INFORMATICS JOURNALS

Online **ISSN :** 3049-3455

Mineral Metal Energy Oil Gas and Aggregate

Contents available at: *www.informaticsjournals.co.in/index.php/2MEOGA*

2MEOGA

Discussion-Opinion-Editorial
Part 2: Greening Steelmaking: All Round Progress made so Far

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Abstract

As of late 2023 for assessing transparency, trends and developments in low-carbon project announcements across the iron and steel industry the projects are now categorised based on their level of detail concerning timeline, planned capacity, investment, technology used and potential to achieve at least 85% CO_2 emission reductions compared to average steelmaking emissions. The plants exceed 50 to 60% emissions reductions, including hydrogen production projects that link direct ties to iron and steel manufacturing. In this part, we will discuss the three leaders in this space.

Keywords: *Adoption, Safety and Risk, Timelines, Water Issues*

1.0 Hybrit

SSAB, LKAB, and Vattenfall, all from Sweden, are making a unique joint effort to fundamentally change the Swedish iron and steel industry. Under the name HYBRIT, they are working together to develop the first fossil-free steel. The HYBRIT technology can potentially reduce Sweden's total carbon dioxide emissions by at least 10 per cent. This is equivalent to one-third of the emissions from the industry and may, in the future, help to reduce emissions from iron and steel production globally. The HYBRIT initiative now presents the results of six years of research in a final report to the Swedish Energy Agency. The report shows that directly reduced iron produced with the HYBRIT process has superior characteristics to iron produced with fossil fuels. HYBRIT has applied for and received several patents based on the successful results. The project is now continuing in the next phase where the process is to be implemented on an industrial scale.

The research results now presented in a final report to the Swedish Energy Agency span from 2018 to 2024, with a focus on scaling up technical solutions from the laboratory to industrial scale, developing an industrial process practice and achieving an integrated value chain for hydrogen-based iron and steelmaking.

Examples of results from the pilot phase are the development of new hydrogen-based technology for efficient fossil-free iron and steel production with 0.0 tonnes of CO_2 emissions per tonne of steel, the development of a new fossil-free iron product (sponge iron) that has significantly better properties than iron reduced with fossil gases such as natural gas, the successful long-term operation of alkaline electrolysers for the production and storage of hydrogen, and the development of an efficient process practice for melting fossil-free sponge iron into crude steel in an electric arc furnace. "The focus of HYBRIT's technical development has been to build up expertise and create technical conditions for the implementation of a fossil-free process in a full-scale production.

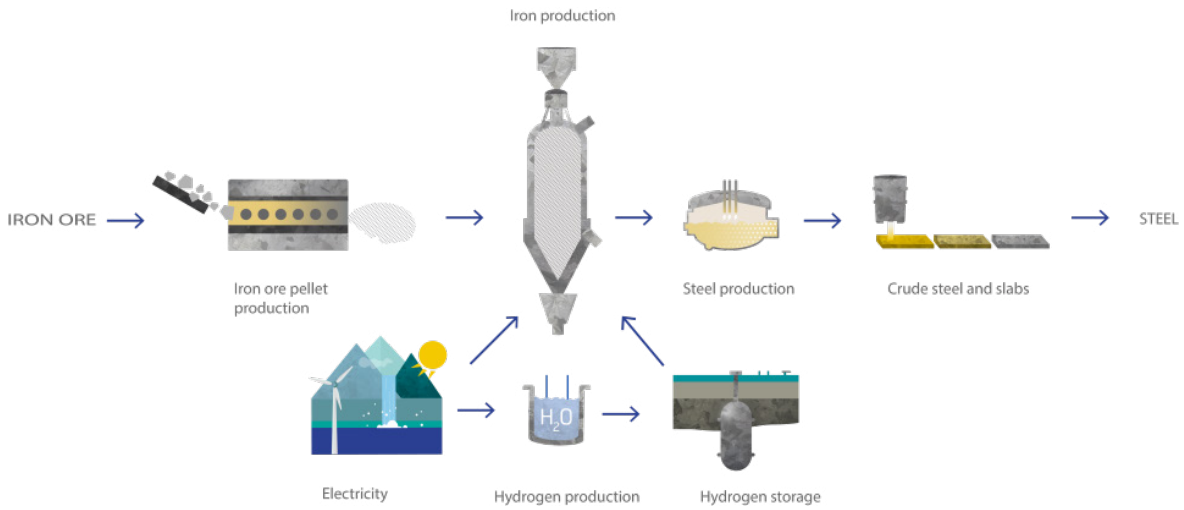


Figure 7. Hybrit scheme.

1.1 HYBRIT Process

Iron ore pellets are fed into the top of a shaft furnace, and hydrogen is heated to between 800 and 900 degrees centigrade and blown in from the middle. The hydrogen rises to the top of the furnace, while the iron ore descends and is gradually reduced by the hydrogen. The metallic iron is collected at the bottom of the furnace. The HYBRIT process is a climate-neutral alternative to the coal-based blast furnace technology that currently produces most of the world's steel. The HYBRIT process produces 42 kilograms of biogenic CO_2 per tonne of iron, compared to 383 kilograms of fossil CO_2 per tonne in a conventional natural gas process[1-3].

1.2 HYBRIT: Hydrogen Storage

HYBRIT's hydrogen storage has now been tested commercially on the electricity market. Its excellent results are important for the industry's transition. Green hydrogen is a prerequisite for producing fossil-free steel. By also adding storage, the variable cost of hydrogen production can be significantly reduced, by between 25 to 40 per cent. HYBRIT is a collaboration between SSAB, LKAB and Vattenfall that started in 2016. The hydrogen storage facility was used specifically on the electricity market for about a month. The mission was to produce hydrogen using fossil-free electricity at a variable electricity price with the lowest possible cost, for example during certain parts of the day or for longer periods when weather-dependent electricity generation was in good supply. The hydrogen was delivered in a steady flow to SSAB.

"Although Vattenfall optimised trading and operations against real electricity prices during a period with low price variations, the results were very good. The tests were conducted in close collaboration between Hybrit Development and Vattenfall. By applying it in actual circumstances, we were able to follow in real-time how much money was saved by using what was stored," says Marie Anheden, senior project manager at HYBRIT.

All research done on the hydrogen storage, which is adjacent to HYBRIT's pilot plant for fossil-free iron in Luleå, has so far shown promising results. Hybrit ordered a 4.5 MW electrolyser solution, for its pilot plant in the northern city of Luleå. The design itself has proven to be well suited for rapid emptying and filling, interspersed by periods of less activity. The latest effort to lower the price of hydrogen production used a simulation tool, a new optimisation model and the 100 cubic meter pilot hydrogen storage in Luleå.

1.3 Comparative Analysis using HYBRIT

A study is to compare the life-cycle energy required for Conventional Steel and HYBRIT Steel. The application chosen for this comparison was a bogie beam of Volvo's articulated hauler A30. An articulated hauler is a heavy-duty dump truck designed to transport large loads over rough terrain and sometimes even on public roads. Articulated haulers are used for mining, quarrying, tunnelling and even more versatile jobs. The articulated

hauler considered for this study was Volvo's A30. The energy consumption of the material extraction and bogie manufacturing phases was negligible as compared to the rest. For HYBRIT Steel, the steel production process had a 4.90% reduction in energy consumption for both A30 Original and A30 Optimized. Also, during the end-of-life phase, HYBRITS teel recovered around 4.8% more energy than Conventional Steel. In total, HYBRIT saved 8.32% and 8.16% of energy for A30 Original and A30 Optimized respectively. HYBRIT Steel consumed 8-10% less energy than Conventional Steel which is worth noting. For applications with less dominant use phases, the percentage of energy saved by HYBRIT Steel would be even larger. In the future, this LCA methodology can be extended for other steel applications[3].

2.0 H2 Greensteel, now known as Stegra

The company, Stegra Boden-plant claims of a process that starts in the 700-megawatt electrolyzer plant – the largest in Europe – where green hydrogen is produced via electrolysis of water**.** Located in the north of Sweden due to its wealth of clean electricity, it has close access to the power grid, availability of raw materials, and logistics infrastructure. By 2030, it will be producing 5 million tonnes of green steel annually. This will take place in a reactor inside the 145-meter-tall direct reduction tower. By replacing coal with green hydrogen and electrifying the steelmaking process, they will be able to cut CO_2 emissions by up to 95% compared to traditional steelmaking. Moving forward, they will continue to reduce emissions even more – getting closer and closer to zero – year by year. Europe's largest electrolyzer will have a giga-scale electrolyzer plant, powered by renewable electricity and with water from the Lule River, seamlessly integrated into our production site. This facility will produce the green hydrogen necessary to make green iron and supply 5 million tonnes of high-quality green steel to the market by 2030[4].

H2 Green Steel is a new (February 2021) announced project that aims to build a giga-scale green hydrogen plant to produce fossil-free steel. Green hydrogen will replace the natural gas to produce sponge iron, and every process step of the entire production flow will be electrified. Thus, virtually the only emissions are steam with the carbon emissions expected to be reduced by up to 95 per cent from the outset. The plant is fully integrated with hot charging at each step along the production flow. Production is expected to begin in 2024[5,6].

2.1 Europe's Largest Electrolyzer at Boden

The giga-scale electrolyzer plant, powered by renewable electricity and with water from the Lule River, is seamlessly integrated into the production site. This facility will produce the green hydrogen necessary to make green iron and supply 5 million tonnes of high-quality green steel to the market by 2030[7,8].



Figure 8. The Boden plant.

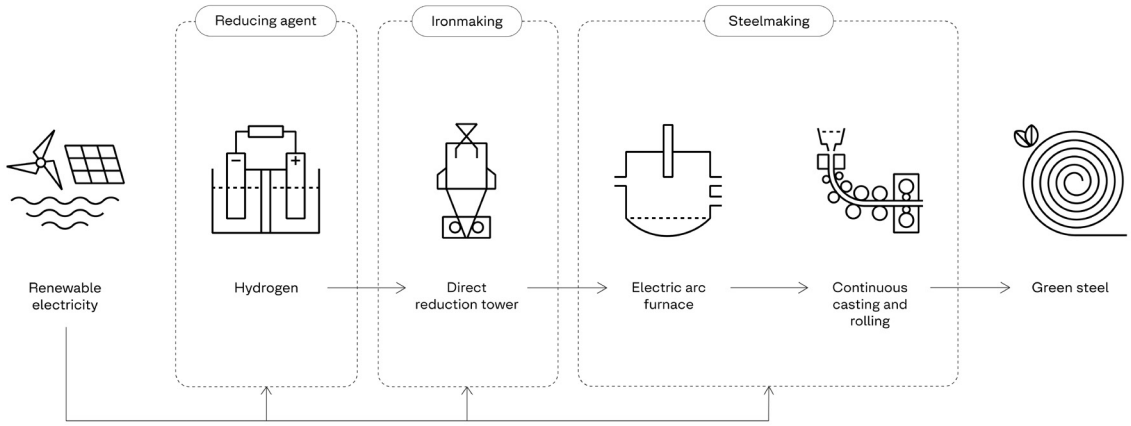


Figure 9. At the Boden plant, the green steel will be the first near-zero product with up to 95% reduction in CO_2 emissions, it will be the greenest ore-based steel produced at scale.



Figure 10. Electrolyser plant at Boden.

2.2 Some of the Partners of Stegra

2.2.1 Porsche

Porsche AG and Stegra have signed an agreement for the supply of CO_2 -reduced steel. The aim is to further improve the emissions balance of Porsche vehicles by using CO_2 -reduced steel.

2.2.2 Ingka Group (IKEA)

Ingka Group, the largest IKEA retailer, signed an agreement with Stegra for the delivery of green steel, to be used in IKEA warehouse racking. The agreement forms part of Ingka Group's ongoing action to reduce its climate footprint.

2.2.3 Scania

The initial contract with Stegra will provide Scania with sustainably produced steel for building its trucks, allowing the company to take another big step towards reducing the climate footprint of its vehicle manufacturing[7].

3.0 Cleveland-Cliffs

Cleveland-Cliffs has set new Greenhouse Gas (GHG) emissions reduction targets. The Company's prior commitment to reduce absolute Scope 1 (direct) and Scope 2 (indirect) GHG emissions by 25% by 2030, relative to 2017 levels, has already been successfully achieved well ahead of schedule. The new goals, as displayed in the adjacent graphic, relative to 2023 levels, are all supported by ongoing and planned technological developments to its ironmaking and steelmaking practices.

As of January 26, 2024, Cleveland-Cliffs Inc. (NYSE: CLF) announced that it has completed a hydrogen (H2) injection trial at its Indiana Harbor #7 blast furnace, the largest blast furnace in North America. This represents the second Cleveland-Cliffs blast furnace to utilize hydrogen as a reductant and fuel source, following the successful trial at Middletown Works in May of 2023. Indiana Harbor #7 is among the largest blast furnaces in the entire world, both in size and production capacity. IH #7 also compares favourably against similar equipment in Japan, Korea, China or Europe, for its technological capability to support the production of high-end steels, including highly specified automotive feedstock. Cliffs recently completed the commissioning of the hydrogen pipeline at Indiana Harbor, which was used for this trial. This successful commissioning marks another significant achievement toward Cliffs' future GHG reduction efforts, completing the pipeline in advance of schedule, below budget and without incident. Cliffs' hydrogen gas supplier, Linde, was a critical partner in the successful execution of this major trial. Lourenco Goncalves, Cliffs' Chairman, President and Chief Executive Officer, said: "Indiana Harbor #7 is the largest blast furnace in North America and we are proud of our ability to be ahead of the curve in using this cutting-edge technology to decarbonize while maintaining both our efficiency and the high standard of quality that comes with steel produced via the blast furnace route. As the American iron and steel leader, we are proud that we are ahead of the rest of the world in using the technologies that make our blast furnace steel the cleanest in the world, including using iron ore pellets, natural gas injection, HBI, and now hydrogen. I congratulate my team on another major step forward. I also thank Linde for their valuable contribution."

However, Cleveland Cliffs has not yet secured a reliable source of hydrogen — green or otherwise — so the furnace will likely rely on methane for the time being. The use of methane gas will reduce onsite greenhouse gas emissions from ironmaking compared to sticking with the coal-dependent current process, but it misses the opportunity to make more significant emissions cuts with green hydrogen. While health impacts from coal and coke are greater than those from methane, the increased gas demand will be felt by communities that are adjacent to the wells and refining facilities, too.

Notably, the DOE is funding a Swedish company SSAB to construct a comparable ironmaking furnace in Mississippi that uses the same technology. This other project, however, is committed to using hydrogen from the start and has already secured a supply agreement with a sustainable hydrogen producer. In its first DOE-hosted public briefing on the prospective project in April 2024, Cleveland Cliffs emphasized the anticipated economic benefits that the investment would bring to the local community. The company estimated that the project would not only preserve the site's existing 2,500 jobs but also add 170 additional union jobs. In addition, the facility is expected to employ 1,200 construction workers.

Cleveland-Cliffs Inc., a flat-rolled steel producer, announced that two projects were chosen for up to $575 million in total funding from the Department of Energy (DOE) to pursue two decarbonization investments at Middletown Works in Ohio and Butler Works in Pennsylvania. The projects will result in substantial reductions in GHG emissions across the Cliffs' footprint.

The Federal funding is being made available through DOE's Industrial Demonstrations Program funded through the Infrastructure Investment and Jobs Act and the Inflation Reduction Act. The Middletown Works DRI Plant and Electric Melting Furnaces could receive up to a $500 million grant. If awarded, the Company would replace its existing blast furnace at its Middletown Works Facility in Middletown, Ohio, with a 2.5mtpa Hydrogen-Ready Direct Reduced Iron (DRI) Plant and two 120 MW Electric Melting Furnaces (EMF) to feed molten iron to the existing infrastructure already on site, including the

BOF, Caster, Hot Strip Mill, and various finishing facilities (Figure 1)

Currently under development, hydrogen ironmaking technologies primarily include Hydrogen Plasma Smelting Reduction (HPSR), hydrogen flash ironmaking, hydrogen-enriched blast furnace ironmaking, and shaft furnace Hydrogen Direct Reduction (H-DR) technologies. The first two technologies use 100% H2 but are currently only successful in laboratory-scale tests. ThyssenKrupp has started injecting H2 in one of the blast furnaces, but coke is still needed in the blast furnace because its framework function cannot be replaced and is only expected to reduce CO_2 emissions by up to 20%. Hydrogen direct reduction is a technology established based on the most successful industrial shaft furnace direct reduction processes, such as Midrex and HYL. Gaseous reducing agents, with an H2 content of 55–85 vol %, are used in these processes, indicating the high possibility of using 100% H2 in the shaft furnace direct reduction. Moreover, replacing natural gas with 100% H2 could reduce the amount of directly emitted CO_2 by up to 91%. Thus, shaft furnace H-DR technology, which employs clean H2 as the reductant, is considered the most promising ironmaking technology for reducing CO_2 emissions, the expected steelmaking route, H-DR-EAF route, is shown in Figure 11[8,9].

The EMF technology is well established and, along with the injection of hydrogen in blast furnaces, is a preferred route for meaningful reduction in carbon emissions for integrated steelmakers worldwide.

The process will dramatically reduce carbon emissions intensity as the facility will have the flexibility to be fueled by natural gas, which would reduce current ironmaking carbon intensity by over 50%; a mix of natural gas and clean hydrogen; or clean hydrogen, which would reduce current ironmaking carbon intensity by over 90%.

Hydrogen demand from this flex-fuel DRI plant stands to support DOE's Hydrogen Earthshot and DOE's Hydrogen Hub initiatives. The Butler Works Induction Reheat Furnaces could receive up to a $75 million grant. If awarded, Cliffs would also replace two of its existing natural-gas-fired high-temperature slab reheat furnaces at Butler Works in Butler, Pennsylvania, with four Electrified Induction Slab Reheat Furnaces to bring optimum efficiency to its production of electrical steels, a critical component of the electrification of the U.S. and the greening of the electrical grid. The primary benefits

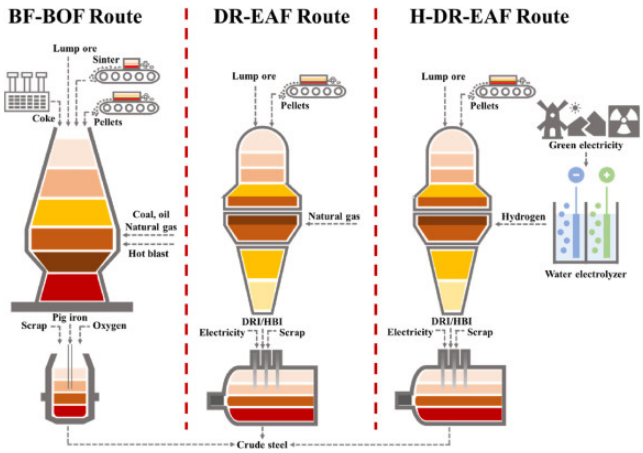


Figure 11. Steelmaking routes with hydrogen route.

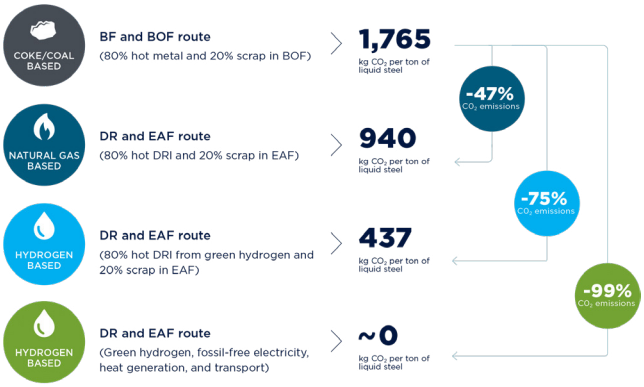


Figure 12. The performance comparison.

of this project are lower carbon emissions, substantially reduced energy costs and improvements in slab quality, allowing for approximately 25,000 tons of additional production capacity from improved process yield.

4.0 Green Steel Making Challenges

Changing to a green steel production process is associated with some challenges:

- It is necessary to reconsider well-proven, effective technologies in which hundreds of billions of dollars have been invested.
- Producing steel by directly reducing iron with gas will cost 20% more than the traditional blast furnace process. When carbon capture technologies are combined with the Direct Iron Reduction Process (DRI), production costs increase by another 10%—replacing natural gas with green hydrogen (without capture) – by 40% of the primary option

"DRI – natural gas." According to the Rocky Mountain Institute, green steel costs in Northern Europe, for example, could be 20 to 30 per cent higher, considering current electricity prices. It's also worth saying that methane gas as fuel is used in this process to produce hydrogen and carbon monoxide, which are then used to convert iron ore into iron. Theoretically, it is possible to reduce CO_2 emissions from each received ton in half, but we cannot talk about the "environmental friendliness" of this process.

- The main problem with Carbon Capture and Storage Technology (CCS) is its high cost. World experience shows that for CCS project implementation, it is necessary to create a consortium of representatives of large businesses. The difficulty of using this technology in metallurgical production, in a «blast furnace-converter» production chain, is caused by generating large volumes of waste gases and relatively low content of carbon dioxide in them – in a converter and blast furnace gas, the share of CO_2 is only 13-16% and 12-22% respectively.
- The volumes of scrap in EAF and DRI production will need to be increased to replace the blast furnace process entirely soon[9,10].

5.0 Hydrogen Adoption in Steelmaking: Safety and Water Challenges

Commonly, these two approaches are followed:

a. The qualitative approach:
   1. FMEA (Failure Mode Effect Analysis) and
   2. HAZOP (HAZard and Operability Method).
b. The quantitative approach:
   1. FMECA (Failure Mode Effects and Criticality Analysis)
   2. RPN (Risk Probable number and Risk Matrix)

5.1 FMEA

Failure Mode and Effects Analysis (FMEA) is a proactive method of uncovering potential failures in business processes to prevent them from happening or mitigate their effect by finding out where they might occur and determining their impact. FMEA's systematic approach to identifying and addressing causes of failures can help prevent costly manufacturing issues, improve product quality and service reliability, as well as increase customer satisfaction.

5.2 HAZOP

A Hazard and Operability (HAZOP) study is a systematic way to identify potential hazards and problems in a process or system. HAZOP studies are often performed on industrial processes to ensure the safety of people and assets, and to maintain productivity.

Here are some key aspects of HAZOP studies:

- Who performs them

A small team typically made up of a process engineer, control instrument expert, risk analyst, operator, and computer systems expert.

- When they are performed

During the design and construction of new facilities, when new processes are added, or when processes change.

- How they are performed

The team breaks down each step of the process and uses guide words to question every part.

- What they look for

Deviations from the original design, the causes of these deviations, and their consequences.

- What they help ensure

Process modifications don't introduce new hazards.

HAZOP studies typically have four phases: definition, preparation, examination, and documentation and follow-up.

5.3 FMECA

Failure Mode, Effects, and Criticality Analysis (FMECA) is a technique used to identify potential failures in a system or equipment, to quantify the risk associated with them and to determine how to prioritize and eliminate them. FMECA is an extension of Failure Mode and Effects Analysis (FMEA), which is a bottom-up analytical method.

FMECA can help with:

a) Safety: Identifying potential safety risks and addressing them before they occur
b) Reliability: Improving equipment reliability and asset integrity
c) Compliance: Improving compliance
d) Downtime: Reducing breakdowns and downtime

e) Resource optimization: Allocating resources more effectively by focusing on the most critical assets
f) Predictive maintenance: Calculating the chances and impacts of potential failures to help teams use predictive maintenance strategies
g) FMECA can help managers by for asking the required resources to avoid the risk in a quantifiable manner.

FMECA is performed by:

1. Following up on the FMEA
2. Performing the Criticality Analysis
3. Criticality is a measure of risk that combines severity and probability of occurrence.

5.4 RPN

The RPN is a numerical value that helps quantify the severity, probability, and detectability of potential risks. It is commonly used in industries such as software development to identify and prioritize potential risk factors. The RPN serves as a valuable tool for risk assessment and management. By assigning numerical

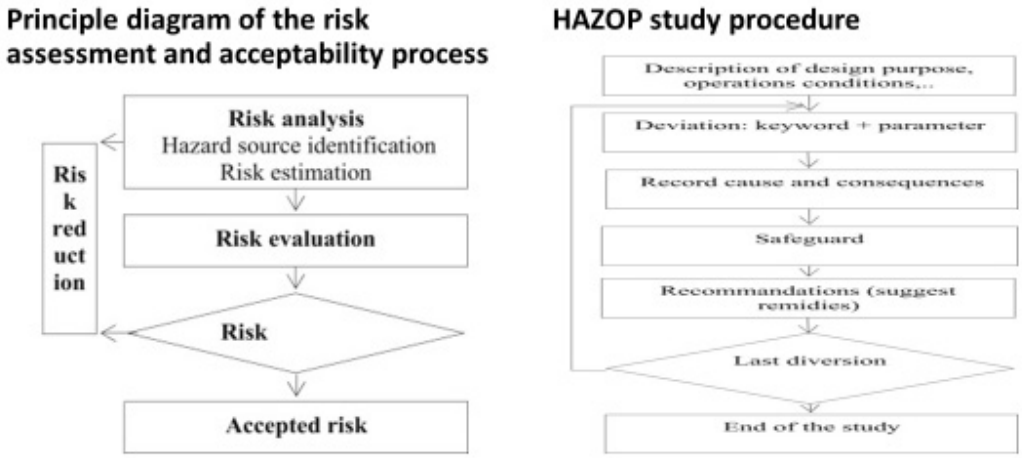


Figure 13. Risk assessment.

		Severity				
		Negligible (1)	Marginal (2)	Moderate (3)	Critical (4)	Catastrophic (5)
Probability	Almost certain (5)	Medium (5)	High (10)	High (15)	High (20)	High (25)
	Likely (4)	Low (4)	Medium (8)	High (12)	High (16)	High (20)
	Possible (3)	Low (3)	Medium (6)	Medium (9)	High (12)	High (15)
	Unlikely (2)	Low (2)	Low (4)	Medium (6)	Medium (8)	High (10)
	Rare (1)	Low (1)	Low (2)	Low (3)	Low (4)	Medium (5)

Figure 14. RPN.

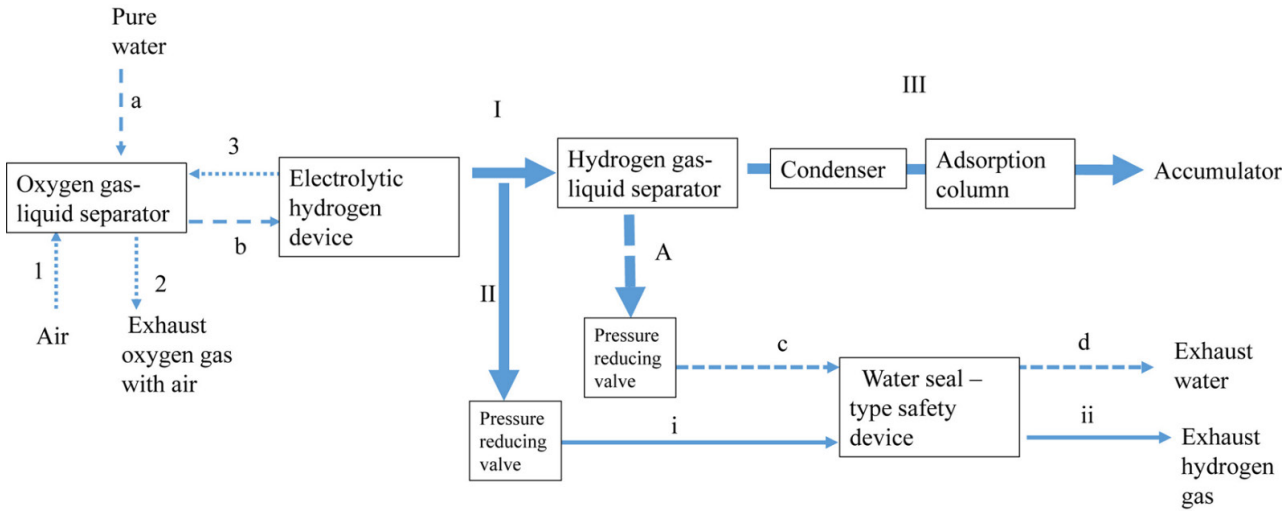


Figure 15. A schematic of an electrolyzer.

Parameter	Pressure	Guide word	More
Deviation	Pressure increase		
Trigger phenomenon	Fire at hydrogen station		
Leakage mode	Large hydrogen leak from fracture in piping		

Scenario		Safety measures
1	The device or piping is heated by fire at the hydrogen station	
2	Temperature of the device or piping increases	
3	Pressure in the device or piping increases	Monitoring of pressure in the system Interlocks based on pressure monitoring Safety valve
4	The strength of the material of the device or piping decreases	
5	Destruction of the device or piping	Hydrogen sensor
6	Leakage of hydrogen	
7	Ignition	
8	Fire/explosion	Fire wall/protection wall against hydrogen explosion

Pressure of the system at the failure point (MPa)	82
H_2 inventory of the system at the failure point (Nm^3)	700
Diameter of the leakage point (mm)	10
Jet flame length (m)	36

	Possibility	Severity	Risk
Without safety measures	ii	V	H
With safety measures	i	IV	M

Figure 16. A section HAZOP worksheet of a Hydrogen plant (from online source).

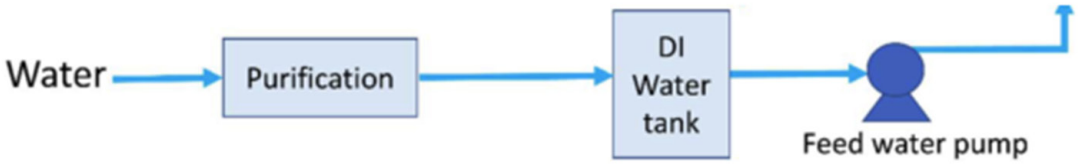


Figure 17. The water quality requirement.

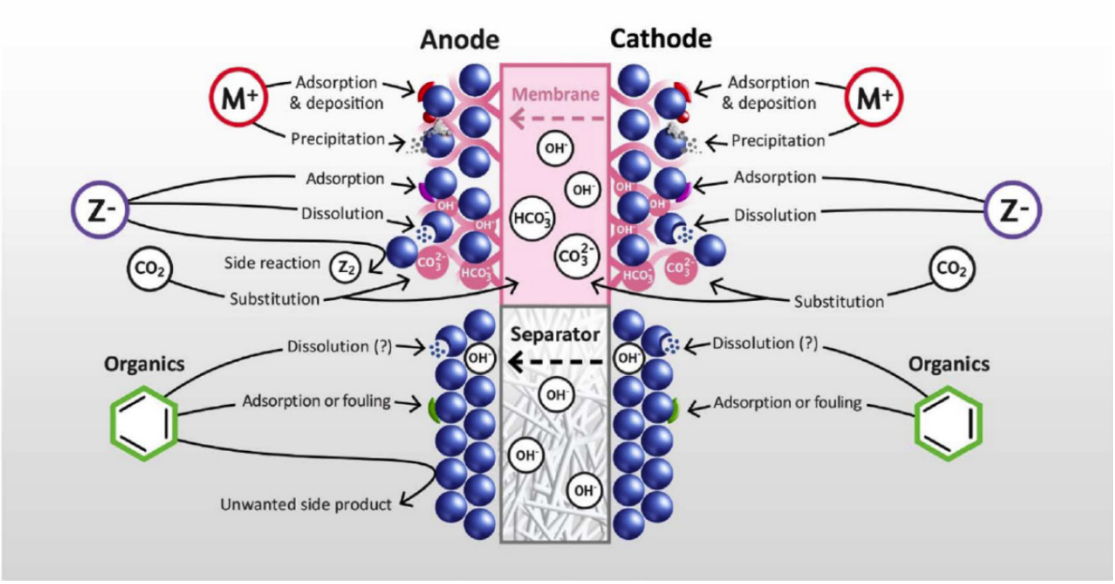


Figure 18. Role of various impurities.

values to different risk factors, it provides a systematic approach to evaluating and prioritizing risks. This allows organizations to allocate resources effectively and implement appropriate risk mitigation strategies.

5.5 Calculating RPN

a. Identify and define potential risks within the installation.
b. Assign numerical values to each risk factor: severity, probability, and detectability.
c. Multiply the severity, probability, and detectability values together to calculate the RPN.
d. Review and prioritize risks based on their RPN values.
e. Develop appropriate risk mitigation strategies for high-priority risks.

A configuration of the high-pressure hydrogen gas generation system with an electrolyzer can be seen in the figure 9. The solid lines and Roman numerals are used for the H2 piping, and thick dotted lines and small letters are used for the water piping. Thin dotted lines and Arabic numerals are used for the piping carrying O_2 or air. Bold lines and capital letters indicate piping in which the pressure is 82 MPa[11].

5.6 An example HAZOP

Let us see a HAZOP results sheet. Upper case and lower case Roman numerals mean the severity and the possibility of an accident. H and M mean the high and the medium risk levels. This demonstrates how a section HAZOP of an electrolyser plant will look like, as in Figure 16.

6.0 A Brief about the Water for Green Hydrogen

Water is a vital part of green hydrogen technology. The water quality requirement can be seen from the figure 17[12].

Various impurities play different roles in the electrolyzer, as can be seen in Figure 18.

N.B. For all-round adoption of green hydrogen, an external consultant team is absolutely necessary for those entering the field. Zelence Industries Private Limited (www.myzelence.com) helps put together a team of external consultants to help plants transition to green hydrogen adoption.

7.0 Disclaimer

The author does not recommend any technology or organization for green hydrogen adoption; he merely suggests pointers for action. Users' discretion is necessary.

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