Proc. of the European Safety and Reliability Conference (ESREL 2026)
Edited by José C. Matos, Paulo B. Lourenço, Michael Beer, Daniel Oliveira, Edoardo Patelli, Hélder S. Sousa, Rui A. Silva and Monica Santamaria
 Published by Research Publishing, Singapore.
doi: 10.3850/ESREL2026061419_esrel26-p26242-cd

Inherent Safety Assessment for Offshore Chemical-based Energy Storage Systems under Hydrometeorological Hazards

Honghao Chen

Department of Mechanical and Industrial Engineering, Norwegian University of Science and Technology – NTNU, Trondheim, Norway.
E-mail: honghao.chen@ntnu.no

Dimitrios Tzioutzios

Department of Mechanical and Industrial Engineering, Norwegian University of Science and Technology – NTNU, Trondheim, Norway.
E-mail: dimitrios.tzioutzios@ntnu.no

Yiliu Liu

Department of Mechanical and Industrial Engineering, Norwegian University of Science and Technology – NTNU, Trondheim, Norway.
E-mail: yiliu.liu@ntnu.no

Integrating new energy technologies into the offshore Oil and Gas (O&G) industry is a significant measure to reduce fossil fuel reliance and greenhouse gas emission. However, the intermittency of renewable sources poses challenges of ensuring stable electricity supply to O&G processes. Thus, it is vital to apply proper energy storage systems for enhancing the stability and efficiency of offshore production processes. Chemical-based Energy Storage Systems (CESSs) are regarded promising due to their advantages of high energy density, long-duration and transportability. Nevertheless, subjected to the potential natural hazards and harsh oceanic environment, the components of CESS may fail and lead to accidents with the hazardous material (e.g. methane, hydrogen and ammonia) leakage, even fire and explosion. Such evolved cascading event can be described as "Natech (Natural hazard triggered technological accident)". This paper presents an inherent safety assessment framework for conceptual CESS, providing a safety-oriented perspective on the sustainability potential of different alternatives. This framework assesses the CESS alternatives based on their flammability, explosibility, and complexity of processes as well as installation vulnerability exposed to potential hydrometeorological hazards. The proposed framework is demonstrated via a case study considering typical alternatives, hydrogen-based systems and ammonia-based systems. The findings of this study aim to support stakeholders in implementing effective risk management strategies, fostering the safe and sustainable deployment of CESSs in offshore industries.

Keywords: Renewable energy storage, Chemical-based energy storage system, Inherent safety, Natech, Offshore process safety.

1. Introduction

Excessive exploitation of fossil fuels has led to the release of greenhouse gases, resulting in rising global temperatures and consequent climate change. The substitution of fossil-based energy with renewable energy sources, such as solar and wind power, is widely regarded as a key strategy for reducing reliance on fossil fuels (Pukazhselvan et al. 2026). However, the inherent intermittency and variability of these renewable sources pose significant challenges to maintaining a stable and continuous energy supply for safety-critical Oil and Gas (O&G) operations (Voldsund et al. 2023). Fluctuations in power availability can adversely affect production efficiency, process safety, and operational reliability, making it essential to incorporate appropriate energy storage solutions capable of buffering these variations and ensure uninterrupted power delivery. Chemical-based Energy Storage Systems (CESSs), converting surplus renewable electricity through electrolysis into chemical energy carriers, are promising in addressing the seasonal energy storage requirements (Lefebvre and Tezel 2017; Stadler and Sterner 2018). In this context, CESSs have attracted attention due to their high energy density, suitability for long-duration storage, and flexibility in terms of embedding with transport and integration with offshore infrastructure.

Nevertheless, the deployment of CESSs in offshore environments raises new safety concerns. This creates a dual safety challenge: the systems must be evaluated not only with respect to their inherent process hazards, but also with respect to their vulnerability to externally triggered accident escalation under severe weather conditions. On the one hand, offshore installations are exposed to harsh oceanic conditions, including strong winds, waves, and extreme weather events, which can compromise the integrity of storage system components. On the other hand, climate change has increased the frequency and severity of natural hazards related to extreme weather, such as storms, thereby posing an escalating threat to the offshore industries. These hydrometeorological hazards represent significant external factors that can cause equipment failure, leading to technological accidents, namely Natech events. In light of the spatial constraints of offshore facilities, the occurrence of natural hazards may result in severe consequences due to the subsequently triggered cascading events. In these cases, efforts towards carbon reduction could be undermined, and the benefits brought by green technologies diminished.

Inherent safety is an appraoch focusing on proactively analyzing and elimating or reducing hazards or risks at hazardous sources (Amyotte and Khan 2021; Kletz and Amyotte 2010). Through the enumeration, comparison, and assessment of potential feasible alternatives in the early design stages, inherent safety approach can help build a system with inherently lower risk, rather than merely relying on add-on risk control measures (Gao et al. 2021; Park et al. 2020). Consequently, various inherent safety assessment tools (ISATs) have been proposed, which attempt to fully exploit limited data available in early design stages. ISATs such as Prototype Index for Inherent Safety (Edwards and Lawrence 1993), Inherent Safety Index (Heikkilä et al. 1996), Integrated Inherent Safety Index (Khan and Amyotte 2005) and Comprehensive Inherent Safety Index (Gangadharan et al. 2013) are representative semi-quantitative methods that assign discrete scores to indicators measuring process hazards. Different from the scored methods, Process Route Index (Leong and Shariff 2009) and Process Stream Index (Shariff et al. 2012) were constructed by dimensionless and scaled processing of hazard indicators for explosive characteristics. Novelly, Ahmad et al. (2014) proposed a continuous numerical ISAT named Numerical Descriptive Inherent Safety Technique to overcome the abrupt changes in interval edge values. In parallel, risk-based ISATs such as Rapid Risk Analysis Based Design (Khan and Abbasi 1998) and Risk-based Inherent Safety Index (Rathnayaka et al. 2014) were also presented with consideration of likelihood of hazardous events. Notably, Tugnoli et al. (2012) proposed a set of inherent safety key performance indicators (IS-KPIs), in which hazard indicators were defined as unit damage radius of accident consequences and were transferred to risk indicators by integrating with credit factor of initial loss of containment (LOC) events.

So far, driven by the objective of achieving inherent safety—and thus promoting inherent sustainability—a growing body of research has applied inherent safety assessment approaches within the decarbonization domain, including cleaner maritime fuel substitution (Zanobetti et al. 2023), onboard greener fuel production (Deng et al. 2024), and onboard carbon capture and storage systems (Zanobetti et al. 2024). These studies have enhanced understanding of the risks associated with the adoption of green technologies and demonstrated the value of inherent safety as a comparative decision-support approach in early design stages. Existing studies on offshore inherent safety mainly focus on internal risk assessment of systems and have paid limited attention to the external disturbances arising from natural hazards. Recently, Tamburini et al. (2025) proposed a set of indicators adapted from IS-KPIs for the liquid hydrogen maritime bunkering infrastructure, which adopted vulnerability models for tanks and pipes under tsunami and wave events. However, these vulnerability models require detailed geometric and operational data which may not be available until the basic engineering stage (Hurme and Rahman 2005). Accordingly, a dedicated ISAT is needed that can: 1) support early-stage comparison of alternative CESS concepts without intensive data collection requirements; and 2) capture both internal process hazards of alternatives and their non-linear increased vulnerability to external hydrometeorological hazards in offshore environments.

To bridge this gap, this study incorporates storm-triggered Natech accidents into inherent safety assessment of CESS alternatives. In doing so, it is expected to facilitate informed conceptual selection of CESSs and the implementation of effective risk management strategies against hydrometeorological hazards for sustainable deployment of CESSs in offshore industries.

The rest of the paper is structured in the following way. Section 2 describes the proposed methodology and equations employed in detail. Section 3 presents an illustrative case study involving two alternative technological pathways of CESS—hydrogen and ammonia production—for converting and storage renewable energy; this section includes a sensitivity analysis to validate the constructed indexes. Finally, the conclusion of this study is drawn in Section 4.

2. Methodology

This section presents the proposed methodology. Subsections 2.1 and 2.2 introduce the likelihood of LOC event and the external impact on the LOC likelihood from hydrometeorological hazards, respectively. Subsection 2.3 exhibits the indicators for assessing the inherent hazardous levels of production processes. Subsection 2.4 integrates the indicators into a risk index, accounting for the risk amplification effect due to the external disturbance from hydrometeorological hazards.

2.1. *Credit factor for loss of containment*

To quantify the likelihood of process hazards developing into accidents, frequency values of LOC events are employed as credit factors and distributed across process streams and equipment. Table 1. presents the categories of LOC events and their corresponding descriptions, as well as the generic failure frequencies for different process equipment. Notably, process vessels refer to units in which materials undergo physical transformations, such as temperature variations or phase transitions. As illustrated in the literature (Iannaccone et al. 2019; Tugnoli et al. 2009), the credit factor in Table 1 summarize the potentials of occurring LOC events based on historical performance of similar equipment, rather than exact failure frequencies of equipment items.

Table 1. Credit factors for LOC events for different equipment (De Haag and Ale 2005; Tugnoli et al. 2009; Zanobetti et al. 2024).

LOC	Description	Reactor	Process vessel	Pressure vessel	Atmospheric vessel	Pipe	Heat exchanger	Compressor	Pump
R1	Small leak, continuous release from a 10 mm equivalent diameter hole	1E-4	1E-4	1E-5	1E-4	N.A.	N.C.	N.A.	N.A.
R2	Catastrophic rupture, release of the entire inventory in 600 s	5E-6	5E-6	5E-7	5E-6	N.A.	N.C.	N.A.	N.A.
R3	Catastrophic rupture, instantaneous release of the entire inventory and release from the full-bore feed pipe	5E-6	5E-6	5E-7	5E-6	N.A.	N.C.	N.A.	N.A.
R4	Pipe leak, continuous release from a hole having 10 % of pipe diameter	N.C.	N.C.	N.C.	N.C.	5E-6	1E-3	1E-3	5E-4
R5	Pipe rupture, continuous release from the full-bore pipe	N.C.	N.C.	N.C.	N.C.	1E-6	5E-5	1E-4	1E-4

*N.A.: Not Applicable; N.C.: Not Considered.

2.2. *Natural hazard indicators*

Natural hazards may also cause LOC events. To estimate the risk arising by multiple hydrometeorological hazards, Muratore et al. (2025) have proposed a semi-quantitative method comprised of a hazard index I_{Hs}, and a vulnerability index I_{Vs}. When multiple hydrometeorological hazards are considered, I_{Hs} consists of three sub-indexes, I_{Hsp} for heavy precipitation, I_{Hsw} for strong wind and I_{Hsl} for lightning, as defined as Eq. (1):

$$I_{Hs} = \frac{1}{3}\left(I_{Hsp} + I_{Hsw} + I_{Hsl}\right) \tag{1}$$

The detailed scoring criteria for each subindex are summarized in Table 2, which are based on the location hydrometeorological data from historical statistics. Notably, the score range of I_{Hs} is from 1 to 4.

Table 2. Scoring criteria for each subindex (Muratore et al. 2025).

Index	Score			
	1	2	3	4
I_{Hsp}	D_{pp}<50	50≤D_{pp}<100	100≤D_{pp}<150	150≤D_{pp}
I_{Hsw}	V_w<3	3≤V_w<5	5≤V_w<7	7≤V_w
I_{Hsl}	N_g<1	1≤N_g<2.5	2.5≤N_g<4	4≤N_g

*D_{pp}: maximum daily precipitation, mm; V_w: wind speed, m/s; N_g: the average number of lightning strikes to the ground per year per square kilometer.

Table 3. Values of vulnerability index for different equipment types (Muratore et al. 2025).

Equipment type	Critical characteristic	Value
Floating roof tank	Filling level ≥50%	4
	Filling level<50%	3
Fixed roof tank	Filling level ≥50%	3
	Filling level<50%	2
Pressurized container	Constructed before Pressure Equipment Directive proposed	3
	Aligning with Pressure Equipment Directive	2
Pipes with pressure	Constructed before Pressure Equipment Directive proposed	2
	Aligning with Pressure Equipment Directive	1
Pipes not under pressure	N.C.	1

*N.C.: Not Considered.

The values of I_{Vs} related to different types of equipment are collected in Table 3.

2.3. *Inherent hazard indicators*

Hazardous levels of chemicals can be characterized from their properties of flammability, explosibility and toxicity, which are the inherent hazard of triggering industrial accidents and causing fatalities and injuries. The following subsection introduces the indicators employed for assessing inherent hazard levels of CESSs.

2.3.1. *Flammability*

The probability of immediate ignition P_{IG} is used to characterize the flammability of chemicals within process systems. It comprises the likelihood of autoignition P_{AIG} and the likelihood of static discharge P_{SDC}, as shown in Eqs. (2)-(4) (Chen et al. 2020; Moosemiller 2011; Wei et al. 2025):

$$P_{IG} = \min\left[(P_{AIG} + P_{SDC}), 1\right] \tag{2}$$

$$P_{AIG} = \begin{cases} 0 & \frac{T}{AIT} < 0.9 \\ 1 - 5000\exp\left(-9.5 \cdot \frac{T}{AIT}\right) & 0.9 \le \frac{T}{AIT} \le 1.2 \\ 1 & \frac{T}{AIT} > 1.2 \end{cases} \tag{3}$$

$$P_{SDC} = 0.0024 \cdot \left(\frac{P}{MIE^2}\right)^{\frac{1}{3}} \tag{4}$$

As shown, P_{IG} is related to the operating temperature (T, °F), operating pressure (P, psig), auto-ignition temperature (AIT, °F) and minimum ignition energy (MIE, mJ). Considering mixtures consisting of multiple flammable hazardous materials, the Le Chatelier mixing principle is adopted to estimate the AIT and MIE of the mixture based on the mass fraction of each component fraction, y_i (Crowl and Louvar 2001; Wei et al. 2025), which are shown in Eq. (5) and (6):

$$AIT_{mix} = \frac{1}{\sum_{i=1}^{n} \frac{y_i}{AIT_i}} \tag{5}$$

$$MIE_{mix} = \frac{1}{\sum_{i=1}^{n} \frac{y_i}{MIE_i}} \tag{6}$$

The score of flammability S_F is defined based on the P_{IG} with a scale factor, as shown in Eq. (7):

$$S_F = 100 \times P_{IG} \tag{7}$$

Considering the mass fraction, the modified score for flammability S_{NF} can then be calculated through Eq. (8):

$$S_{NF} = \sum_{i=1}^{n} y_i \cdot S_F \tag{8}$$

2.3.2. *Explosibility*

The difference between the upper and lower explosive limits is generally considered as a key characteristic of chemicals, reflecting propensity to cause explosions. As explosive limits vary with temperature, the Zebatekis equation is adopted to estimate the upper explosive limit (UEL) and the lower explosive limit (LEL) (Hristova and Tchaoushev 2006), as expressed in Eq. (9) and (10):

$$UEL_i = UEL_{i,o} - \frac{0{,}182(T - 25)}{\Delta H_{ci}} \tag{9}$$

$$LEL_i = LEL_{i,o} - \frac{0{,}182(T - 25)}{\Delta H_{ci}} \tag{10}$$

Likewise, the Le Chatelier mixing principle is adopted to estimate the explosive limits of mixtures based on the mass fraction of each component (Crowl and Louvar 2001; Wei et al. 2025), deriving Eq. (11) and (12) shown as follows:

$$UEL_{mix} = \frac{1}{\sum_{i=1}^{n} \frac{y_i}{UEL_i}} \tag{11}$$

$$LEL_{mix} = \frac{1}{\sum_{i=1}^{n} \frac{y_i}{LEL_i}} \tag{12}$$

The score of explosibility S_E can be obtained by a logistic function based on the difference between upper and lower explosive limits δ_{EL}, as shown in the Eq. (13) and (14) (Ahmad et al. 2014, 2016; Ahmad et al. 2019):

$$\delta_{EL} = UEL_{mix} - LEL_{mix} \tag{13}$$

$$S_E = 100 \times \left(\frac{1}{1 + 1096.63 \times \exp(-0{,}14 * \delta_{EL})} \right) \tag{14}$$

Likewise, by incorporating the mass fraction of hazardous materials within the process stream, a modified score for explosibility, S_{NE}, is calculated as defined in Eq. (15) below:

$$S_{NE} = \sum_{i=1}^{n} y_i \cdot S_E \tag{15}$$

2.3.3. *Toxicity*

The toxicity of chemicals can be characterized using the threshold limit values (TLV) of toxicants, among which short-term exposure limit (TLV-STEL) is regarded as particularly significant for acute toxicity events. In general, lower values of TLV indicate greater toxicity hazards. Ahmad et al. (2014, 2016) proposed a logistic function to score the chemical toxicity while ensuring the comparability with other hazardous attributes, thereby demonstrating its suitability to develop an inherent safety assessment tool (Ahmad et al. 2019). Accordingly, the toxicity score is calculated by incorporating the mass fraction of each component, as given in Eq. (16):

$$S_{NT} = \sum_{i=1}^{n} y_i \cdot 100 \times \left(1 - \frac{1}{1 + 403.4288 \times \mathrm{e}^{(-0{,}012 \cdot TLV_i)}} \right) \tag{16}$$

2.4. *Index integration*

The score of I_{HZ}, representing the overall hazard level of a process stream is defined as the sum of the inherent hazard indicators, as shown in Eq. (17):

$$I_{HZ} = S_{NF} + S_{NE} + S_{NT} \tag{17}$$

A lower value of I_{HZ} indicates less hazardous compared to the one with a higher I_{HZ} value.

To incorporate the likelihood of release from the hazardous sources and consider the amplification effect due to the natural hazards, the Stream Risk Index (SRI) is constructed, as shown in Eq. (18):

$$SRI_j = \left(\frac{1}{-\lg \max_k \left(cf_{j,k} \right)} \right)^{\frac{1}{I_{HS,j} \times I_{VS,j}}} \times I_{HZ,j} \tag{18}$$

where $\max_k \left(cf_{j,k} \right)$ is the maximum value of k credible LOC events for unit j. It should be pointed out that these two equations are not suitable for the case in which the credit factor cf higher than 1E-1.

As for the equipment, the hazardous level of equipment is represented by the average I_{HZ} value of the streams associated with it. Therefore, an Equipment Risk Index (ERI) can be calculated according to Eq. (19):

$$ERI_j = \left(\frac{1}{-\lg \max_k \left(cf_{j,k} \right)} \right)^{\frac{1}{I_{HS,j} \times I_{VS,j}}} \times \frac{1}{s} \sum_{q=1}^{s} I_{HZ,j,q} \tag{19}$$

After all, the total scores for the steam risk and equipment risk—TSRI and TERI, respectively—can be calculated based on the sum index value of each unit, as shown in Eqs. (20) and (21):

$$TSRI = \sum_{j=1}^{N} SRI_j \tag{20}$$

$$TERI = \sum_{j=1}^{N} ERI_j \tag{21}$$

Finally, the overall inherent safety index for the process alternative that accounts for hydrometeorological hazards, defined as HMI, is given by Eq. (22):

$$HMI = \sqrt{TSRI \times TERI} \tag{22}$$

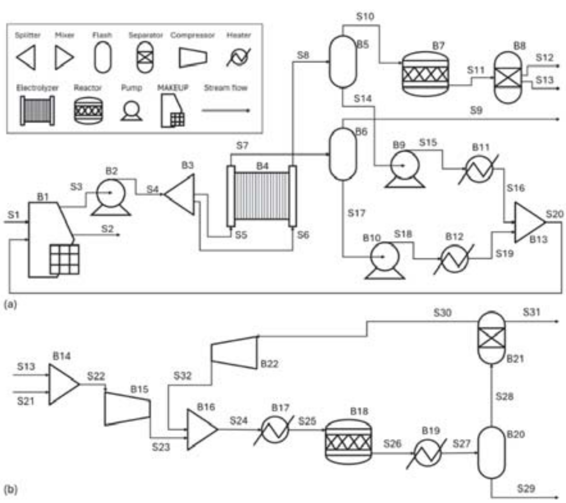

Fig. 1. Flowchart of process modules of alternatives for the case study: (a) Module M1: water electrolysis hydrogen production module; (b) Module M2: hydrogen-based ammonia synthesis module.

3. Illustrative case study

3.1. *Case description*

In this section, an alkaline electrolysis process for green hydrogen production (A1) and the corresponding hydrogen-based ammonia production process (A2) are adopted as two alternatives for renewable energy storage in order to demonstrate the application of the proposed methodology. Simplified process flow diagrams of these two processes are shown in Fig. 1.

As illustrated in Fig. 1(a), in the hydrogen production process consists of Module M1, water is introduced into the system at the make-up unit (B1), where it is combined with a recycled water stream. The resulting water flow is then divided by a splitter (B3) into cathode and anode inlet streams for the alkaline electrolysis cell (B4), producing H_2 and O_2 gases. The outlet streams from the cathode and anode are subsequently processed by flash steamers B5 and B6, respectively, to achieve phrase separation. The vapor stream from B5 is directed to reactor B7 to convert the residual oxygen into water, thereby purifying the hydrogen stream.

For the ammonia production process, an ammonia synthesis Module M2 is appended to the downstream section of the hydrogen production process, utilizing the produced hydrogen as a feedstock, which is shown in Fig. 1(b). A mixed stream of nitrogen and hydrogen is introduced into reactor B18 after compression in B15 and heating in B17. Likewise, a flash steamer B20 is employed to separate the produced ammonia from unconverted reactants, which are then recycled back into the process.

The proposed hypothetical scheme is assumed to operate at a location characterized by a heavy precipitation value (D_{pp}) of 120, a wind speed value (V_w) of 6, and a lightning density value (N_g) of 2.5. Under these conditions, I_{Hs} is calculated as 3, according to Table 2. Furthermore, all streams are regarded as pipes to determine the I_{Vs} score. Accordingly, the I_{Vs} score for all the equipment involved in the process can be obtained from Table 3.

Table 4. Process parameters of streams in Module M1.

Stream	T (°C)	P (bar)	Mass fraction						
			H_2	O_2	H_2O	KOH	H_3O^+	K^+	OH^-
S1	25	8	0	0	1	0	1.91E-09	0	1.70E-09
S2	0	0	0	0	0	0	0	0	0
S3	73.305	7	1.68E-06	9.68E-06	0.117415	0	2.98E-21	0.615030	0.267544
S4	73.309	7.2	1.68E-06	9.68E-06	0.117415	0	2.98E-21	0.615030	0.267544
S5	73.309	7.2	1.68E-06	9.68E-06	0.117415	0.882574	0	0	0
S6	73.309	7.2	1.68E-06	9.68E-06	0.117415	0	2.98E-21	0.615030	0.267544
S7	75	7	2.71E-06	0.033367	0.146649	0.819982	0	0	0
S8	75	7	0.001549	9.93E-06	0.092825	0.905617	0	0	0
S9	74.968	7	8.11E-05	0.998642	0.001278	0	0	0	0
S10	74.98	7	0.98347	0.006305	0.010221	0	0	0	0
S11	81.801	7	0.982680	0	0.017320	0	0	0	0
S12	81.801	7	0	0	1	0	9.92E-09	0	8.87E-09
S13	81.801	7	1	0	0	0	0	0	0
S14	74.98	7	2.30E-06	1.65E-08	0.092955	0	1.84E-21	0.632081	0.274961
S15	74.981	7	2.30E-06	1.65E-08	0.092955	0	1.84E-21	0.632081	0.274961
S16	72.8	7	2.30E-06	1.65E-08	0.092955	0	1.54E-21	0.632081	0.274961
S17	74.968	7	2.72E-09	3.72E-05	0.151668	0	7.16E-21	0.591142	0.257153
S18	74.968	7	2.72E-09	3.72E-05	0.151668	0	7.16E-21	0.591142	0.257153
S19	72.8	7.1	2.72E-09	3.72E-05	0.151668	0	6.00E-21	0.591142	0.257153
S20	72.844	7	1.70E-06	9.78E-06	0.108383	0	2.31E-21	0.621324	0.270282

Table 5. Process parameters of streams in Module M2.

Stream	T (°C)	P (bar)	Mass fraction		
			H_2	N_2	NH_3
S21	82	7	1	0	0
S22	81.867	7	0.823529	0.176471	0
S23	849.734	200	0.823529	0.176471	0
S24	465.432	200	0.874388	0.125612	0
S25	500	200	0.874388	0.125612	0
S26	481	250	0.524633	0.050106	0.425261
S27	30	250	0.524633	0.050106	0.425261
S28	29.999	250	0.804656	0.076815	0.118529
S29	29.999	250	0.013676	0.001369	0.984955
S30	29.999	250	0.912856	0.087145	0
S31	29.999	250	0	0	1
S32	16.676	200	0.912848	0.087152	0

The processes were simulated via Aspen Plus. The results for the process depicted in Fig. 1(a) are compiled in Table 4, while the results for the process shown in Fig. 1(b) are presented in Table 5.

3.2. *Results and discussion*

Fig. 2 presents the I_{HZ} values for each stream involved in proposed processes in the case study. In Module M1, stream S10, S11 and S13, which contain hydrogen, are identified as highly hazardous due to their increased flammability and explosibility. The flammability scores (S_F) of S10, S11 and S13 are 98.347, 98.268, and 100, respectively, while the corresponding explosibility scores (S_E) are 93.635, 93.606, 95.256. These high values imply that the hydrogen purification sub-process constitutes the most hazardous part of the proposed CESS. Consequently, particular attention should be paid to process streams containing large amounts of flammable and explosive substances. The S_F and S_E values of S10 are slightly higher than those of S11, which can be attributed to the higher mass fraction of hydrogen in S10 despite its lower operating pressure. Stream S13, representing the hydrogen product, exhibits the highest I_{HZ} value. This indicates that transferring hydrogen to storage units, as well as its use as a feedstock for ammonia production, represents the stage associated with the highest risk.

In Module M2, streams downstream ammonia synthesis (i.e., S26, S27, S28, S29 and S31) show considerable toxicity hazard, with toxicity scores (S_T) of 98.125 and 99.624 for S29 and S31, respectively. With the exception of S31, which corresponds to the ammonia product stream, all these streams also present varying degrees of flammability and explosibility hazards. Although these hazards originate from hydrogen processing, the S_F and S_E values of these streams are substantially lower than those of the hydrogen purification streams due to dilution with nitrogen which significantly reduces the mass fraction of hazardous substances. Moreover, it is shown that the lower I_{HZ} value of S31 compared with S13 indicates that transport and storage of ammonia are inherently safer than those of hydrogen when used as chemical-based renewable energy storage medium.

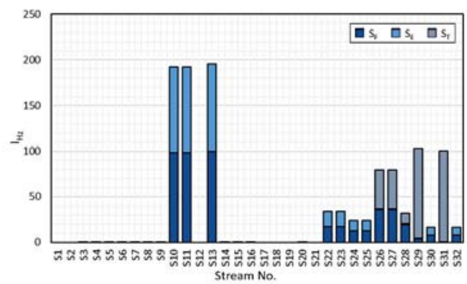

Fig. 2. Values of inherent hazard index of streams.

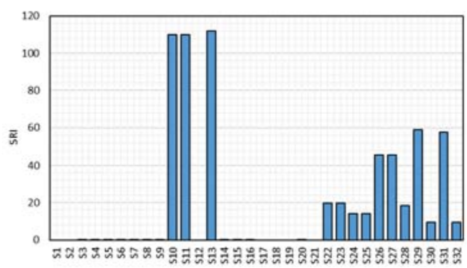

Fig. 3. Values of SRI for streams.

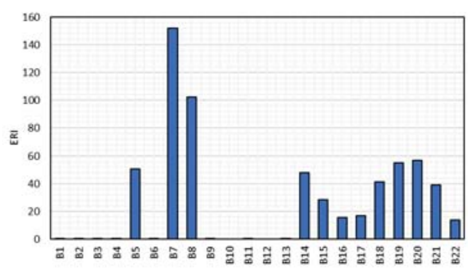

Fig. 4. Values of ERI for the equipment involved.

The SRI results in Fig. 3 show a similar distribution to that of the I_{HZ} results illustrated in Fig. 2. Nevertheless, when the likelihood of leakage is taken into account, the SRI scores are lower than the corresponding I_{HZ}. This reduction arises because the parameters characterizing the LOC potential due to external hydrometeorological hazards are incorporated as a scaling coefficient, which functions as an approximately linear modifier for the inherent hazard indicator.

Fig. 5 and Fig. 6 illustrate the TSRI and TERI scores of the two CESS alternatives, respectively, together with the corresponding average scores. As shown, the incorporation of the ammonia synthesis process raises the total risk levels of alternative A2 at both the stream and equipment level. As a result, the TSRI and TERI values of alternative A2 increase to 645.422 and 622.179, respectively, compared with those of alternative A1 (i.e., 332.315 and 305.693). This increase is primarily due to the larger number of equipment and process streams handling hazardous materials in alternative A2. Meanwhile, the average scores of both indicators for A2 alternative also increased slightly. However, the relative increases in TSRI and TERI suggest that Module M2 possesses risk levels broadly comparable to Module M1. This implies that, for a single offshore site, separating the water electrolysis hydrogen production module and operating only the green ammonia synthesis module could significantly reduce onboard risk. Nonetheless, the resulting risk transfer to the upstream supply chain warrants further discussion.

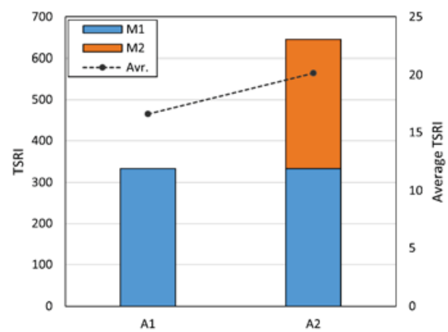

Fig. 5. Values of TSRI of CESSs in case study.

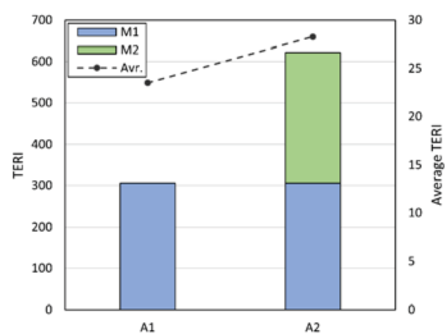

Fig. 6. Values of TERI of CESSs in case study.

The final overall score, HMI, for the two alternatives are exhibited in Fig. 7. Aligned with the results in Fig. 5 and

Fig. 6, the incorporation of ammonia synthesis process raises overall risk level of the CESS alternative A2, leading to the high HMI value of 633.694. Meanwhile, the HMI value of alternative A1 equals to 318.726. This comparison highlights a safety trade-off between storage and processing: converting a more hazardous material into a safer one through additional processing can reduce storage-related risks but simultaneously introduces new inherent hazards and increases the overall risk of the process. This could be regarded as a kind of risk transfer. Nevertheless, considering the relative increase in HMI, CESS alternative A1 can be regarded as a simpler and comparatively safer option for converting renewable energy into long-duration stored energy.

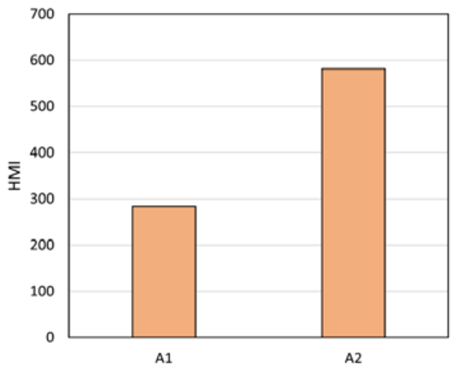

Fig. 7. Values of HMI of CESSs in case study.

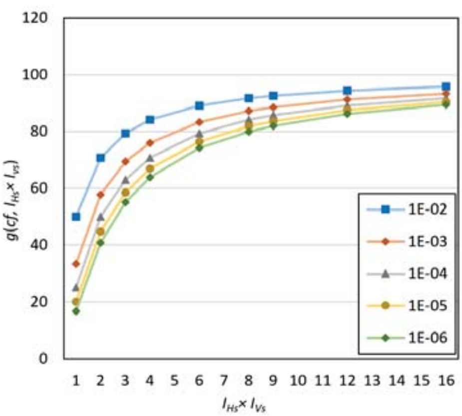

Fig. 8. Sensitivity analysis on proposed index.

A sensitivity analysis was conducted to verify the robustness. Eqs. (18) and (19) are represented by function $g(cf, I_{Hs} \times I_{Vs})$, assuming a hypothetical constant of 100 to score the hazard level. Fig. 8 illustrates the changes in the risk index as the product of the natural hazard indicators ranges from 1 to 16 under different LOC credit factors (cf). As shown, curves associated with higher base cf scores consistently exhibit higher risk levels and remain above those corresponding to lower cf values. Moreover, all curves in Fig. 8 demonstrate an increasing trend as the product of I_{Hs} and I_{Vs} increases, clearly reflecting the non-linear amplification effect of Natech events on system risks. The rate of increase of the function g gradually diminishes, and the differences among the curves decrease accordingly, implying that external risks stemming from natural hazards become dominant when hazard intensity and equipment unit vulnerability are exceptionally high. Therefore, under such extreme Natech conditions, system risk becomes increasingly governed by external natural hazard drivers rather than by inherent unit safety performance, highlighting the necessity of prioritizing Natech-oriented risk mitigation strategies.

4. Conclusion

In this study, a semi-quantitative index method was proposed to evaluate the inherent safety performance of different CESSs, taking into account the impact of typical natural hazards on offshore facilities, including heavy precipitation, strong winds, and lightning. Two semi-quantitative indexes, I_{Hs} and I_{Vs}, were implemented as correction coefficients for credit factors, reflecting the potential for LOC events in such facilities. The inherent hazard levels of CESSs were estimated based on the flammability, explosibility and toxicity of chemicals within process streams or equipment, using logistic functions. The proposed method requires simple local hydrometeorological data and the process parameters obtained from process flow diagram, which both are available in the conceptual design stage. The case study highlighted the proposed method's usefulness in identifying the inherently safer process alternative, as well as the key hazardous streams and equipment, providing valuable guidance for elaborating hazard reduction strategies and drafting risk management plans.

This work can be extended to other decarbonization processes, such as carbon-neutral methane and carbon-neutral methanol production. However, with assumption of the process operated under static conditions, the semi-quantitative index developed in this study may not fully characterize facility vulnerability. The uncertainties arising from uncertain natural hazard intensity and frequency, fluctuation of operational condition would also cause dynamic changes of the actual risk level. In such a context, the assessment outcomes should not be interpreted as precise or fully deterministic representations of risk. Rather, they reflect comparative judgments made on the basis of currently available information. As more comprehensive information on process systems becomes available at the detailed engineering and operational stages, the proposed method needs to be further expanded and refined to accommodate various data requirements. For future research, dedicated probabilistic models describing the joint distribution of frequencies and intensities of hydrometeorological hazards, and vulnerability models for process equipment under hydrometeorological hazards ought to be developed and compiled to support and improve the proposed method, thereby prompting a more detailed and rigorous assessment method for inherent safety levels.

Acknowledgement

The authors are sincerely grateful for the financial support from the Research Council of Norway (grant No.: 352375).

References

Ahmad, S. I., H. Hashim, and M. H. Hassim. (2014). Numerical Descriptive Inherent Safety Technique (NuDIST) for inherent safety assessment in petrochemical industry. *Process Safety and Environmental Protection 92* (5), 379–389.

Ahmad, S. I., H. Hashim, and M. H. Hassim. (2016). A graphical method for assessing inherent safety during research and development phase of process design. *Journal of Loss Prevention in the Process Industries 42*, 59–69.

Ahmad, S. I., H. Hashim, M. H. Hassim, and R. Rashid. (2019). A graphical inherent safety assessment technique for preliminary design stage. *Process Safety and Environmental Protection 130*, 275–287.

Amyotte, P. R., and F. I. Khan. (2021). The role of inherently safer design in process safety. *The Canadian Journal of Chemical Engineering 99* (4), 853–871.

Chen, C., N. Khakzad, and G. Reniers. (2020). Dynamic vulnerability assessment of process plants with respect to vapor cloud explosions. *Reliability Engineering & System Safety 200*, 106934.

Crowl, D. A., and J. F. Louvar. (2001). *Chemical process safety: fundamentals with applications*: Pearson Education.

De Haag, P. U., and B. Ale. (2005). Guidelines for quantitative risk assessment. *Netherlands: Committee for the Prevention of Disasters*.

Deng, Z., M. Bai, M. Qi, Y. Tian, H. Qu, and Y. Liu. (2024). Inherent safety assessment of on-board methanol reforming hydrogen production fuel cell system considering jet fire and vapor cloud explosion. *International Journal of Hydrogen Energy 50*, 1047–1061.

Edwards, D. W., and D. Lawrence. (1993). Assessing the inherent safety of chemical process routes: is there a relation between plant costs and inherent safety? *Process Safety and Environmental Protection: Transactions of the Institution of Chemical Engineers, Part B 71* (4), 252–258.

Gangadharan, P., R. Singh, F. Cheng, and H. H. Lou. (2013). Novel methodology for inherent safety assessment in the process design stage. *Industrial and Engineering Chemistry Research 52* (17), 5921–5933.

Gao, X., A. A. Abdul Raman, H. F. Hizaddin, M. M. Bello, and A. Buthiyappan. (2021). Review on the Inherently Safer Design for chemical processes: Past, present and future. *Journal of Cleaner Production 305*, 127154.

Heikkilä, A. M., M. Hurme, and M. Järveläinen. (1996). Safety considerations in process synthesis. *Computers and Chemical Engineering 20* (SUPPL.1), S115–S120.

Hristova, M., and S. Tchaoushev. (2006). Calculation of Flash Points and Flammability Limits of Substances and Mixtures. *Journal of the University of Chemical Technology and Metallurgy 41* (3), 291–296.

Hurme, M., and M. Rahman. (2005). Implementing inherent safety throughout process lifecycle. *Journal of Loss Prevention in the Process Industries 18* (4), 238–244.

Iannaccone, T., G. Landucci, G. E. Scarponi, S. Bonvicini, and V. Cozzani. (2019). Inherent safety assessment of alternative technologies for LNG ships bunkering. *Ocean Engineering 185*, 100–114.

Khan, F. I., and S. A. Abbasi. (1998). Inherently safer design based on rapid risk analysis. *Journal of Loss Prevention in the Process Industries 11* (6), 361–372.

Khan, F. I., and P. R. Amyotte. (2005). I2SI: A comprehensive quantitative tool for inherent safety and cost evaluation. *Journal of Loss Prevention in the Process Industries 18* (4), 310–326.

Kletz, T. A., and P. Amyotte. (2010). *Process plants: A handbook for inherently safer design*: Crc Press.

Lefebvre, D., and F. H. Tezel. (2017). A review of energy storage technologies with a focus on adsorption thermal energy storage processes for heating applications. *Renewable and Sustainable Energy Reviews 67*, 116–125.

Leong, C. T., and A. M. Shariff. (2009). Process route index (PRI) to assess level of explosiveness for inherent safety quantification. *Journal of Loss Prevention in the Process Industries 22* (2), 216–221.

Moosemiller, M. (2011). Development of algorithms for predicting ignition probabilities and explosion frequencies. *Journal of Loss Prevention in the Process Industries 24* (3), 259–265.

Muratore, A., G. Grillone, M. Bellissimo, G. Giannelli, and V. Nastasi. (2025). Index Method for the Assessment of Natech Risk from Storms. *Chemical Engineering Transactions 119*, 439–444.

Park, S., S. Xu, W. Rogers, H. Pasman, and M. M. El-Halwagi. (2020). Incorporating inherent safety during the conceptual process design stage: A literature review. *Journal of Loss Prevention in the Process Industries 63*, 104040.

Pukazhselvan, D., K. S. Sandhya, D. P. Fagg, and F. Blaabjerg. (2026). The future of clean transportation: Hydrogen, batteries, ammonia, and green methane in perspective. *Renewable and Sustainable Energy Reviews 226*, 116286.

Rathnayaka, S., F. Khan, and P. Amyotte. (2014). Risk-based process plant design considering inherent safety. *Safety Science 70*, 438–464.

Shariff, A. M., C. T. Leong, and D. Zaini. (2012). Using process stream index (PSI) to assess inherent safety level during preliminary design stage. *Safety Science 50* (4), 1098–1103.

Stadler, I., and M. Sterner. 2018. "2.3 - Urban Energy Storage and Sector Coupling." In Peter Droege (Eds.), *Urban Energy Transition (Second Edition)*, pp. 225–244. Elsevier.

Tamburini, F., F. Ricci, and V. Cozzani. 2025. "Evaluating Natech Risks in the Liquid Hydrogen Maritime Bunkering Infrastructure." ASME 2025 44th International Conference on Ocean, Offshore and Arctic Engineering.

Tugnoli, A., G. Landucci, and V. Cozzani. (2009). Key performance indicators for inherent safety: Application to the hydrogen supply chain. *Process Safety Progress 28* (2), 156–170.

Tugnoli, A., G. Landucci, E. Salzano, and V. Cozzani. (2012). Supporting the selection of process and plant design options by Inherent Safety KPIs. *Journal of Loss Prevention in the Process Industries 25* (5), 830–842.

Voldsund, M., A. Reyes-Lúa, C. Fu, M. Ditaranto, P. Nekså, M. J. Mazzetti, O. Brekke, A. U. Bindingsbø, D. Grainger, and J. Pettersen. (2023). Low carbon power generation for offshore oil and gas production. *Energy Conversion and Management: X 17*, 100347.

Wei, H., J. Dang, Z. Deng, Y. Yan, and Y. Liu. (2025). Inherent safety assessment of water electrolysis hydrogen production systems. *International Journal of Hydrogen Energy 139*, 766–778.

Zanobetti, F., G. Pio, M. Bucelli, L. Miani, S. Jafarzadeh, and V. Cozzani. (2024). Onboard carbon capture and storage (OCCS) for fossil fuel-based shipping: A sustainability assessment. *Journal of Cleaner Production 470*, 143343.

Zanobetti, F., G. Pio, S. Jafarzadeh, M. M. Ortiz, and V. Cozzani. (2023). Inherent safety of clean fuels for maritime transport. *Process Safety and Environmental Protection 174*, 1044–1055.