-Hernando:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Fernando Antonio Frechoso-Escudero:** Writing – review & editing, Supervision, Methodology, Conceptualization.

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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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Appendix A. Literature review

This appendix provides a detailed description of the studies reviewed in the context of green hydrogen deployment as feedstock in industry. The studies were selected for their relevance to the research objectives and their focus on the non-energy uses of hydrogen

Koivunen et al. [27] examines the integration of green hydrogen into the Finnish steel industry using the EnergyPLAN model, focusing on direct reduction processes with hydrogen. While the entire industrial sector is considered, the analysis remains at a high level, using a top-down analysis approach. Additionally, the study's time horizon is limited to 2040, which may constrain its ability to provide a dynamic long-term perspective. Chisalita et al. [28] conducts a comprehensive cradle-to-gate environmental assessment for various ammonia production methods, including electrolytic hydrogen production. This assessment utilises data generated by specialised software, offering detailed insights into mass and energy balances, as well as thermodynamic properties. These data serve as inputs for the environmental analysis, streamlining the determination of parameters like CO_2 intensities for each process. Marzouk [29] analyses, based on the scenarios presented in the IRENA and IEA annual reports, how much green and blue hydrogen can be introduced into the global energy system (by sector, including industrial) to meet the goals of the Paris Agreement. The paper concludes that there is great potential for hydrogen in the industrial sectors; however, it also highlights significant uncertainties about its future presence. While it includes the industrial sector, the analysis does not provide in-depth exploration, and the range of scenarios analysed is somewhat limited. Contreras Fregoso et al. [30] uses a multi-regional model to analyse the potential of green hydrogen in the electricity sector and in the industry oil refining sector in Mexico, proposing a future scenario (specifying the percentage of hydrogen presence over the total share) to decarbonise these sectors. The research highlights the fact that, despite transport decarbonisation targets, the role of hydrogen in the refinery sector will continue to be important and its clean generation is therefore of interest. This study is the only one in the review to utilise recursive simulations (involving feedback loops and cumulative effects), which adds value to the analysis. However, it could benefit from a broader consideration of non-energy uses of hydrogen, and the model developed is not publicly available, which limits transparency. Mathiesen et al. [31] introduces IndustryPLAN, a tool for analysing climate change mitigation strategies in the European industry, focusing on hydrogen-based processes and technology applications. While the tool is open-acces, it is noteworthy that the tool lacks dynamic calculations, does not capture rebound dynamics or feedbacks, and does not offer insights into installed capacity requirements for hydrogen production or electricity generation technologies, nor does it assess the feasibility of implementation. It also assumes the use of green hydrogen produced from electricity, though it does not account for the indirect CO_2 emissions (i.e., those associated with the production of electricity). Lopez et al. [32] examines the energy system requirements of a defossilised global steel industry using the World Gross Domestic Product to estimate the steel demand. The paper specifies the associated hydrogen and electricity requirements, as well as the resulting CO_2 emissions. However, it does not consider a transition from conventional steam methane reforming hydrogen production to electrolysis, nor does it consider the process of direct reduction with natural gas to produce steel. Rechberger et al. [33] proposes a process-based model (evaluated at plant level) to analyse the feasibility of using direct reduction processes with natural gas and/or hydrogen to produce steel, calculating indicators of energy requirements (e.g., kWh demanded per ton of steel produced) and CO_2 emission intensities of the processes, and concluding the feasibility of both processes to achieve the objectives of the Paris Agreement. Trollip et al. [34] utilises the SATIM model to assess steel production capacities with hydrogen-based direct reduction, aiming to minimise costs associated with transitioning from traditional methods in South Africa by 2030. While the study offers valuable insights, the model's single-year time horizon limits its ability to capture dynamic long-term perspectives. Nurdiawati and Urban [35] undertakes a process analysis to examine the niche development of hydrogen production technologies to decarbonise the industrial oil refinery sector in Sweden. Egerer et al. [36] offers valuable insights into Germany's future industrial hydrogen demand by presenting static scenarios that assess hydrogen's role as both a feedstock and energy carrier, while also highlighting the potential for production relocation to regions with favourable renewable energy costs. However, the study could be further strengthened by incorporating hydrogen use in refineries (including oil refining and biodiesel treatment), adopting a dynamic analysis, and expanding the range of scenarios analysed. Manuel [37] uses an integrated energy system analysis optimisation model (IESA-Opt) to analyse, on an hourly scale, the feasibility of decarbonisation in the Netherlands in the industrial sector (including high-value chemicals, hydrocarbons, ammonia and steel production) using hydrogen-based technologies, among others. The study concludes that it is feasible for the energy system to incorporate hydrogen-based industries to achieve decarbonisation. However, the model is applied to a single year (2050) and analyses only one scenario, which may limit the assessment of long-term dynamics and potential variations. Plazas-Niño et al. [38] have modelled the hydrogen supply chain and demand using the OSeMOSYS model, applying it to Colombia, and have suggested an update to the National Hydrogen Roadmap to make its deployment more ambitious. Although they present a wide range of hydrogen scenarios, they do not delve into measures related to hydrogen's use as a feedstock, which is only briefly mentioned in the baseline scenario. Although feedstock applications are included in the model, they receive limited attention, with the focus primarily on the transport sector and, within the industrial sector, on hydrogen's use for heat production. Oshiro et al. [39] have developed a detailed energy system model that considers various technologies, including the conversion and use of hydrogen-based energy carriers. They conclude that such fuels could play a role in reducing residual CO_2 emissions by 5 to 10 % in mitigation scenarios. However, the study focuses solely on hydrogen's use as a feedstock in the steel sector and conducts a static evaluation for the year 2050. The study could be enhanced by considering other hard-to-abate sectors where hydrogen plays a key role, such as chemicals or refineries. Wiese et al. [40] present a scenario at the European level based on sufficiency, renewables and industrial relocalisation, achieving 100 % RES by 2050, with very limited need for imports. Hydrogen is considered for non-energy uses including ammonia, oil and biodiesel refining, steel manufacturing and methanol synthesis for olefins and aromatics. Total demand for these uses reaches 413.9 TWh (385 TWh for the EU).

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apenergy.2025.126325.

Data availability

Data will be made available on request. The hydrogen energy model is available via Zenodo at https://doi.org/10.5281/zenodo.15511227 (Ref. [79]).

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