



Inherent safety assessment of the blue hydrogen value chain

Federica Tamburini , Alessandro Tugnoli, Valerio Cozzani ^{*} 

LISES – Laboratory of Industrial Safety and Environmental Sustainability, Department of Civil, Chemical, Environmental, and Materials Engineering, University of Bologna, Via Terracini n.28, 40131, Bologna, Italy

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ABSTRACT

Ensuring safety across the blue hydrogen value chain is essential in the short term decarbonization perspective. A novel consequence-based methodology is developed to quantitatively assess inherent safety across entire value chains since early design. The methodology has the unprecedented capability of identifying the safety-critical components and of accounting for interdependencies. The application to the blue hydrogen value chain identified hydrogen production as the most hazardous fixed asset, CO₂ pipelines as the more hazardous transport systems, and liquefied hydrogen accidents as those having the wider potential impact area, even if their likelihood is 50% lower than that of accidents involving compressed gaseous hydrogen. The approach, providing sound-consequence based hazard indexes, closes gaps in conventional inherent safety assessment often based on semi-quantitative metrics, and support the safe deployment of blue hydrogen technologies providing a clear overview of the safety critical components of the blue hydrogen value chain.

1. Introduction

Nowadays, the significant increase in carbon dioxide (CO₂) emissions has become a primary international concern [1,2]. Several strategic initiatives are being implemented worldwide for the decarbonization of processes and commodities [3,4], which involve transitioning away from fossil fuels toward cleaner energy sources and sustainable practices, aiming at the reduction of greenhouse gas emissions and at the mitigation of climate change [5]. In this framework, the development and utilization of hydrogen (H₂) as a clean or low-carbon energy carrier is gaining momentum [6–8]. Depending on the feedstock and production process, a broad spectrum of hydrogen types is available [9]. Among these options, blue hydrogen positions itself as a key transitional solution, playing a crucial bridging role in the pathway toward a sustainable energy future [10]. Blue hydrogen is generated from natural gas (NG) using steam methane reforming (SMR), with Carbon Capture and Storage (CCS) employed to mitigate the release of CO₂ into the atmosphere [11–14]. CCS consists of capturing carbon emissions from flue gases, transporting them, and storing them underground in deep geological formations to prevent their release into the atmosphere [15, 16]. While CCS alone offers a short-term solution for reducing carbon emissions from fossil fuel-based industries, blue hydrogen enhances its effectiveness by providing a cleaner alternative to traditional grey hydrogen [17]. The well-established and consolidated nature of grey

hydrogen provides a solid foundation for developing blue hydrogen, allowing CCS to be integrated as an add-on without the need to build an entirely new production infrastructure. Blue hydrogen also complements green hydrogen, which is produced through renewable energy-powered electrolysis of water [12], by offering a more immediate and scalable solution to decarbonize sectors heavily reliant on hydrocarbons. Given the current dependency on fossil fuels and the time required for the widespread adoption of renewable energy, blue hydrogen can serve as a pragmatic intermediary, allowing for significant emission reductions while paving the way for the long-term transition to green hydrogen and a truly carbon-neutral energy system [18].

The blue hydrogen value chain encompasses the entire production process of hydrogen from NG, including the extraction or sourcing of NG, its conversion to H₂ through processes like the SMR, the capture and storage of CO₂ emissions produced during hydrogen production, and finally, the distribution and utilization of H₂ as a low-carbon energy carrier [19,20]. Due to the inherent hazards of hydrogen, it is crucial to address safety and manage risks across every step of the value chain from the earliest design phases, both to enable safe industrial deployment and to improve societal acceptance of this emerging technology [21]. This highlights the importance of consistently applying inherent safety principles throughout the entire blue hydrogen value chain.

Inherent safety emphasizes the management of risk by the elimination or reduction of hazards since the design phase, rather than relying

^{*} Corresponding author.

E-mail address: valerio.cozzani@unibo.it (V. Cozzani).

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on protective measures or controls [22]. Assessment methods for inherent safety involve the systematic identification and quantification of hazards, enabling the comparison of design alternatives with respect to their inherent risk footprint. The inherent safety screening of the hydrogen value chain is thus crucial, given the unique hazards associated with hydrogen, such as high flammability and explosivity risks [23], to identify and prioritize the most critical systems and units, where the adoption of appropriate safe design criteria is required to mitigate and control the risk.

A broad range of inherent safety assessment approaches has been developed in the literature, some of which are potentially applicable to entire industrial value chains [24]. These indicators are commonly grouped into four categories. Parameter-based indicators, such as the Prototype Index of Inherent Safety (PIIS) [25] and the Inherent Safety Index (ISI) [26], quantify inherent safety through scoring of material, process, and equipment attributes, including toxicity, flammability, and operating conditions. Consequence-based indicators, including the Hazard Identification and Ranking – Fire and Explosion Damage Index (HIRA-FEDI) [27], the Integrated Inherent Safety Index (I2SI) [28], and the Inherent Safety Key Performance Indicator (IS-KPI) [22], evaluate the severity of potential outcomes from fires, explosions, or toxic releases. Risk-based indicators, such as the Risk-Based Inherent Safety Index (RISI) [29] and the Anticipated Inherent Risk Index (AIRI) [30], combine consequence and probability to provide a probabilistic assessment of inherent safety. Finally, safety-environment indicators, including the Inherent Benign-ness Indicator (IBI) [31] and the Inherent Chemical Process Route Index (ICPRI) [32], extend the assessment to consider environmental and health impacts alongside safety.

A closer look at these methods highlights key limitations. Many indicators listed in Table 1 remain qualitative or semi-quantitative, limiting the accuracy of hazard assessment. Few methods are designed for ex-ante application, i.e., for evaluation during the early design stage when decisions can effectively reduce risk. Effective applications across entire value chains are scarce, and comprehensive analyses of full hydrogen pathways, including blue hydrogen, are almost entirely absent [33–37]. Existing studies on hydrogen technologies tend to focus on specific segments or components of the value chain, such as hydrogen

storage or production units [33–36], or consider only partial chains (e.g., from hydrogen production to end-user utilization [37]). In addition, VOSviewer software [38] was used to visualize the co-occurrence of indexed keywords, overlaid with the average publication year of the documents retained in the bibliometric analysis reported in Table 1, offering insights into the temporal evolution of research themes. The resulting map is provided in the Supplementary Material in Fig. A1, showing interconnected clusters centered on inherent safety, process design, and risk assessment, with a temporal gradient indicating growing attention from 2010 to 2020. Taken together, these findings highlight the lack of comprehensive evaluations that account for interdependencies, potential hazard propagation, and systemic risks along the entire value chain. These gaps underscore the need for a quantitative, consequence-based framework capable of assessing inherent safety along all stages of the value chain, capturing potential hazard propagation and systemic risks.

Aiming to fill this gap, the present study proposes a novel, systematic, quantitative, consequence-based methodology to assess the inherent safety of blue hydrogen value chains. The methodology is designed for ex-ante application during the early conceptual design stage, enabling proactive identification and mitigation of potential hazards before key design choices are fixed. The elementary components of the value chain are first identified, focusing on the core technologies, and their inherent safety performance is assessed. The analysis is then extended to encompass the entire value chain, capturing interdependencies between units. The detailed assessment of results obtained from the analysis of alternative value chains embodying different technological options is used to highlight the systematic and versatile nature of the approach. The methodology also supports modular integration with environmental assessment, facilitating a multi-dimensional evaluation of safety and sustainability trade-offs where relevant. Overall, it provides a systematic, quantitative, and holistic tool to support safer and informed decision-making in emerging industrial technologies, including complex hydrogen pathways.

The structure of the paper is the following. In Section 2, a brief overview of the blue hydrogen value chain is provided. Section 3 presents the innovative methodology developed to quantitatively assess the inherent safety of entire value chains through the evaluation of key hazard indexes. Section 4 describes the alternative blue hydrogen value chains considered as the case study. The results of the application of the methodology to the case study, including the inherent safety indexes of both individual value chain components and the overall value chains, are presented and discussed in Section 5. Concluding remarks are outlined in Section 6.

2. Overview of the blue hydrogen value chain

Blue hydrogen is a promising short to medium-term decarbonization option characterized by the implementation of CCS in hydrogen production processes from fossil fuels [10]. Its value chain spans from the mining of raw materials to the final delivery and utilization of hydrogen as a low-carbon energy carrier [40], thus involving multiple interconnected stages with distinct environmental and safety implications. It can be produced from several non-renewable feedstocks, including natural gas, brown coal, and black coal, as shown in Fig. 1 [20].

Natural gas, mostly composed by methane (CH₄), is currently the primary feedstock considered for blue hydrogen production, due to its widespread availability [41]. Brown coal (lignite) and black coal (bituminous coal) represent alternative feedstock options, although they differ in terms of environmental impact [42]. The production of hydrogen from such raw materials typically involves processes as SMR, autothermal reforming (ATR), or gasification, depending on the feedstock utilized (see Fig. 1) [9]. When NG is used as a feedstock, SMR is normally selected as the conversion process [30]. Fig. 2 provides an overall schematization of the blue hydrogen value chain [40].

All the aforementioned fossil-based hydrogen production processes

Table 1

Representative sample of inherent safety approaches reported in the literature for application along the value chain.

Inherent safety indicator	Acronym	Category	Approach	Reference
Prototype Index of Inherent Safety	PIIS	Parameter-based	Qualitative/ Semi-quantitative	[25]
Hazard Identification and Ranking – Fire and Explosion Damage Index	HIRA-FEDI	Consequence-based	Qualitative/ Semi-quantitative	[27]
Inherent Safety Index	ISI	Parameter-based	Qualitative/ Semi-quantitative	[26]
Integrated Inherent Safety Index	I2SI	Consequence-based	Quantitative	[28]
Inherent Safety Key Performance Indicator	IS-KPI	Consequence-based	Quantitative	[22]
Inherent Benign-ness Indicator	IBI	Safety-environment	Quantitative	[31]
Inherent Chemical Process Route Index	ICPRI	Safety-environment	Quantitative	[32]
Risk-Based Inherent Safety Index	RISI	Risk-based	Quantitative	[29]
Anticipated Inherent Risk Index	AIRI	Risk-based	Quantitative	[30]
Stream Safety Index	SSI	Risk-based	Quantitative	[39]

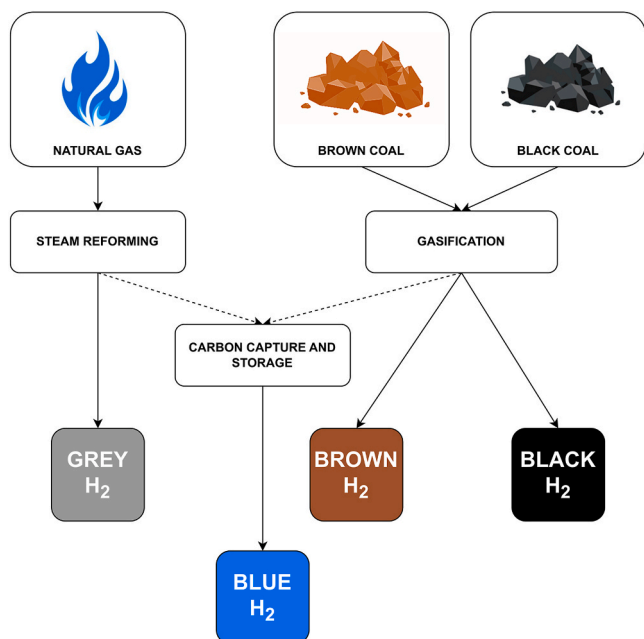


Fig. 1. Types of hydrogen colors based on feedstocks and production processes (adapted from Refs. [9,20]). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

generate CO₂ as a by-product. When considering blue hydrogen production, CCS methods may be applied to mitigate the environmental impact. Post-combustion capture processes stand out as the preferable choice for reducing CO₂ emissions from hydrogen production owing to their relative maturity, ability to be retrofitted to existing plants, and broad applicability [43]. Examples include chemical or physical absorption, adsorption, calcium looping, and cryogenic distillation [44]. However, other CO₂ capture methods, such as pre-combustion or oxy-fuel combustion processes, can also be considered [14].

Once captured, CO₂ is conditioned and transported via pipeline, ship, rail or road tanker, or by a combination of these systems, to a suitable underground storage site, where it can be securely stored preventing its release to the atmosphere [14,45]. Alternatively, Carbon Capture and Utilization (CCU) technologies offer the potential to convert captured CO₂ into valuable products, further enhancing the sustainability of the blue hydrogen value chain [46].

The produced H₂ can be stored and delivered to end-users in different forms, including liquid hydrogen (LH₂), compressed gaseous hydrogen (CGH₂), and other solutions [37]. In the case of LH₂, H₂ is liquefied at extremely low temperatures (−253 °C) for transportation and storage [47]. Specific vacuum-insulated cryogenic tanks and transport vessels are used to maintain the low temperatures required for storage and transportation [48]. Upon deliver to the final user, LH₂ is converted back to its gaseous state through vaporization [37]. In the case of CGH₂ supply chain, instead, H₂ is compressed to high pressures (up to 700 bar) for storage and transportation [34]. CGH₂ is then transported to end-users via pipeline, tank trailer, compressed gas cylinders or combinations of the above. At the point of use, the CGH₂ is depressurized to match the operating pressure of the end-use system.

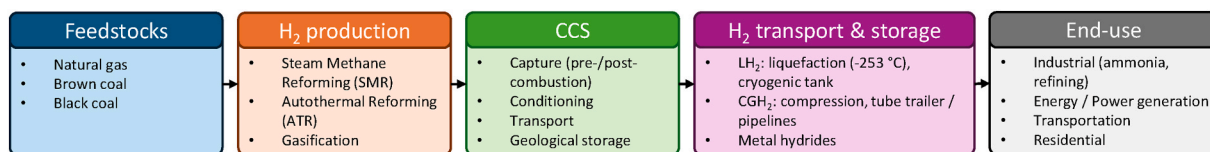


Fig. 2. Blue Hydrogen value chain scheme [40]. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Currently, CGH₂ and LH₂ transport and storage are the most mature and currently the most widely used technologies for H₂ transport and storage. An overview of alternative technologies for hydrogen transportation, which generally have lower technology readiness levels (TRLs), is provided by Ref. [49]. Among these, metal hydrides [50] is perhaps the alternative technology with the highest TRL. Metal hydrides are compounds formed between metals and hydrogen, in which the metal acts as a storage medium for the hydrogen [51]. In this process, H₂ is absorbed into the metal lattice at relatively low pressures and temperatures and released when needed through heating or depressurization. Metal hydrides offer advantages such as high storage densities and relatively low operating pressures. However, challenges such as slow kinetics and limited reversibility of some metal hydride systems still need to be addressed for their widespread adoption [52].

Beyond technological aspects, safety issues across the blue hydrogen value chain deserve consideration. Although no incidents have been specifically documented for fully integrated blue hydrogen plants, individual components of the value chain have experienced safety-related events. In particular, both grey hydrogen production facilities and CCS infrastructures have been associated to documented accidents, including leaks, fires, explosions, and equipment failures such as valve or flange malfunctions [53,54]. Historical incidents in hydrogen production and handling illustrate these hazards: for example, a pipe rupture during SMR start-up in 1996 highlighted the risks associated with high-temperature and high-pressure gas systems, and multiple incidents involving hydrogen refueling stations and distribution infrastructure have been linked to equipment failures such as flange leaks, valves, and weld joint defects [55].

Different segments of the blue hydrogen value chain present specific hazards: CO₂ pipelines carry risks of rupture, leaks, and uncontrolled releases [45], LH₂ handling involves cryogenic hazards and flammability concerns, and CGH₂ storage and transport introduce high-pressure containment and embrittlement challenges [23]. Analyses of HIAD 2.1 incident database [55] reveal that a significant portion of hydrogen-related accidents involve fires and explosions, often triggered by human or design errors, with a notable share occurring in distribution (40%) and storage (24%) segments of the infrastructure. Material challenges such as hydrogen embrittlement and high-pressure containment further complicate the safety landscape, particularly in long pipelines and storage systems where loss of integrity can lead to rapid releases and elevated hazard scenarios. These real-world examples and mechanistic failure modes demonstrate that inherent hazards are not limited to isolated units but may propagate across multiple stages of the value chain, motivating the need for comprehensive, value chain-level safety assessment.

3. Methodology

An innovative methodology for the quantitative assessment of the inherent safety of a value chain has been developed in the present study. It is based on a consequence-driven inherent safety metric, specifically conceived to provide a quantitative assessment of the inherent safety performance of entire value chains. The assessment of inherent hazard indexes enables the comparison among alternative value chains and the identification of the most vulnerable system components and/or equipment items, highlighting specific stages of the value chain that

show criticalities and/or require more detailed evaluation within the framework of risk assessment and management.

Fig. 3 shows the flowchart of the methodology, which is structured into four main steps, each including several sub-steps. Its cyclical approach promotes continuous improvement and modification throughout the process. The feedback loops, linking the various steps of the methodology, reflect the iterative nature of the assessment, ensuring that new data and potential system modifications are included as the analysis progresses. In the following sections, the metric and the single methodological steps required for the calculation of the inherent hazard indexes are discussed.

3.1. Step 1: Preliminary phase

This preliminary phase (Step 1 in Fig. 3) consists of three sub-steps (1.1 to 1.3), which are intended to set the system boundaries and to collect the required information concerning the selected reference value chain and its constituents.

The starting point of the methodology (Step 1.1 in Fig. 3) involves the identification and the selection of the reference value chain (RVC) of interest. Defining the value chain also entails determining the system boundaries, i.e., deciding which processes are included in the system. This step ensures that the selected value chain aligns with the strategic objectives of the analysis.

In Step 1.2 (see Fig. 3), the selected RVC is broken down into single elementary components (ECs), each representing a section of the value chain performing a specific function (e.g., production, large-scale storage, transport, etc.). Relevant data are then collected to define the different ECs. Since each EC may consist of one or more equipment items (EIs), including process equipment (e.g., columns, heat exchangers, reactors), storage units (storage tanks, process buffers), or transport systems (e.g., pipelines), it is crucial to gather detailed information on the

system layout, such as simplified process flow diagrams (PFDs) or similar technical schemes, and equipment items, their functional activities, operational parameters (i.e., pressure and temperature), substances involved (including their thermodynamic and dangerous properties), and any pertinent historical data (if available). The EIs composing each EC are thus identified. This breakdown allows for a thorough assessment of the potential hazards associated with specific operations and provides the context for the following steps of the methodology. For clarity, Fig. A2 in the Supplementary Material displays an example of a conceptual scheme of a RVC.

In Step 1.3 (see Fig. 3), the relevant EIs having a major accident hazard inherent potential are identified. The MIMAH (Methodology for the Identification of Major Accident Hazards) procedure [56] or the TNO Purple Book [57] may be used for this purpose. For instance, MIMAH provides a classification of the hazardous substances involved in the process [58], assigning each EI to one of 16 predefined hazard classes that reflect the type and severity of the inherent hazard (see Table A1 in the Supplementary Material). An indexing method is then applied to determine which EIs are relevant by comparing the inventory (mass) of hazardous material contained in the EI to specific threshold quantities. If the amount exceeds the threshold, the EI is flagged. This systematic approach ensures that only EIs with a significant potential to cause major accidents are retained in the analysis.

3.2. Step 2: Critical event assessment

This second step of the methodology (Step 2 in Fig. 3) includes two sub-steps (2.1 and 2.2), involving the identification and characterization of critical events leading to end-point scenarios and to the assignment of credit factors.

More in detail, Step 2.1 (see Fig. 3) consists of the identification of critical events (CEs), defined as losses of containment of materials and/or energy from process equipment and pipework, potentially affecting each EI. In order to identify the CEs, the MIMAH procedure [56] may be used, providing a list of 12 potential critical event categories, which are detailed in Table A2 in the Supplementary Material. These can be associated to the EIs following a specific procedure based on two matrices. The first matrix intersects the EI classes (as referenced in Step 1.3 and in Table A1 in the Supplementary Material) with the 12 potential critical event categories (see Table A2 in the Supplementary Material), while the second matrix correlates the potential CEs to the physical state of the substance (see Step 1.2).

The characterization of the CEs is based on the definition of reference release modes (RRMs), which assume specific factors for the release geometry, duration, entity, and conditions. Each CE is linked to at least one RRM, derived from the analysis of literature data [57,59–63]. Examples of these RRMs are provided in Table 2 [59,61,63]. A complete list of RRMs associated with each CE is reported by Delvosalle et al. [61].

In Step 2.2 (see Fig. 3), a credit factor is assigned to each RRM to evaluate its inherent proneness to cause releases. Credit factors are derived from baseline data available for the failure frequencies of standard components [57,61–66], when no historical data is available. The credibility of a given CE varies across different EIs due to the inherent characteristics of their design and operational modes (e.g., due to the presence of rotating parts, network complexity, etc.) [59,67]. In case of non-standard technologies, approaches such as the Failure Mode and Effect Analysis (FMEA) [68] or the Fault Tree Analysis (FTA) [69] may be applied to obtain the credit factors.

Calculating the credit factors for transport and transfer units needs additional specifications. In particular, in the case of pipelines, credit factors are obtained multiplying the length of the pipeline by the baseline value of the failure frequency per unit length, λ_{km} , obtained from literature data [63]. In the case of rail, road, and ship/barge tankers, the length of a single voyage, L_v (km/voyage), and the total number of voyages per year, ν (voyage/year), are used to obtain the credit factor λ_y (1/year), as follows [64]:

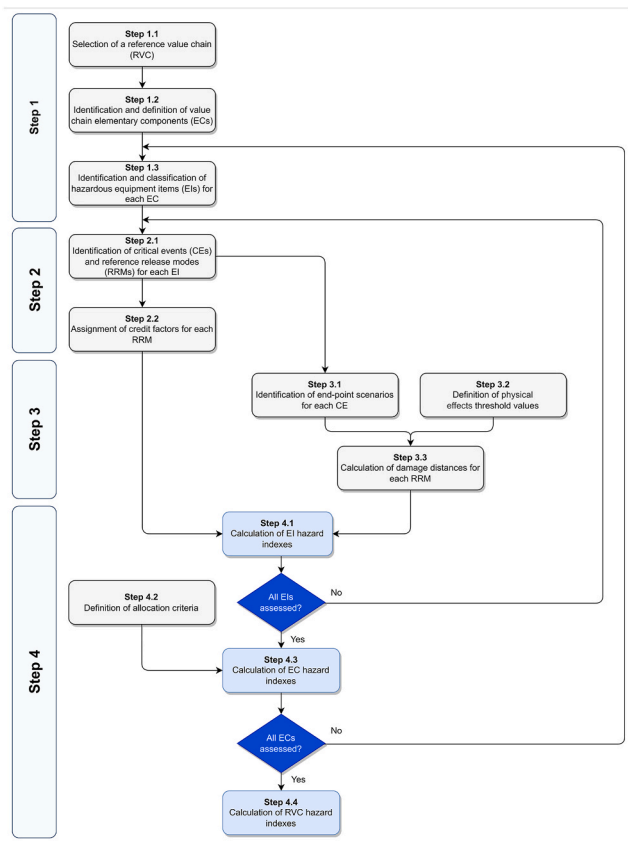


Fig. 3. Flowchart of the methodology developed in the present study.

Table 2

Sample list of reference release modes (RRMs) associated with critical events (CEs) for process equipment (i.e., pumps, compressors, pressure vessels, heat exchangers) and pipelines considered in the case study (adapted from Refs. [59, 61,63]).

Critical event	RRM description
<i>Process equipment</i>	
CE8-CE9 CE7-CE10	RRM_1: Small pipe leak, continuous release from a hose having 10% of pipe diameter
	RRM_2: Medium pipe leak, continuous release from a hose having 22% of pipe diameter
	RRM_3: Pipe rupture, continuous release from the full-bore pipe
	RRM_4: Small leak, continuous release from a 10 mm equivalent diameter hole
	RRM_5: Medium leak, continuous release from a 35 mm equivalent diameter hole
	RRM_6: Large leak, continuous release from a 100 mm equivalent diameter hole
	RRM_7: Catastrophic rupture, release of the entire inventory in 600 s at constant rate
	RRM_8: Catastrophic rupture, instantaneous release of the entire inventory
<i>Pipelines</i>	
CE8-CE9	RRM_9: Small pipeline leak, continuous release from a 10 mm diameter hole
	RRM_10: Medium pipeline leak, continuous release from a 50 mm diameter hole
	RRM_11: Large pipeline leak, continuous release from a 100 mm diameter hole
	RRM_12: Pipeline rupture, continuous release from both sides of the full-bore conduit

$$\lambda_y = \lambda_{km} \cdot L_v \cdot v \tag{1}$$

Examples of credit factors assessed in the case study analyzed in the present study are provided in Table 3. These values were retrieved from baseline failure frequency datasets and past accident analyses [63,70].

3.3. Step 3: Consequence analysis

The third step of the methodology (Step 3 in Fig. 3) involves three sub-steps (3.1 to 3.3), addressing the analysis of the consequences of the CEs.

First, in Step 3.1 (see Fig. 3) the end-point (accident) scenarios (*j*) are

Table 3

Credit factors related to the reference release modes (RRMs) of interest for process equipment (y^{-1}) and pipelines ($km^{-1}y^{-1}$) (n.a., not applicable; n.c., not considered) [63,70].

RRM	Credit factor			
	Pump	Compressor	Pressure vessel	Heat exchanger
<i>Process equipment</i>				
RRM_1	5.0×10^{-4}	1.0×10^{-3}	1.8×10^{-6}	1.8×10^{-6}
RRM_2	4.5×10^{-4}	8.8×10^{-4}	6.5×10^{-7}	6.5×10^{-7}
RRM_3	1.0×10^{-4}	1.0×10^{-4}	1.2×10^{-7}	1.2×10^{-7}
RRM_4	n.a.	n.c.	5.0×10^{-4}	n.c.
RRM_5	n.a.	n.c.	5.0×10^{-5}	n.c.
RRM_6	n.a.	n.c.	5.0×10^{-6}	n.c.
RRM_7	n.a.	n.c.	5.0×10^{-6}	n.c.
RRM_8	n.c.	5.0×10^{-6}	5.0×10^{-6}	5.0×10^{-6}
<i>Pipelines</i>	CO ₂ on-land pipeline ^a	CO ₂ sealine ^a	CH ₄ on-land pipeline ^b	CH ₄ sealine ^b
RRM_9	2.8×10^{-4}	7.2×10^{-3}	9.1×10^{-5}	3.5×10^{-3}
RRM_10	4.0×10^{-5}	8.5×10^{-4}	2.0×10^{-5}	4.1×10^{-4}
RRM_11	1.4×10^{-5}	1.7×10^{-4}	6.5×10^{-6}	8.2×10^{-5}
RRM_12	2.6×10^{-5}	2.6×10^{-4}	1.3×10^{-5}	1.2×10^{-4}

^a pipeline diameter: 8 in.
^b pipeline diameter: 14 in.

identified for each RRM associated to the EIs through the adoption of case-specific or baseline post-release event trees. Generally, two factors are considered when building the event trees: the type of equipment item and the pre- and post-release physical state of the hazardous substance. The MIMAH procedure [59] and the TNO Purple Book [57] provide a comprehensive set of baseline event trees. However, methods described in Refs. [57,59,67] can be used to obtain case-specific event trees.

It is then necessary to define threshold values of physical effects for damage to humans in the different scenarios (Step 3.2 in Fig. 3). Threshold values derived from technical standards can be considered, as those reported in Table A3 in the Supplementary Material [22].

In Step 3.3 (see Fig. 3), the threshold values are used to calculate the damage distance for each end-point scenario identified in Step 3.1. The damage distance is defined as the maximum distance from the release location at which the physical effect of the considered scenario equals the specific threshold value. Models for consequence analysis [67,70, 71], alongside software tools such as PHAST [72], EFFECTS [73], OLGA [74], TAMOC [75], and ALOHA [76], can be adopted for this estimation. The possible occurrence of escalation scenarios [77] is not considered in the calculation of the reference damage distances.

3.4. Step 4: Assessment of hazard indexes

Once the severity of the impacts of the end-point scenarios has been assessed, in the fourth step of the methodology the hazard indexes are calculated (Step 4 in Fig. 3) by four sequential sub-steps (4.1 to 4.4).

In Step 4.1 (see Fig. 3), the hazard indexes proposed by Crivellari et al. [33] are calculated for each EI:

$$EPI_{e,k} = \sigma \cdot \pi \cdot \left(\max_i \left(\max_j \left(\max(d_{j,i,e,k}, c) \right) \right) \right)^2 \tag{2}$$

$$EHI_{e,k} = \sigma \cdot \pi \cdot \sum_{i=1}^{n_{e,k}} \lambda_{i,e} \cdot \left(\max_j \left(\max(d_{j,i,e,k}, c) \right) \right)^2 \tag{3}$$

where the $EPI_{e,k}$ (m^2) and $EHI_{e,k}$ (m^2/y) indexes are respectively the potential and inherent hazard indexes of the e^{th} EI in the k^{th} EC. In these equations, $d_{j,i,e,k}$ represents the expected damage distance calculated for the j^{th} end-point scenario of the i^{th} RRM affecting the e^{th} EI in the k^{th} EC. The constant c (set at 5 m) defines a “near field” zone, delimiting the area in which integral consequence models are deemed as unreliable [22]. The term $\lambda_{i,e}$ indicates the credit factor for the i^{th} RRM affecting the e^{th} EI, and $n_{e,k}$ represents the number of RRMs considered for the e^{th} EI in the k^{th} EC. In Eq. (3), σ is a corrective factor that is equal to 1 for all EIs except for road, rail, and ship/barge tankers. In the latter case, σ accounts for the number of tanker trips (n) required to transport the production capacity of the upstream EC, as well as the trip duration:

$$\sigma = n \cdot \frac{\tau_v}{\tau_y} \tag{4}$$

where τ_v is the time of a trip (h) and τ_y is the number of hours in a year (8766 h).

Eq. (2) and Eq. (3) provide respectively the maximum impact area ($EPI_{e,k}$) that may arise from the worst-case scenario considered for each EI, and the maximum credible impact ($EHI_{e,k}$) considering all alternative end-point scenarios associated with the EI of interest. An iterative approach must be adopted to ensure that all the EIs within a specific EC of the value chain are systematically assessed.

In Step 4.2 (see Fig. 3), an allocation criterion is applied. The purpose of this step is to determine the appropriate number of equipment items required for each elementary component so that a coherent and functional value chain is established. Each EC corresponds to a key technology in the chain and is characterized by a specific size, which, depending on the technology involved, can be expressed as a

potentiality (kg/h), as a storage mass (kg), or as the number of transport units (-). Since each technology has inherent limitations in terms of size, a single item may not be sufficient to guarantee the required performance of the overall value chain. The allocation process therefore ensures that the value chain is properly dimensioned by calculating a scaling factor (S_k), which expresses how many units of each EC are necessary to sustain the desired output.

An example of allocation criteria applied in the case study discussed in Section 4 is a linear approach based on a reference conversion yield, which represents the amount of final product to which the indexes are related. To allocate resources coherently, the scaling factor is calculated accordingly and integrated into the final evaluation of the indicators (see Step 4.3), ensuring that the potentiality of the system is consistently and accurately reflected throughout the analysis. This linear approach is adopted to enable transparent and consistent aggregation of hazard contributions at an early design stage and to support robust comparison between alternative value chain configurations, while acknowledging that more refined or non-linear allocation schemes may be needed in later design phases as detailed, site-specific data become available.

In Step 4.3 (see Fig. 3), the hazard indexes associated with each EC of the value chain are calculated. Specifically, the elementary component potential index, CPI_k (m^2), and the inherent component hazard index referred to the k^{th} EC of a single chain, CHI_k (m^2/y), can be derived as follows:

$$CPI_k = S_k \cdot \sum_{e=1}^{N_k} EPI_{e,k} \quad (5)$$

$$CHI_k = S_k \cdot \sum_{e=1}^{N_k} EHI_{e,k} \quad (6)$$

where N_k represents the number of EIs involved in the k^{th} EC, and S_k is the scaling factor in the k^{th} EC obtained from the allocation criterion (see Step 4.2).

Finally, in Step 4.4 (see Fig. 3), the overall potential and inherent hazard indexes of the value chain, namely VPI (m^2) and VHI (m^2/y), are calculated as follows:

$$VPI = \sum_{k=1}^M CPI_k \quad (7)$$

$$VHI = \sum_{k=1}^M CHI_k \quad (8)$$

with M representing the number of ECs within the value chain.

4. Case study

The novel methodology was applied to evaluate the two alternative reference value chains illustrated in Fig. 4, representing distinct production and distribution configurations for blue hydrogen based on LH_2 (see Fig. 4-a) and CGH_2 (see Fig. 4-b)). Both value chains cover all stages, from raw material extraction to the final delivery and end use of hydrogen as a low-carbon energy carrier. The configuration and main components of each value chain were defined according to data available in the literature [78–80].

Four distinct macro-areas in the value chains were identified and represented using different colors (see Fig. 4).

- *NG production*, colored in green and tagged with the number 1, includes NG upstream production and transport;

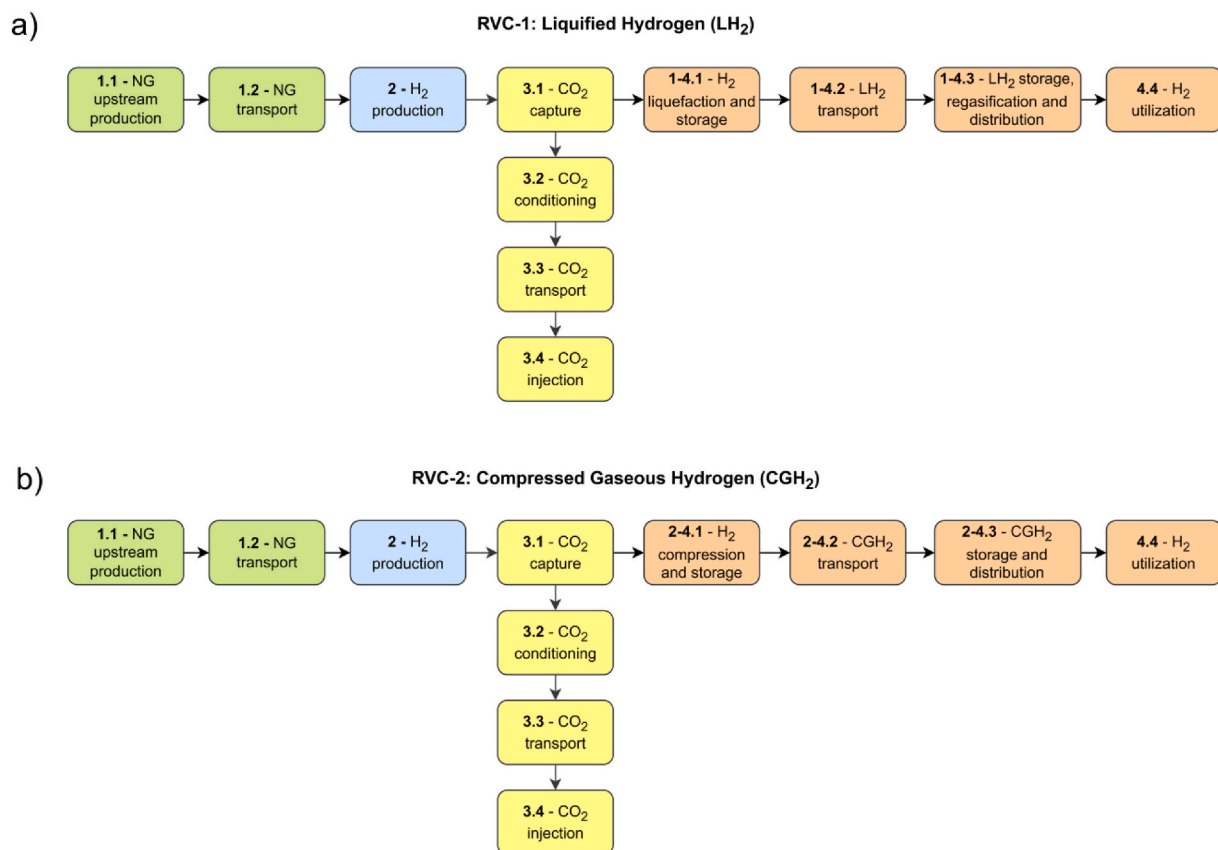


Fig. 4. Reference schemes of the blue hydrogen value chains considered in the case study: a) RVC-1: liquefied hydrogen (LH_2) transportation and distribution; b) RVC-2: compressed gaseous hydrogen (CGH_2) transportation and distribution. The different elementary components are detailed in Table 4. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

- *H₂ production*, colored in blue and tagged with the number 2, involves the conversion of NG into H₂, resulting in the generation of CO₂ as a by-product;
- *CCS*, colored in yellow and tagged with the number 3, entails the capture of CO₂, its conditioning, transportation, and subsequent injection into underground storage sites;
- *H₂ storage and distribution*, colored in orange and tagged with the number 4, includes the liquefaction, storage, compression, regasification, transport, distribution, and utilization of H₂.

Table 4 reports a short description of each elementary component of the value chain, along with the corresponding tags, distinguishing between fixed assets and transport systems. For the sake of clarity, shared elementary components are labeled with a tag consisting of two numbers: the first indicates the macro area (1, 2, 3 or 4), and the second identifies the specific EC (e.g., 1.1). In case the EC coincides entirely with the macro area, only the first number is shown (e.g., 1). ECs that differ between the two value chains include an additional preliminary number that corresponds to the respective value chain (e.g., 1-4.1 and 2-4.1, etc.).

As illustrated in **Fig. 4**, the two value chains share the same macro areas for NG and H₂ production, and for CCS. In particular, all elementary components pertaining to upstream natural gas production and transportation, as well as those associated with carbon capture and storage and hydrogen utilization, are identical across both value chains. However, significant differences emerge in the downstream hydrogen processes. In value chain RVC-1, hydrogen undergoes liquefaction and is stored on-site as LH₂. As a result, the transportation and final distribution occur in the liquid phase, with regasification taking place at the final user during distribution. Differently, value chain RVC-2 transports and distributes hydrogen to the final user in the gaseous phase, after compression and on-site storage as CGH₂. Consequently, as shown in **Fig. 4** and **Table 4**, the two value chains differ significantly in only three elementary components (i.e., 4.1, 4.2, and 4.3) within the macro area named “H₂ storage and distribution”.

The assumed characteristics of the elementary components in the two value chains analyzed in this case study are summarized below. Additional details concerning system layouts, technical schemes, substances involved, operating conditions, and EIs are provided in the Supplementary Material. In order to model heat and mass balances throughout the whole process, as well as the transient CH₄ and CO₂ flows in pipelines and sealines, Aspen Plus [81], Multiflash [82], and OLGA [74] software tools were used. Aspen Plus [81] and Multiflash [82] were employed for process simulation and thermodynamic property evaluation, respectively, while OLGA [74] was used for transient multiphase flow modeling of the pipeline and sealine transport. For clarity, this case study is conducted as an ex-ante, early-stage, screening-level assessment focusing on inherent safety. Simplified

assumptions regarding system layouts, substances, and operating conditions are applied consistently to allow comparison of hazard profiles. A detailed quantitative risk assessment is beyond the scope of this study, as the necessary data are typically unavailable at early conceptual design stages. Such quantitative analyses are more appropriately applied ex-post, once the basic design of the selected option has been consolidated.

In both RVCs, natural gas serves as the feedstock for blue hydrogen production. The extraction process is expected to involve a subsea system linked to a top-side production separator and a test separator. For the purpose of this inherent safety and early-stage analysis, pure CH₄ was assumed for NG composition, with a production rate of 101 t/h. This assumption is consistent with common practice in preliminary hazard and risk screening studies, where CH₄, being the dominant constituent of commercial natural gas, largely governs dispersion and flammability behavior [83]. While minor fractions of heavier hydrocarbons and inert components may influence specific thermophysical properties, their effect on the order of magnitude of consequence distances is generally limited at this level of analysis and within the uncertainties associated with early design assumptions. Nevertheless, the adopted methodology is sufficiently general and may also be applied to more complex natural gas compositions, including higher molecular weight hydrocarbons, inert species, and hydrogen sulphide, should a more detailed compositional definition be required at later design stages.

A 67 km-long, 14-inch sealine, operating under adiabatic conditions was considered for the transport of NG to the onshore hydrogen production site. The pipeline extends from 70 m-deep extraction wells to the hydrogen production facility located 7 km inland, comprising a 60 km seabed-laid offshore and a 7 km buried onshore section. The buried onshore section is assumed to be installed at a depth of 1.5 m, while the offshore section is assumed to be stabilized on the seabed by a layer of gunite to ensure it remains securely laid. The operating pressure and temperature are assumed to be 80 bar and 45 °C, respectively. Detailed information on the features and on the lay-out assumed for the NG production system, adapted from that proposed by Crivellari et al. [33], is provided in **Figure C1** of the Supplementary Material.

The hydrogen production process is based on a steam methane reforming unit combined with a pressure swing adsorption (PSA) unit. A simplified PFD of this conventional hydrogen production process, adapted from Tugnoli et al. [35], is presented in **Figure C2** of the Supplementary Material.

To curb carbon emissions, CO₂ is assumed to be removed from the flue gases at the hydrogen production plant via an amine scrubbing-based capture process, designed according to the guidelines provided by Madeddu et al. [84]. This process achieves an 89.8% capture rate using monoethanolamine (MEA) as a solvent. The captured CO₂ undergoes purification and compression in a conditioning unit equipped with compressors, coolers, and separators. The resulting CO₂ achieves a

Table 4
Description of the elementary components of the value chains and classification into fixed assets and transport systems [37].

Elementary component		Type of industrial facility	
Tag	Description	Fixed asset	Transport system
1.1	NG upstream production	✓	
1.2	NG transport (pipeline)		✓
2	H ₂ production (SMR)	✓	
3.1	CO ₂ capture	✓	
3.2	CO ₂ conditioning	✓	
3.3	CO ₂ transport (pipeline)		✓
3.4	CO ₂ injection	✓	
1-4.1	H ₂ liquefaction and storage	✓	
2-4.1	H ₂ compression and storage	✓	
1-4.2	LH ₂ transport (cryogenic tanks)	✓	✓
2-4.2	CGH ₂ transport (tube trailers)		✓
1-4.3	LH ₂ storage, regasification and distribution	✓	
2-4.3	CGH ₂ storage and distribution	✓	
4.4	H ₂ utilization	✓	

purity of over 95% and a residual water content of 200 ppm, meeting ISO 27913 [85] pipeline transportation requirements. The dense-phase CO₂ stream, flowing at a rate of 198 t/h, is assumed to be transported via a 15 km-long, 8-inch pipeline to the final injection site, involving a 13 m-deep depleted oil and gas reservoir. The operating pressure and temperature of the CO₂ pipeline are assumed to be 120 bar and 40 °C, respectively. The transport process is considered adiabatic, with the pipeline divided into 8 km buried onshore and 7 km seabed-laid offshore sections. The buried onshore section is assumed to be installed at a depth of 1.5 m, while the offshore section is assumed to be stabilized on the seabed by a layer of gunite to ensure it remains securely laid. Injection is assumed to be performed by a platform wellhead equipped with risers and pump units. Further details on the processes of the CCS value chain are provided in Figure C3 (CO₂ capture and conditioning) and Figure C4 (CO₂ transport and injection) of the Supplementary Material. Geological storage of CO₂ is considered out of scope of the inherent safety assessment, since the risks span over a different time scale [14].

In RVC-1, hydrogen produced via SMR is assumed to be liquefied and stored in a large-scale facility with a maximum capacity of 27000 kg. LH₂ is then transported using single vacuum-jacketed cryogenic tanks, each with a maximum capacity of 3000 kg, to minimize the surface-to-volume ratio. Distribution occurs after vaporization and compression at the distribution site to meet the pressure requirements (250 bar) of the final user.

Differently, in RVC-2, hydrogen produced via SMR is assumed to be compressed to 400 bar and stored on-site in a large-scale facility with a maximum capacity of 27000 kg. CGH₂ is then transported using tube trailers, each carrying up to 320 kg (32 kg per vessel). For final distribution and end use, the pressure is reduced to 250 bar. Process flow diagrams for the hydrogen liquefaction, storage, compression, regasification, transport, and distribution processes, adapted from Landucci et al. [34,37], are provided in Figures C5-C8 of the Supplementary Material.

The substances involved in the RVCs are characterized by inherent hazardous properties. Specifically, CH₄, diethylene glycol (C₄H₁₀O₃), and H₂ are flammable [86–88], whereas methanol (CH₃OH) and MEA are both flammable and toxic [17,89]. CO₂, in contrast, is only mildly toxic [15]. As indicated in Table A3 in the Supplementary Material, the flash fire threshold, represented by the lower flammability limit (LFL), is 50000 ppm for CH₄ [90], 16000 ppm for C₄H₁₀O₃ [88], 40000 ppm for H₂ [90], 60000 ppm for CH₃OH [89], and 55000 ppm for MEA [91]. For toxic cloud scenarios, the immediately dangerous to life and health concentration (IDLH), which represents the maximum level of a hazardous substance to which workers can be exposed without suffering severe or life-threatening health effects for 30 min, is 6000 ppm for CH₃OH [30,92] ppm for MEA [92], and 40000 ppm for CO₂ [93].

In the case study, for the sake of simplicity the analysis focused only on human impacts. Thus, technical guidelines such as the MIRAS (Methodology for the Identification of Reference Accident Scenarios) procedure [59] and the TNO Purple Book [57] recommend identifying potential end-point scenarios based on the hazardous substance involved and its physical state after the release. The end-point scenarios listed in Table 5 were thus identified.

Furthermore, the conversion yield of the SMR process (approximately 880 kg/h) was selected as the allocation basis for the linear approach outlined in Step 4.2 of the methodology (see Fig. 3). This value represents the reference production potentiality for determining the scaling factors of the elementary components. Table 6 provides a detailed overview of the ECs, including the intrinsic capacity limits, the average annual transportation route length for vehicle-based systems, and the corresponding scaling factors calculated for each component. The latter ensures an accurate assessment and comparison of the results by reflecting the number of facilities and transport modes required to maintain a functional value chain. Clearly enough, hydrogen distribution parameters may vary according to specific situations such as, e.g., territory, road network, vehicle characteristics. In the current study,

Table 5

End-point scenarios considered in the case study as a function of the substance involved and its post-release physical state (i.e., gas (G), liquid (L), solid-gas (S-G), and liquid-gas (L-G)) [67].

End-point scenario	CH ₄		H ₂		MEA	CO ₂		C ₄ H ₁₀ O ₃	CH ₃ OH
	G	L	G	L-G	L	G	S-G	L	L
Toxic Cloud (TC)					✓	✓	✓		✓
Flash Fire (FF)	✓		✓		✓			✓	✓
Fireball (FB)				✓					
Jet Fire (JF)	✓		✓						
Pool Fire (PF)				✓	✓			✓	✓
Vapor Cloud	✓		✓		✓			✓	✓
Explosion (VCE)									
Physical Explosion (PE)	✓		✓		✓	✓			

Table 6

Features of the elementary components (ECs) of the value chains: size (i.e., potentiality (kg/h), mass (kg), or number of transport units (–)), average annual route length of tankers (km), and scaling factor (S).

EC tag ^a	Size	Distance (km) ^b	S
1.1	1.0 × 10 ⁵ kg/h	-	0.30
1.2	1.0 × 10 ⁵ kg/h	-	0.05
2	880 kg/h	-	1
3.1	2.0 × 10 ⁵ kg/h	-	0.05
3.2	2.0 × 10 ⁵ kg/h	-	0.05
3.3	2.0 × 10 ⁵ kg/h	-	0.05
3.4	2.0 × 10 ⁵ kg/h	-	0.05
1-4.1, 2-4.1	27000 kg	50000	1
1-4.2	3000	-	9
1-4.3	320	-	84
1-4.3, 2-4.3	500 kg	-	80
4.4	5 kg	10000	65170

^a see Table 4.

^b Only for transport units.

these parameters were adapted from those of gasoline delivery and utilization for a representative European scenario [94]. Details concerning the determination of the single scaling factors are provided in the Supplementary Material.

The effects of the end-point scenarios identified in Table 5 were simulated using consequence modelling software. The selection of the most appropriate software depends on whether the release occurs subsea or to the atmosphere. Specifically, in the present study, OLGA [74] and TAMOC [75] software were applied to model the dispersion of hazardous substances in the water column. OLGA, a dynamic multiphase flow simulator, was used to model the source term, while TAMOC, a specialized modeling package designed for steady-state underwater single- and multi-phase spill scenarios, was applied to model the seawater dispersion [15]. Additionally, the PHAST software [72] was used to simulate atmospheric releases and sealine accident scenarios, in particular in cases where the released plume reached the sea surface and atmospheric dispersion became significant, as observed in shallow-water releases [13]. For jet fire consequence assessment, the model of Clay was used [71]. Finally, the equations reported in Section 3 were used to evaluate the final inherent safety indexes and were applied based on the output data generated by PHAST software [72].

5. Results and discussion

5.1. Results of the case study

The potential and inherent hazard indexes calculated for the elementary components of the reference blue hydrogen value chains are summarized in Table 7.

Due to the features of the value chains, the *CPI* and *CHI* values of the

elementary component of the two value chains differ only in the hydrogen downstream processes (ECs 1-4.1, 1-4.2 and 2-4.1 to 2-4.3). When the transportation of hydrogen is considered, the *CPI* decreases when switching from LH₂ to CGH₂, while the *CHI* increases. In contrast, in the subsequent storage and distribution processes, the *CPI* is higher, and the *CHI* is lower for CGH₂ compared to LH₂. Furthermore, the liquefaction and storage processes exhibit the highest potential hazard index (i.e., the greatest impact area), but not the highest inherent hazard index, which is observed for hydrogen production. This indicates that H₂ production poses the highest credible risk to human targets.

Fig. 5 compares the potential (Fig. 5-a) and inherent (Fig. 5-b) hazard indexes of the different macro areas considered for the value chain.

As shown in Fig. 5-a) and in Table 7, the liquid hydrogen value chain (RVC-1) shows the highest value of the overall potential index, due to the higher value of the macro area dedicated to hydrogen storage and distribution. The hydrogen production process, instead, is the main contributor to the overall potential index of the compressed gaseous hydrogen value chain (RVC-2). A similar trend is also observed for the inherent hazard index (see Fig. 5-b)). However, the difference between the two value chains in this case is much smaller, approximately 3%, compared to the 54% difference observed when considering the potential hazard index. This suggests that, although the damage distances of accident scenarios are higher for the liquid hydrogen value chain, the credibility of equipment failures leading to hydrogen releases in the compressed gaseous hydrogen value chain generates a comparable inherent hazard. It should also be remarked that in the case of the inherent hazard index, the hydrogen production macro area scores the highest index value, followed by natural gas production, CCS, and finally, hydrogen storage and distribution processes.

Additional insights can be obtained normalizing the *CHI* values against the maximum *CHI* value within each value chain and separating the contributions of scenarios caused by toxicity and flammability. The results obtained for the NG production, hydrogen production, and CCS macro areas, that are the same in the two RVCs considered, are shown in Fig. 6.

As shown in Fig. 6, in the case of NG and H₂ production, the hazard index is driven solely by flammability scenarios, resulting in an *FCHI* value equal to the *CHI*. In contrast, within the CCS value chain (Fig. 6-c)), toxicity-related hazards become significant due to potential CO₂ release scenarios, while MEA contributes primarily to flammability hazards. Among the components of this macro area, CO₂ transport and

Table 7
Potential and inherent hazard indexes calculated for each elementary component of the reference value chains and for the value chains themselves (RVC-1: liquid hydrogen; RVC-2: compressed gaseous hydrogen).

EC tag ^a	RVC-1		RVC-2	
	CPI (m ²)	CHI (m ² /y)	CPI (m ²)	CHI (m ² /y)
1.1	2.0 × 10 ⁴	6.6 × 10 ¹	2.0 × 10 ⁴	6.6 × 10 ¹
1.2	1.1 × 10 ³	1.2 × 10 ¹	1.1 × 10 ³	1.2 × 10 ¹
2	2.1 × 10 ⁶	4.1 × 10 ²	2.1 × 10 ⁶	4.1 × 10 ²
3.1	1.2 × 10 ⁵	6.2 × 10 ⁰	1.2 × 10 ⁵	6.2 × 10 ⁰
3.2	1.6 × 10 ⁴	9.8 × 10 ⁻¹	1.6 × 10 ⁴	9.8 × 10 ⁻¹
3.3	1.9 × 10 ⁴	4.4 × 10 ¹	1.9 × 10 ⁴	4.4 × 10 ¹
3.4	1.5 × 10 ³	1.4 × 10 ⁰	1.5 × 10 ³	1.4 × 10 ⁰
1-4.1	3.5 × 10 ⁶	3.8 × 10 ¹	-	-
2-4.1	-	-	3.0 × 10 ⁵	2.2 × 10 ¹
1-4.2	1.3 × 10 ⁵	1.8 × 10 ⁰	-	-
2-4.2	-	-	1.1 × 10 ⁵	4.4 × 10 ⁰
1-4.3	3.0 × 10 ⁴	1.6 × 10 ⁰	-	-
2-4.3	-	-	3.1 × 10 ⁴	9.7 × 10 ⁻¹
4.4	5.3 × 10 ³	1.5 × 10 ⁻¹	5.3 × 10 ³	1.5 × 10 ⁻¹
	VPI (m ²)	VHI (m ² /y)	VPI (m ²)	VHI (m ² /y)
	5.9 × 10 ⁶	5.8 × 10 ²	2.8 × 10 ⁶	5.7 × 10 ²

^a see Table 4.

injection show moderate, comparable hazards, while CO₂ conditioning demonstrates the lowest hazard.

Fig. 7 presents a comparison of the *CHI* values with respect to the maximum *CHI* value within each value chain and separates between contributions from toxicity and flammability scenarios specifically in the H₂ storage and distribution area for the two value chains considered.

Fig. 7 shows that, as expected, the only contributions to the hazard index derive from scenarios associated with hydrogen flammability, and the *FCHI* values are coincident with the *CHI* value. As evident from the figure, hydrogen storage and distribution is associated to moderate *CHI* values. The highest hazards are associated with tube trailers (CGH₂ in Fig. 7-b)) compared to cryogenic tanks (LH₂ in Fig. 7-a)). Overall, Figs. 6 and 7 show that flammability is the dominant contributor to hazard indexes across all macro areas, except in the CCS value chain, where toxicity plays a more significant role.

Fig. 8 shows a comparison of the overall hazard indexes obtained for fixed assets and transport systems in the macro areas considered in the RVCs where the transport of NG, H₂ or CO₂ is present (thus H₂ production is not considered in this and in the following figure, since no transport system is present in the macro area).

Fig. 8 shows that the inherent hazard of transport system is comparable and may even exceed that of fixed assets, as in the case of CCS, where the inherent hazard index associated to the CO₂ pipeline is higher than that of the CO₂ capture, conditioning, and injection phases (see Fig. 8-b)). Differently, for the case study considered, in both RVC-1 and RVC-2, the hydrogen fixed assets score higher cumulative hazard index values than those of the hydrogen transport systems. Notably, a higher HI value is associated to the transport of compressed gaseous hydrogen (RVC-2) with respect to LH₂ (RVC-1), mostly due to the higher number of trucks needed to transport the same amount of hydrogen.

More in general, Fig. 8 shows that the inherent hazard of transport systems is relevant with respect to that of fixed assets when long-range transportation of relevant quantities of hazardous substances is considered, as in NG production and CCS.

These observations are confirmed by Fig. 9, reporting the normalized values of the inherent hazard indexes calculated for each macro area, distinguishing the contributions of fixed assets from those of transport systems.

Fig. 9-a) shows that, as expected, in the case of NG production, inherent hazards due to flammability are dominant for both fixed assets and transport systems and the *CHI* value is always coincident with the *FCHI* value. Differently, Fig. 9-b) shows that in the case of CCS, toxicity is dominant for both fixed assets and transport systems and in the case of transport systems the *CHI* value is equal to the *TCHI* value. Fig. 9-c) and Fig. 9-d) show that in the case of H₂ storage and distribution in RVC-1 and RVC-2, respectively, flammability is the dominant hazard contributor both in the case of fixed assets and transport systems.

Finally, a quantitative sensitivity assessment was conducted focusing on the CCS value chain as a representative segment of the overall system. This segment includes contributions from both toxic and flammability hazards, making it suitable to reflect the behavior of the entire value chain. The sensitivity analysis was performed using a Monte Carlo approach, sequentially applying normal distributions to key input parameters: first to damage distances, then to credit factors, and finally to scaling factors, each with a mean of 1 and a standard deviation of 0.25. Robustness was assessed by examining the cumulative *CHI* values, which remained within 83%, 97%, and 72% of their nominal values for damage distance, credit factor, and scaling factor, respectively, as shown in Fig. 10. This confirms that the relative ranking and comparative conclusions are stable despite uncertainties in the input parameters.

5.2. Discussion

The present study introduces a rigorous and systematic approach to the quantitative assessment of inherent safety across entire value chains. By employing quantitative hazard indexes, the approach enables a

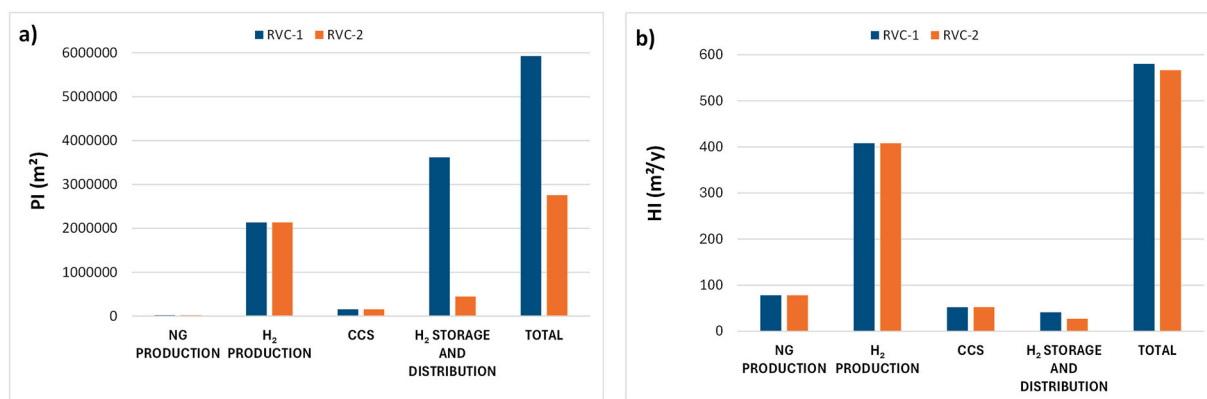


Fig. 5. a) potential (PI) and b) inherent hazard (HI) indexes of the different macro areas of the value chain (RVC-1: liquid hydrogen; RVC-2: compressed gaseous hydrogen). The ECs included in each macro area are shown in Fig. 4.

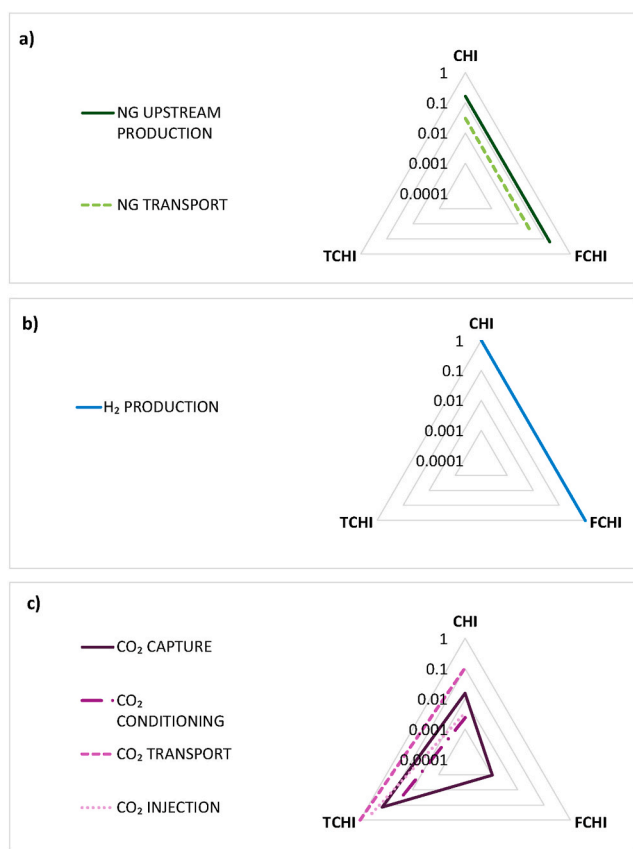


Fig. 6. Comparison among the normalized EC inherent hazard indexes (ratio among the CHI and the maximum calculated CHI value) per macro area: a) NG production; b) H₂ production; c) CCS. The specific contributions of scenarios caused by toxicity (TCHI) and flammability (FCHI) hazards are also shown. In NG and H₂ production toxic hazards are absent, since no toxic component was assumed to be present in the NG feedstock.

detailed comparison between alternative value chain configurations, identifying the most vulnerable core technologies that pose significant safety concerns. This framework provides not only a strategy to pinpoint components requiring further risk analysis but also a clearer understanding of the contributions of individual process units and transport systems to the overall inherent hazard of the value chain. Furthermore, the iterative feedback-loop structure of the methodology promotes continuous improvement and refinement, ensuring that updated information and new insights can be seamlessly integrated throughout the

analysis.

The application of the proposed approach to blue hydrogen value chains provides valuable insights into the safety characteristics of these emerging decarbonization technologies. Overall, the results show that liquid hydrogen distribution facilities exhibit higher potential hazard indexes compared to the compressed gaseous hydrogen infrastructure, primarily due to the larger impact areas associated with cryogenic operations. The production of H₂ emerges as the most inherently hazardous fixed asset, reflecting the higher credibility of equipment failures and releases in this phase. This is followed by the extraction of natural gas and by the compression or liquefaction of hydrogen. Across all macro areas, flammability is confirmed as the dominant hazard contributor, while toxicity plays a significant role only within the carbon capture and storage segment, where it is associated with the handling of CO₂ and MEA streams.

The assessment of transport systems relative to fixed assets reveals that their hazard contribution grows in importance when large inventories and extensive networks are involved. In particular, when considering inherent rather than potential hazard indexes, CO₂ pipeline transport emerges as the most hazardous transport operation, highlighting the need for robust containment and continuous monitoring strategies.

Thus, since transport directly influences the overall hazard index of transportation systems (and not of fixed assets), the optimization of the transport infrastructure is crucial to reduce the risk. Hazard indexes increase markedly when long-range transportation of hazardous substances by pipeline or road/rail are considered becoming major contributors to the total inherent hazard of the value chain, as in the case of CCS (see Fig. 8). This result underscores the importance of careful route planning, pressure management, and continuous monitoring, particularly in H₂ and CO₂ logistics, to effectively manage the transport risks and to ensure resilient system design.

It should be noted that the present study focuses exclusively on inherent safety assessment and does not consider domino effects, environmental and economic consequences, or long-term CO₂ storage risks. These aspects are explicitly out of scope of the methodology, even if they are recognized as important for a comprehensive risk evaluation in real industrial applications. Their omission may lead to an underestimation of specific hazards under full-scale operational conditions. Thus, a dedicated assessment is advised as a follow-up of the present analysis. The present methodology, addressing the early-stage inherent safety screening, provides a solid basis for such an assessment. Future work may extend the approach to harmonize follow-up detailed studies addressing the above-mentioned additional risk dimensions with the results of the hazard screening obtained by the present methodology.

Altogether, the findings demonstrate the relevance of a robust and systematic methodology for assessing the inherent safety of entire value

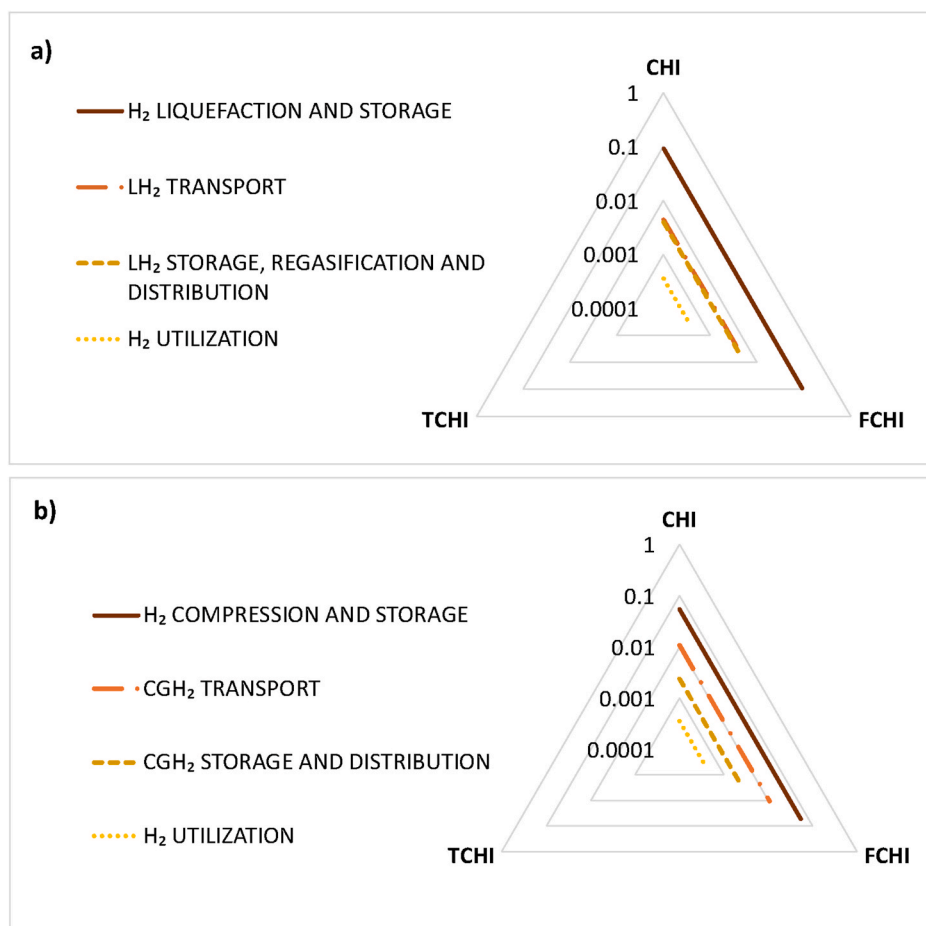


Fig. 7. Comparison among the normalized EC inherent hazard indexes (ratio among the CHI and the maximum calculated CHI value) for the H₂ storage and distribution macro-area: a) RVC-1; b) RVC-2. The specific contributions of scenarios caused by toxicity (TCHI) and flammability (FCHI) hazards are also shown.

chains, particularly in the context of emerging decarbonization technologies. By addressing safety gaps across the value chain, the proposed approach stands out as a critical tool for advancing secure and sustainable design practices. When compared with established value chain assessment methodologies, such as Life Cycle Assessment (LCA), recognized for their comprehensive evaluation of environmental and social impacts, the novel developed inherent safety methodology offers a unique focus on inherent safety considerations, complementing existing frameworks. This alignment with best-performing methodologies such as LCA underscores its relevance and potential as a benchmark for safety-driven decision-making in hydrogen infrastructure and in other safety-critical industries.

6. Conclusions

A novel, quantitative, and systematic methodology was developed to evaluate the inherent safety of entire value chains from the earliest stages of the design lifecycle. By employing a robust, consequence-based approach, the methodology addresses the limitations of conventional inherent safety methods, which are often fragmented and do not provide a comprehensive, chain-wide perspective.

The methodology was applied to a case study involving two alternative blue hydrogen value chains. The results demonstrate its effectiveness in advancing inherent safety across all stages, from natural gas production to hydrogen utilization, while supporting the broader development of a safe and sustainable hydrogen economy.

Crucially, the methodology is able to specifically address the early design phase, when detailed data are limited. In this context, the inherent safety indexes serve as ex-ante screening and ranking tools to

guide preliminary design choices rather than as absolute decision criteria. Their application highlights safer options and enables iterative, informed decision-making, with results progressively refined and integrated with more detailed analyses in subsequent project phases. By adopting this approach, the methodology ensures proactive implementation of inherent safety principles, allowing potential hazards to be identified early while accommodating the evolving nature of the design process.

The flexibility of the methodology makes it applicable beyond hydrogen technologies, extending to industries such as automotive and packaging, where safety is equally vital. By offering a comprehensive framework for assessing and comparing inherent risks, it becomes a valuable tool for decision-makers to manage hazards effectively while promoting sustainable practices. The same flexibility also enables future applications to compare alternative technologies and value chain configurations within and across sectors. In this way, the methodology establishes a solid foundation for advancing safety management across sectors, ensuring that innovation and decarbonization efforts are pursued securely and responsibly.

Overall, this study bridges a significant gap in the availability of methodological approaches for assessing the inherent safety of full value chains, facilitating in-depth investigations of emerging decarbonization technologies. It also represents a pioneering contribution to enhance knowledge of safety considerations as hydrogen economies expand.

CRedit authorship contribution statement

Federica Tamburini: Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **Alessandro Tugnoli:**

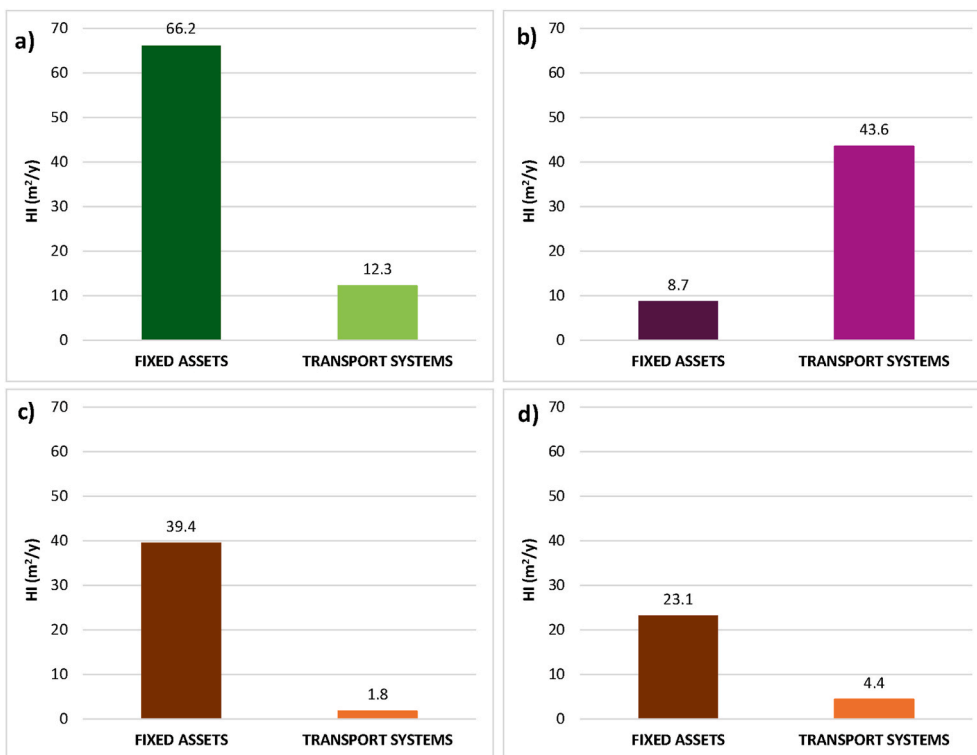


Fig. 8. Inherent hazard indexes (HIs) calculated separately for the fixed assets and transport systems of each macro-area of the value chains including transport systems (RVC-1: liquid hydrogen; RVC-2: compressed gaseous hydrogen): (a) NG production; (b) CCS; (c) H₂ storage and distribution for RVC-1; (d) H₂ storage and distribution for RVC-2.

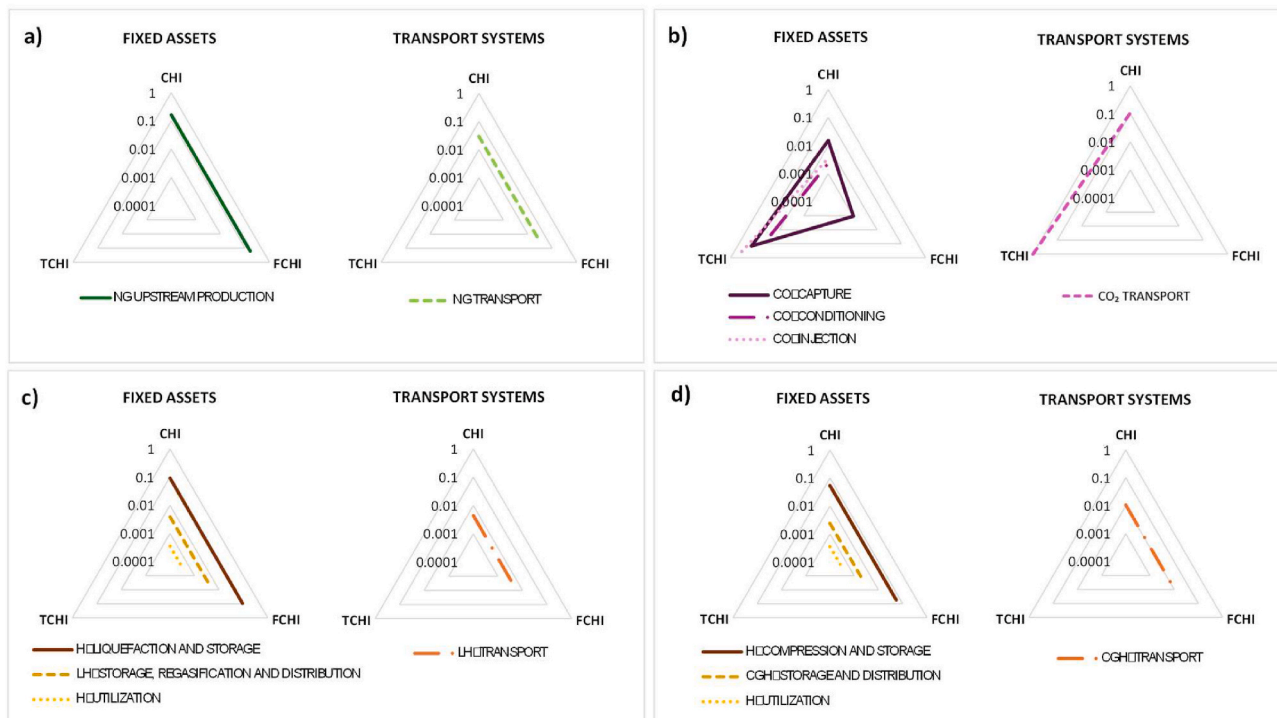


Fig. 9. Comparison among the normalized inherent hazard indexes (ratio among the CHI and the maximum calculated CHI value) of the different macro areas of the value chains involving transport systems (RVC-1: liquid hydrogen; RVC-2: compressed gaseous hydrogen), considering separately fixed assets and transport systems in each macro area: a) NG production; b) CCS; c) H₂ storage and distribution for RVC-1; d) H₂ storage and distribution for RVC-2. The contributions due to toxicity (TCHI) and flammability (FCHI) are also shown separately.

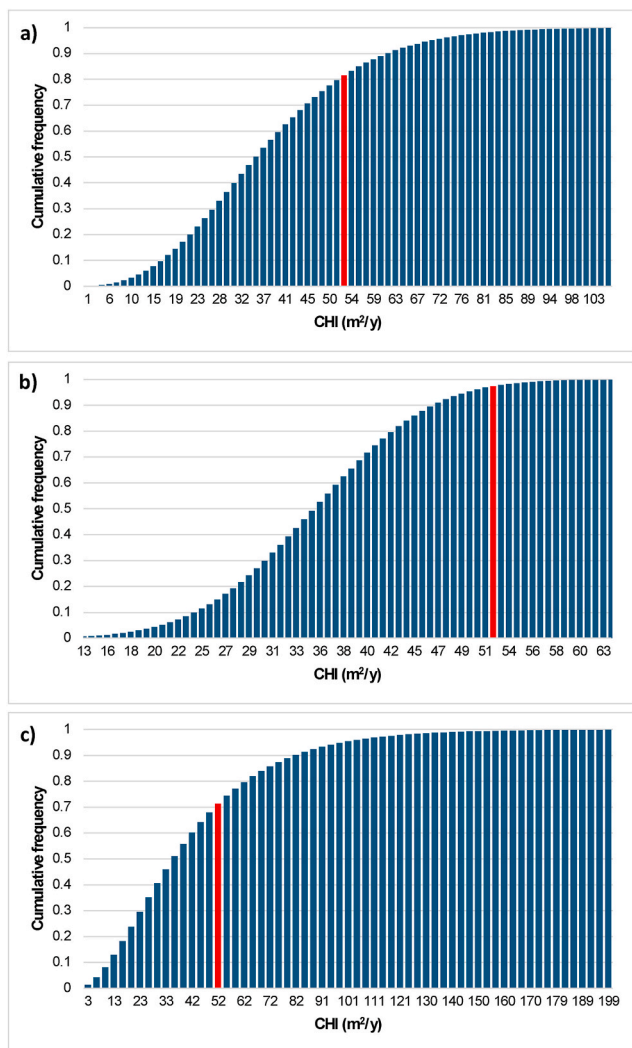


Fig. 10. Cumulative distributions of the CHI for: a) damage distance, b) credit factor, and c) scaling factor. Blue bars represent the cumulative frequency of CHI values, while the red vertical line indicates the reference CHI (52 m²/y). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Validation, Methodology, Investigation, Conceptualization. **Valerio**

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.ijhydene.2026.154322>.

Abbreviations

ATR	Autothermal reforming
C ₄ H ₁₀ O ₃	Diethylene glycol
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilization
CE	Critical event
CGH ₂	Compressed gaseous hydrogen
CH ₃ OH	Methanol
CH ₄	Methane
CHI	Elementary Component inherent Hazard Index
CO ₂	Carbon dioxide
CPI	Elementary Component Potential hazard Index
EC	Elementary component
EHI	Equipment item inherent Hazard Index

(continued on next page)

Cozzani: Writing – review & editing, Supervision, Methodology, Investigation, Writing, Conceptualization.

Declaration of competing interest

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

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(continued)

EI	Equipment item
EPI	Equipment item Potential hazard Index
FB	Fireball
FCHI	Flammable elementary Component inherent Hazard Index
FF	Flash fire
FMEA	Failure Mode and Effect Analysis
FTA	Fault Tree Analysis
G	Gas
H ₂	Hydrogen
HI	Inherent hazard index
IDLH	Immediately Dangerous to Life and Health concentration
JF	Jet fire
L	Liquid
LCA	Life Cycle Assessment
LFL	Lower flammability limit
L-G	Liquid-Gas
LH ₂	Liquid hydrogen
MEA	Monoethanolamine
MIMAH	Methodology for the Identification of Major Accident Hazards
MIRAS	Methodology for the Identification of Reference Accident Scenarios
NG	Natural gas
PE	Physical explosion
PF	Pool fire
PFDF	Process flow diagram
PI	Potential hazards index
PSA	Pressure swing adsorption
RRM	Reference release mode
RVC	Reference value chain
S-G	Solid-Gas
SMR	Steam methane reforming
TC	Toxic cloud
TCHI	Toxic elementary Component inherent Hazard Index
TRL	Technology readiness level
VCE	Vapor cloud explosion
VHI	Value chain inherent Hazard Index
VPI	Value chain Potential hazard Index

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