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# Hydrogen-based Steel Making - The future?

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***Abstract***

*A largest energy consumer i.e. 5% of global energy consumption and 7% of global $CO^2$ emissions are produced by the iron and steel sector. The steel industry is a significant contributor to anthropogenic $CO^2$ emissions, largely due to the use of carbon as a reducing agent in the production of virgin steel. The main cause of these emissions is the decrease in iron ore. While recycling scrap steel in electric arc furnaces (EAFs) can help reduce demand for virgin steel, global demand for high-quality steel is expected to rise with economic growth and technological advancement. Therefore, technical solutions to reduce emissions from iron ore-based steelmaking are critical. Using hydrogen (H2) instead of carbon for the direct reduction of iron oxide/ore in steelmaking, combined with EAFs, presents a promising path toward fossil-free steel production. Hydrogen reduction of iron ore is theoretically feasible from a thermodynamic and kinetic perspective, but it remains an immature technology requiring significant research and development (R&D) to overcome processing challenges. Hydrogen-based iron and steelmaking holds significant potential for reducing $CO^2$ emissions in the steel industry, but it is not yet a mature technology. The transition to hydrogen reduction will require extensive R&D, substantial investment in new infrastructure, and a reliable supply of low-cost, low-carbon hydrogen. As global efforts to expand renewable energy capacity continue, the feasibility and economic competitiveness of hydrogen-based steelmaking are likely to improve, making it a crucial component of a low-carbon future. he paper uses a combination of microeconomic analysis and technical assessment to evaluate the future role of hydrogen-based iron and steel production as well as its possible impact on global material flows.*

**Keywords:** Direct reduced iron; blast furnace; hydrogen; steel making; $CO_2$ emission; energy consumption

## INTRODUCTION

Steel is a critical component in various sectors that underpin economic growth and development. Its applications span infrastructure, housing, transportation, and industrial machinery, making it essential for both urbanization and industrialization. As countries develop, their steel consumption typically increases, reflecting the expansion of these foundational sectors. India consumes roughly 74 kg of steel per person, which is much less than the 229 kg global average.

This discrepancy highlights a substantial potential for growth in steel consumption, which is closely linked to the country's economic development.

The questions of global warming and the current political efforts to control greenhouse gas emission as manifested in the Kyoto protocol motivate reconsideration of the sources of $CO_2$ and of the options for abatement. Reaching zero emissions in the steel industry by 2050 is a formidable challenge but is essential to meet the goals of the Paris Agreement and mitigate dangerous climate change. Policy backing, technological advancement, investments in renewable energy, and industrial

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cooperation will all be necessary to achieve this. The dominant technologies for production of steel are Blast-Furnace-Basic Oxygen Furnace route which rely on carbon as reducing agent. Hydrogen-based direct reduction represents a transformative opportunity for the steel industry to achieve zero emissions by 2050, in line with the Paris Agreement targets. Initiatives like GrInHy, H2FUTURE, and HYBRIT are at the forefront of this transition, demonstrating the feasibility and potential of H-DR. While challenges remain, particularly in terms of cost and infrastructure, the declining costs of renewable electricity and increasing policy support provide a favorable environment for the adoption of hydrogen in steelmaking. As technology advances and economies of scale are realized, H-DR could become the standard for sustainable steel production, significantly reducing the industry's carbon footprint and contributing to global climate goals.[1].

## GLOBAL STEEL SCENARIO

### Production Scenario

World crude steel production reached 1878 million tonnes (Mt) for the year 2020 withaverage growth by 3% in last 5 years. In 2020, China accounted for 56.7% of the global market for steel (by volume) (Figure 1).

DRI production worldwide was driven by India, which remained the world’s largest DRI producer, despite a decline in the country’s output by 8.7% yoy in 2020 to 33.6 Mt. The country accounted for 31.7% of the global production in 2020, maintaining a similar %share in last five years [3].

India, presently hold the 2nd position in world, in terms of crude steel production (Table-1). In 2019 crude steel production was 111 Mt and consumption was 87.2 Mt. 56.2% of Indian steel produced through Electric route (EAF & IF), while 43.8% through BOF route.

### Steel Consumption

India’s steel consumption stood at 88.5 Mt in 2020, a sharp decline of 13.5% on the previous year’s 102.5 Mt due to pandemic COVID-19 contributed to the global economic downturn. India now consumes 74 kg of steel per person, far less than the 229 kg global average (Figure 2).

This Figure reflects the quantity of finished steel used per person annually and indicates considerable room for growth in steel consumption as the country continues to develop economically.

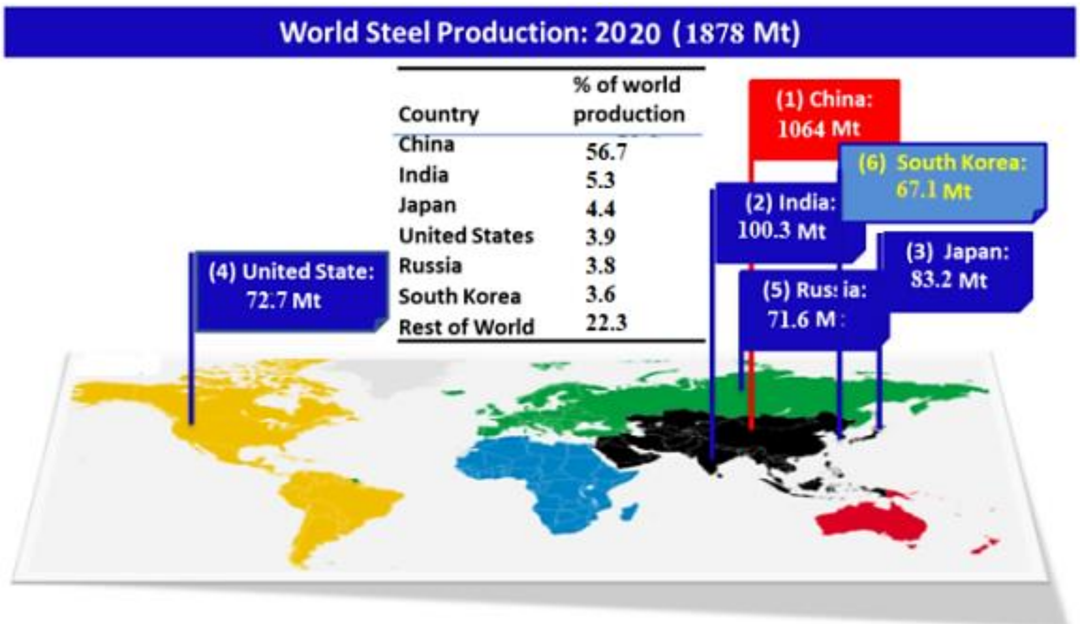


**Figure 1.** World Steel Production Map: 2020[2].

 

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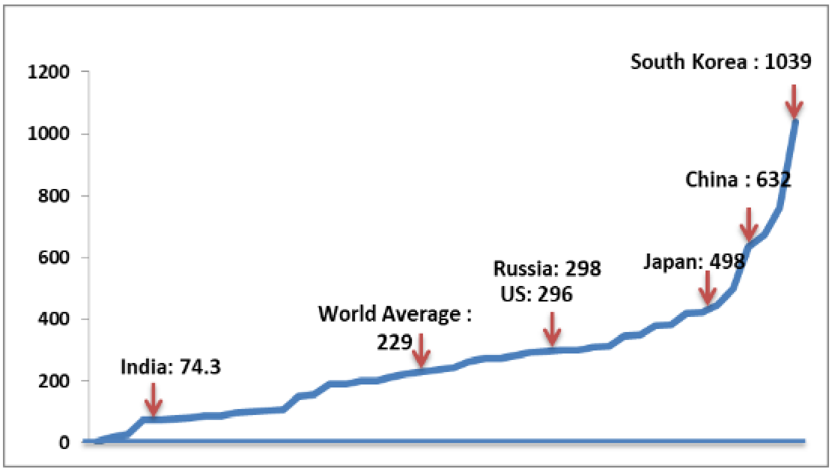


**Figure 2.** Apparent steel use per capita [2]

**Table 1.** DRI, Hot metal & Crude steel production: Jan-Dec 2020[2] (Unit in Mt).

| Crude steel production by process, 2020 | | | | Hot Metal Production | DRI Production |
|---|---|---|---|---|---|
| Country | Crude steel production | Oxygen Process (%) | Electric Process (%) | | |
| China | 1064.8 | 90.8 | 9.2 | 887.5 | 0 |
| India | 100.3 | 45.5 | 55.5 | 67.8 | 33.6 |
| Japan | 83.2 | 74.6 | 25.4 | 61.6 | 0 |
| US | 72.7 | 29.4 | 70.6 | 18.3 | 3.5 |
| Russia | 71.6 | 65.9 | 32.1 | 51.9 | 8.5 |
| S. Korea | 67.1 | 69.0 | 31.0 | 45.4 | 0 |
| World Total | 1878 | 73.2 | 26.3 | 1319.4 | 106.0 |

## Demand and Supply Forecast

Developed countries' steel consumption almost saturated at the level of 500 kg per capita as seen in Figure 2. That means, there are huge potential for Indian steel Industry to grow. Based on the historical experiences of different countries, the most important factors influencing the demand for steel are the pace of investment and the degree of industrialization.

For India, focusing on these factors can drive substantial growth in steel consumption, supporting its broader economic development goals. By enhancing production capacity, promoting sustainable practices, encouraging investment, and providing robust policy support, India can meet its growing steel demand and foster long-term economic growth.

The National Steel Policy, which outlines goals for production and demand growth through 2030, was introduced by the Ministry of Steel in 2017 in an effort to promote faster growth and a stronger emphasis on energy-efficient methods in the steel industry (Figure 3). With a 158 kg per capita steel consumption, the aim for steel production capacity was 300 Mt for 2030–31.

## PROCESS&TECHNOLOGY

### Conventional Steel Production Process

Compared to many other nations, India's steel industry is significantly more diverse, with a large variety of variously sized facilities in both the primary and secondary steelmaking sectors (Table 2).

### *Blast Furnace*

Basic Oxygen Furnace (BF-BOF), coal-based/gas based DRI- Electric Arc Furnace (EAF) are two most used route for steel making.

 

**Process of Steel Making**

Reduction/Smelting of iron ore/sinter in blast furnace and then refined to liquid steel in converter. Melting of CI Scrap/pig iron in electric furnace or alternatives routes and then refined to steel (Figure 4).

**Emission Norms and Environmental Issue**

India, along with Africa, would be among the few global regions that still anticipate increase in the demand for iron and steel in 2050. China's steel consumption has already peaked, with Western nations charting a fall. Therefore, the world must find a means to move toward zero carbon steel, and India must follow suit if its long-term development is to be compatible with a global scenario that limits warming to 2°C. Process route wise the energy efficiency of Indian steel plant is given in Table -3. Energy consumption in Indian steel plant is high as compared to Japan, Italy, Sweden, UK, Germany and USA (Figure 5). Plant wise energy consumption and $CO_2$ emission in India are shown in Figure 6 (a)& Figure 6 (b) respectively.

**Table 2.** Total working unit and capacity utilization of India steel industry.

| Type of Industry | No. of units | Total Capacity | No. of working units | Capacity utilization |
|---|---|---|---|---|
| BF-Hot Metal | 61 | 8.87 Mt. | 60 | 84.4% |
| BOF | 18 | 55.27 Mt. | 18 | 85.9% |
| EAF | 56 | 40.73 Mt. | 50 | 65.7% |
| IF | 1187 | 46.41 Mt. | 999 | 68.8% |
| Sponge Iron | 346 | 51.53 Mt. | 312 | 61.5% |

**Table 3.** Energy Efficiency (GCal/tcs).

| Process | BF-BOF route | DR-IF/EAF Route |
|---|---|---|
| Inefficient plant | 7.3 | 7.1 |
| Indian Average | 6.8 | 6.5 |
| Theoretical Minimum | 5.3 | 4.0 |

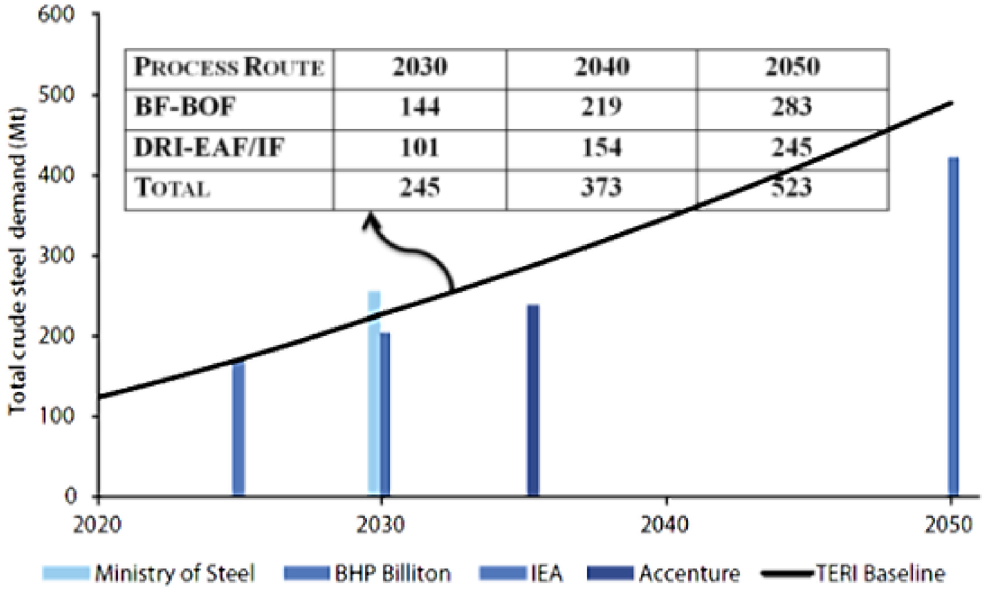


**Figure 3.** Comparison of different projections for Indian crude steel demand Source: MoS (2017); Gaur and Chaliawala (2018); IEA (2019b); Accenture (2017) [1].

 

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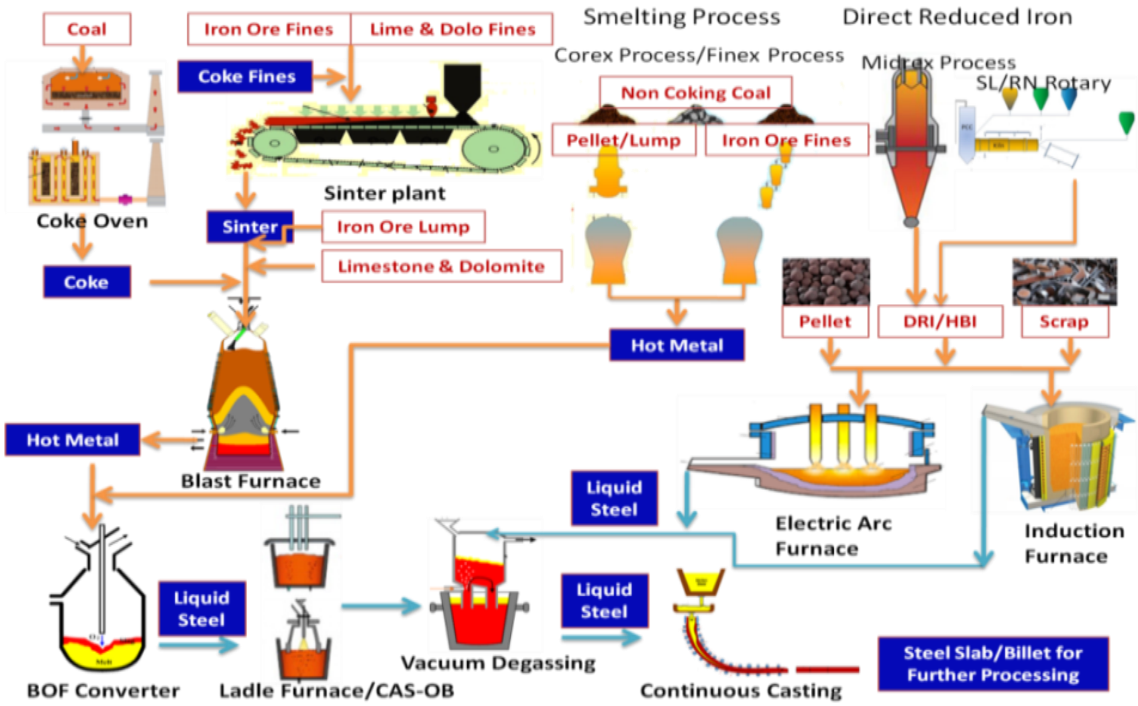


**Figure 4.** Schematic Diagram of Iron and Steel Making Process.

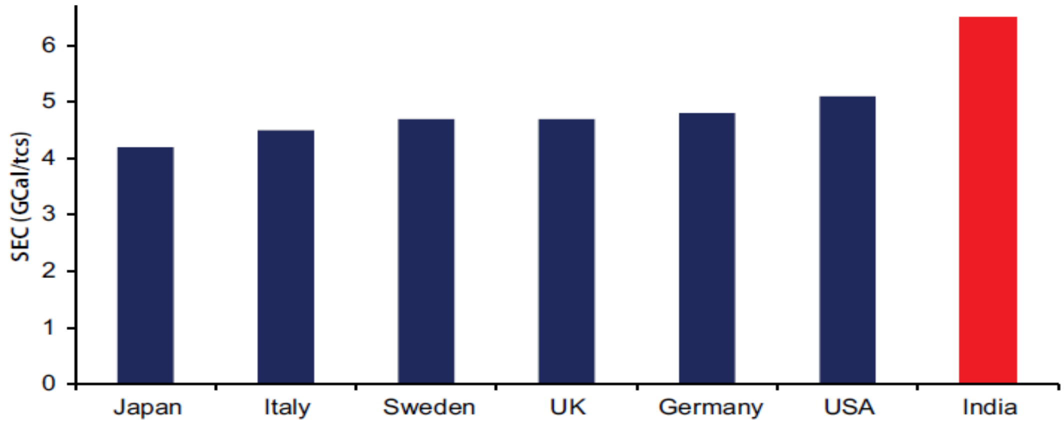


**Figure 5.** Average specific energy consumption of integrated steel plants by country.

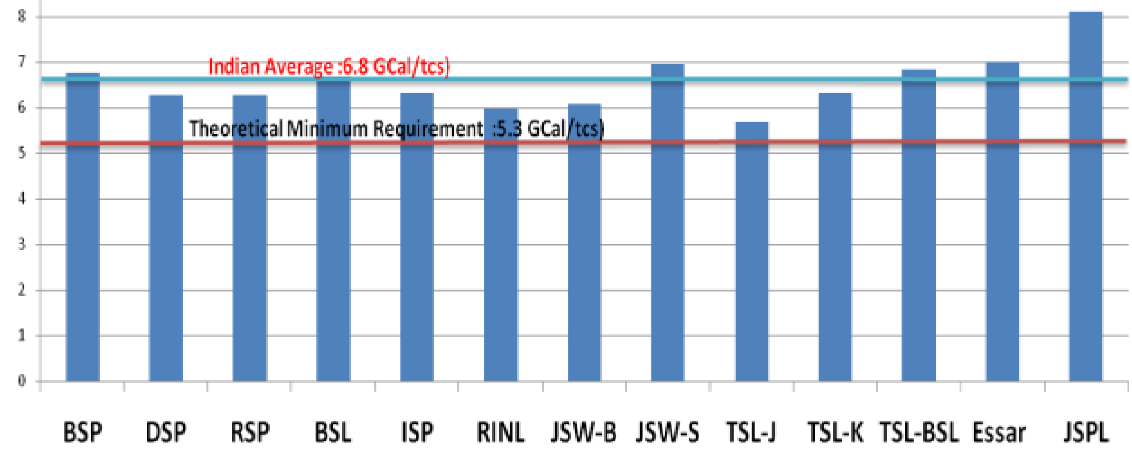


**Figure 6 (a).** Average specific energy consumption of integrated steel plants in India.

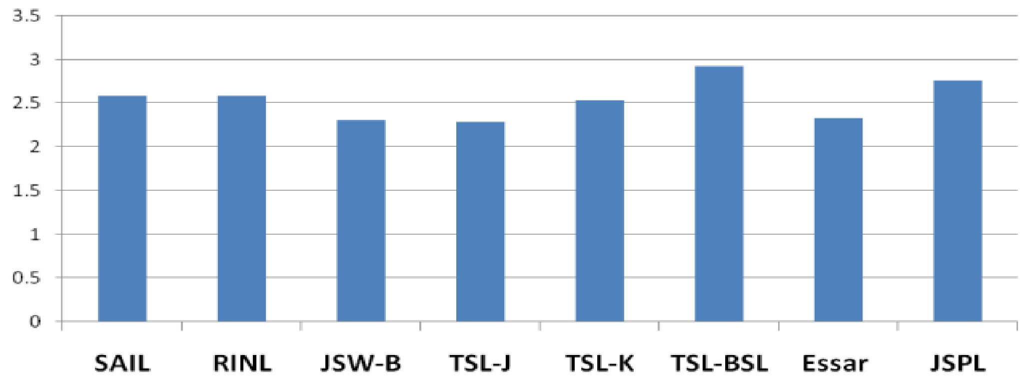


**Figure 6 (b).** Specific $CO_2$ Emission (T/tcs)of integrated steel plants in India.

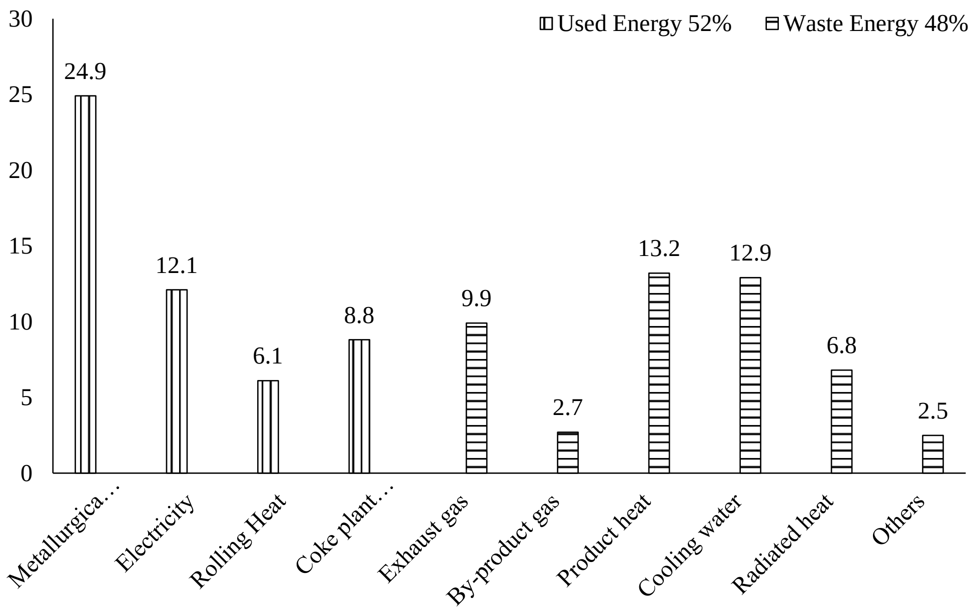


**Figure 7.** Energy employed and wasted in the BF-BOF route.

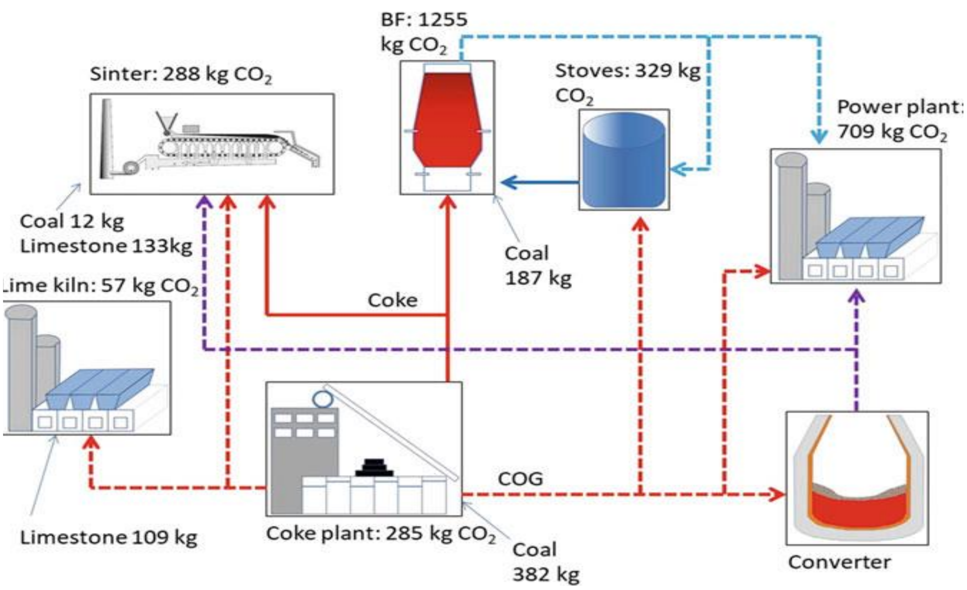


**Figure 8.** $CO_2$ emissions in the integrated steel mill.

 

Out of total energy applied in steel industry, 52% of the energy inputs are utilized for metallurgical reaction, electricity generation, and heat requirement in process and 48% are wasted in atmosphere (Figure 7). Similarly $CO_2$ emission is shown in Figure 8 for 1 ton production.

## HYDROGEN METALLURGY IN IRON MAKING

### Why hydrogen: Reason behind Hydrogen

Several countries signed the Paris agreement to mitigate global warmingand proposed plans to reduce carbon emission.On the basis of global warming and energy transformation, governments prioritize the development and utilization of carbon-free or low-carbon energy by two ways:

- By adopting Energy and Resource efficient technology
- Implementation of Deep De-carbonization Options

Hydrogen energy, with its diverse sources, low-carbon emission, high efficiency, and wide application range, has been regarded as the most promising clean energy in the 21st century. Hydrogen metallurgy mainly includes blast furnace iron-making with the addition of hydrogen and the production of direct reduction iron by hydrogen.

### Hydrogen utilization in Iron Making

There are two large technological areas for hydrogen utilization for iron reduction in steel industry:

#### *Direct reduction of Iron Ore*

For the last one decade new metallurgical technologies based reduction of iron ore by hydrogen or hydrogen rich mixed gas on pre-metallization of iron ore materials, or the production of metallised pellets, or direct production of iron are considered and taken trial on several industry.

#### *Hydrogen injection in Blast Furnace*

In the blast-furnace production of hot metal, the influence of wider hydrogen application, mainly because of the development of the injection of alternative fuels— deoxidizing agents, into blast furnace tuyeres.

### Thermodynamics of Iron Oxide Reduction with Hydrogen

Reduction of $Fe_2O_3$, i.e. hematite (iron ore) occurs in several steps of reaction to produce metallic iron, Fe. Stepwise reduction to Fe takes place from Fe2O3 to Fe3O4, or magnetite, and then proceeds to Fe if the reduction temperature is less than 570oC.

The intermediate oxide, wüstite$Fe_{(1-x)}O$, is not stable at temperatures lower than 570°C. At reduction temperatures higher than 570°C, wüstite also must be considered in the reduction progress. The reduction of iron oxide took place at different temperatures are:

- $3Fe_2O_3 + H_2 = 2Fe_3O_4 + H_2O$ T <570°C
- $Fe_3O_4 + 4H_2 = 3Fe + 4H_2O$ T >570°C
- $(1-x)\ Fe_3O_4 + (1-4x)\ H_2 = 3Fe_{(1-x)}O + (1-4x)\ H_2O$
- $Fe_{(1\_x)}O + H_2 = (1-x)\ Fe + H_2O$

The thermodynamics of iron oxide reduction which shown in Baur–Glässner diagram (Figure 9) displays the stability areas of differentiron oxide phases depending on the temperature and gas oxidation degree. At higher temperatures, the equilibrium shifts towards the formation of iron because the stability of iron oxide decreases, allowing for easier reduction with hydrogen. Le Chatelier's concept, according to which an equilibrium system will adjust to offset external changes, is consistent with this phenomenon.

 

In this case, the increase in temperature favours the forward reaction of iron oxide reduction. This leads to an increase in theoretical gas utilization and the thermodynamic driving force for reduction. Iron ore reduction with CO is carried out at certain temperature only due to kinetics/Thermodynamic reason.

Reduction behaviour of $H_2$ as reducing agent investigatedand reported in the several literature [3] and are summarized in Table-4

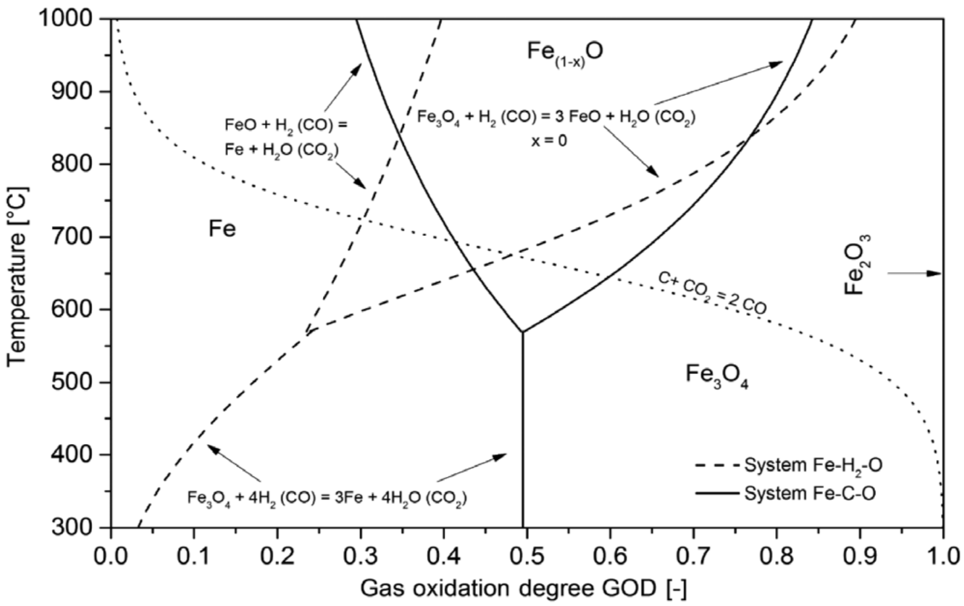


**Figure 9.** Baur–Glässner diagram for the Fe–O–$H_2$ and Fe–O–C system including the Boudouard equilibrium.

**Table 4.** Reduction behaviour of $H_2$ as reducing agent investigations reported in the literature [3].

| Reducing agentused | Main results regarding reduction behaviour |
|---|---|
| $Fe_3O_4$with $H_2$,@ 900ºC–1100ºC | • Increasing reduction rate with increasing temperature<br>• Reaction rate slows down at 900-950ºC<br>• Rate limitation by solid-state diffusion |
| $Fe_2O_3$with $H_2$ @ 500ºC–1100ºC | • The reduction rate of samples with high porosity (54%) increases with increasingtemperature<br>• Reductionrate decrease at 650ºC due to the formation of a dense iron layer |
| FeO with $H_2$ @ 238–417ºC | • Rate-limiting due to phase-boundary reaction |
| $Fe_2O_3$pellets with $H_2$-CO mixed gas @ 850 ºC | • Reduction with pure $H_2$ is faster compared with CO and gas mixtures<br>• Slow Phase-boundary reaction and limited gas diffusion slowdown the reduction process |
| FeO pellets H2-CO 900ºC–1100ºC | • Highest reduction rate with $H_2$, increasing amount of CO in the reducing gas lowers thereduction rate<br>• At initial stage, the reaction start time is high, resulting slow down the reaction with CO. |
| $Fe_2O_3$ and $Fe_3O_4$with$H_2$-CO mixed gas @ 450–1100ºC | • Reduction of $Fe_2O_3$ occurs faster than that of $Fe_3O_4$ due to pores formation.<br>• Rate of reduction is high with $H_2$ as compared with CO |
| $Fe_2O_3$briquettes with$H_2$-CO mixed gas @ 800ºC–1000ºC | • Reduction rate increases with temperature and $H_2$-content in the reducing gas mixture |

 

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Iron oxide reduction with $H_2$ or mixture of CO-$H_2$ is a complex process due to many parameters that have an influence on the reduction rate and depends on the process concept, the reduction parameters, and the input material. Change in ratio of indirect, direct and $H_2$ Reduction with BF Operation Conditions is shown in Figure 10. The following conclusions can be made according to the literature review:

- During the iron oxide reduction, mechanisms takes place are mass transfer of gaseous species (gas diffusion), pore diffusion, phase boundary reaction, solid-state diffusion, nucleation, and growth [4].
- A higher temperature leads to better kinetic behaviour [5].
- Hydrogen is a better reducing agent compared with carbon monoxide due to better kinetic behaviour [5].
- An increase in the absolute pressure in conjunction with increasing partial pressures of the reducing gas components leads to a better reduction rate [4-6].
- Water vapour in the reducing gas mixture affects the reduction rate drastically due to thermodynamic driving force decreases and water vapour absorption on free reaction sites. [6].
- The molecule size and viscosity of hydrogen are lower compared with carbon monoxide therefore hydrogen shows better diffusion behaviour compared with carbon monoxide [6].

**Replacement of Carbon by Hydrogen in Smelting & DRI Process**

***ULCOS project***

Ultra-low $CO_2$ steelmaking (ULCOS) is a project jointly initiated by 15 European countries and 48 enterprises toachieve at least 50% reduction in $CO_2$emission [7]. The overall route is shown in Figure 11. This ternary figure also presents all existing energy structures, where coal is close to carbon on a carbon–hydrogen line, natural gas is near hydrogen, and $H_2$ is produced through water electrolysis on the hydrogen-electricity line.

Five processes are mainly promoted in ULCOS:

1. Top gas recycling of BF (TGR-BF),
2. Direct reduction (ULCORED),
3. Smelting reduction (HISARNA),
4. Electrolytic iron ore process (ULCOWIN/ULCOLYSIS), and
5. Hydrogen-based steelmaking

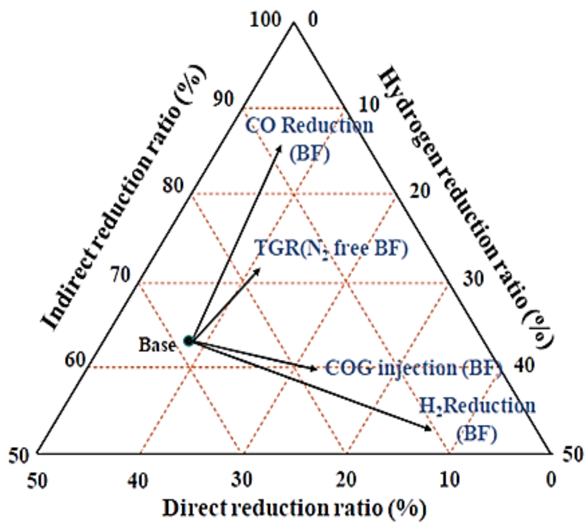


**Figure 10.** Change in Ratio of Indirect, Direct and $H_2$ Reduction with BF Operation Conditions.

 

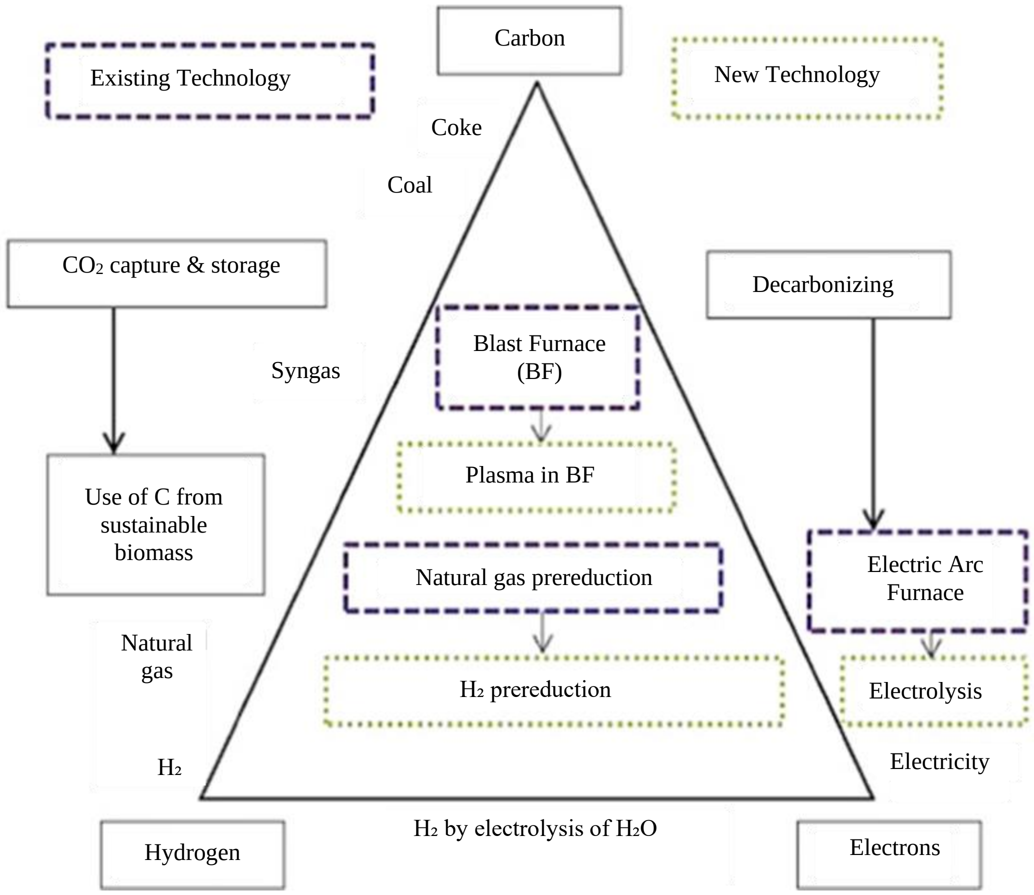

**Figure 11.** Route of ULCOS [7].

Hydrogen-based steelmaking process is shown in Figure 12. The carbon emission of the shaft furnace is negligible; however, when carbon emission generated by electric power is considered, $CO_2$ emission during the whole process per ton of crude steel is only 300 kg, and this value is equivalent to 84% reduction compared with that of 1850 kg from a traditional BF process.

***H2FUTURE by Voestalpine [8]***

Voestalpine launched the H2FUTURE project in 2017 with the goal of lowering CO2 emissions from the steel industry by creating a novel technology that might eventually replace coke with hydrogen, reducing CO2 emissions by 80% by the year 2050.

***SuSteel (Sustainable Steelmaking) Project [9]***

The objective of the SuSteel project is based on the concept of hydrogen plasma technology for the smelting reduction of iron ores and thus direct production of steel. Hydrogen-plasma utilized both for reduction of iron oxide and melting of pure iron. In order to advance the development of this proven technology for the actual implementation, a 250kW pilot plant is being built at the Donawitz site of voestalpine. An additional advantageof the process would open up completely new possibilities in the alloying of different steels.

***SALCOS project of Salzgitter AG [10]***

In 2019, Salzgitter low CO2 steelmaking (SALCOS) was proposed by Salzgitter AG and Tenova to take hydrogen as a reducing agent in iron-making and reduce $CO_2$ emissions. This project is designed to gradually transform a conventional and carbon-intensive BF conversion process to a DRI–electric arc furnace process and use surplus hydrogen for multiple purposes. In Green Industrial Hydrogen (GrIn-Hy-1.0), which was facilitated in 2016, a reversible electrolysis process is used to produce hydrogen and oxygen, and excess hydrogen is stored. Subsequently, GrInHy 2.0 was launched in 2019. The remarkable feature of GrInHy 2.0 is the use of waste heat from a steel plant to produce water vapour, which is applied to generate electricity from green renewable energy. Hydrogen is then produced via high-temperaturewater electrolysis.

***Flash iron-making technology in the US [11]***

A novel flash iron-making technology (FIT) involves the reduction of iron concentrate to DRI with a high metallization rate under a suspension state. The reducing gas can be $H_2$, $CH_4$, or other gases. This process is developed on the basis of iron ore resources in the US, where 60% of iron ore is taconite with a small particle size of less than 25–38 μm (Figure 13). In this process, iron oxide concentrates are directly used without pelletizing or sintering.

***HYBRIT in the Nordics [12]***

The core concept of this project is direct reduction by hydrogen made via water electrolysis, and its goal is to reduce $CO_2$ emissions by 10% in Sweden and 7% in Finland. This HYBRIT new process is similar to direct reduction in existing shaft furnaces, but 100% hydrogen is used as a reducing agent. In HYBRIT, the main processes are pelletizing, hydrogen production, direct reduction by hydrogen, and electric furnace smelting. The $CO_2$ emission in HYBRIT decreases by 1575 kg (98.44%), and its energy consumption reduces by 1356 kW·h (25.17%) compared with that in the BF process.

The layout of the HYBRIT production process and as a comparison the blast furnace production process is given schematically in Figure 14.

***MIDREX process with $H_2$addition [13]***

At present, running shaft furnaces are mostly based on Midrex processes by using NG, coal, and oil-gasified gas. The reducing gas should have a high hydrogen content (Figure 15) of 55vol%–80vol% to ensure that a high-temperature alloy furnace tube is not corroded and to prevent iron ore pellet from sticking. In Midrex plant at Voestalpine, the contents of $H_2$ and CO in the reducing gas are about 55vol% and 36vol%, respectively, and the $H_2$/CO molar ratio is about 1.50. The $H_2$/CO molar ratio in the FMO Midrex plant in Venezuela is 3.3–3.8 because of steam reforming technology. Coal gasification technology is used in some shaft furnaces to obtain a reducing gas with a $H_2$/CO molar ratio of 0.37–0.38. Therefore, Midrex has been successfully applied to produce DRI at a $H_2$/CO molar ratio of 0.37–0.38.

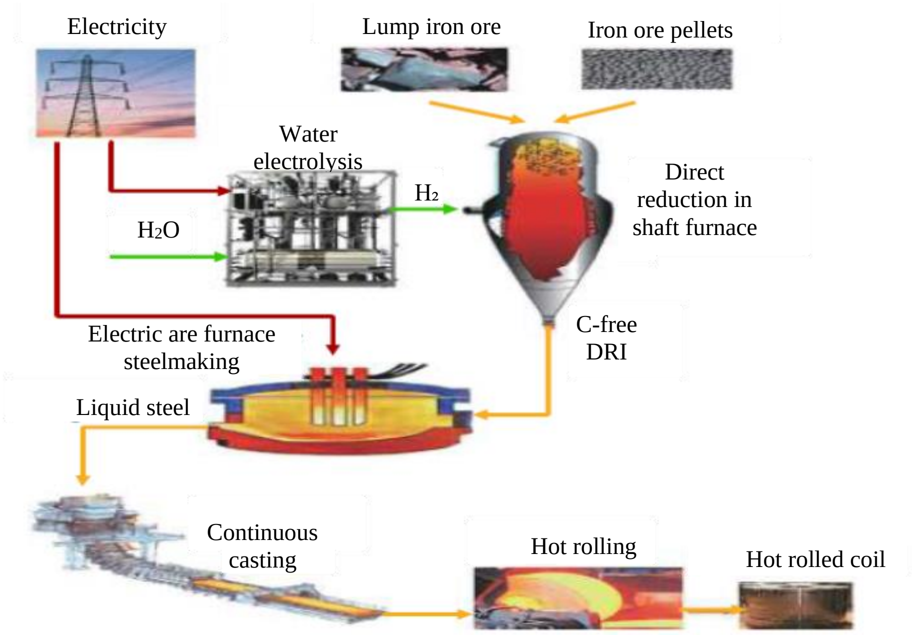


**Figure 12.** Hydrogen-based steelmaking in ULCOS project.

 

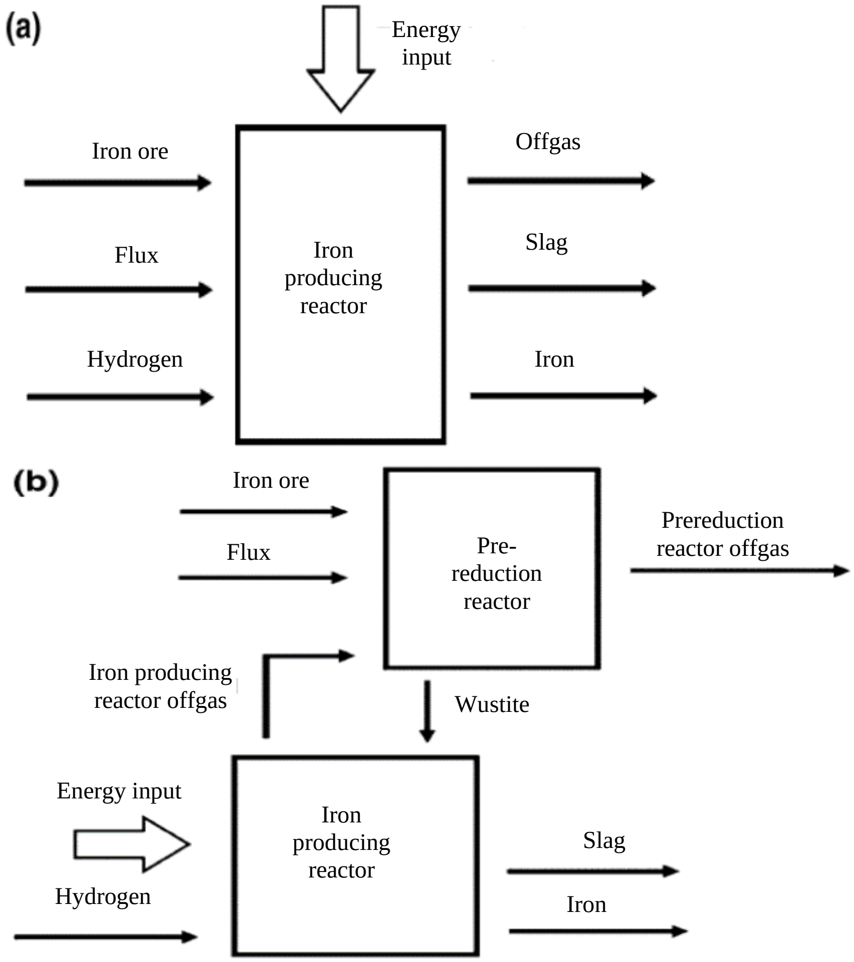


**Figure 13.** Schematic diagram of iron production using hydrogen: (a) 1- step process and (b) 2-step process.

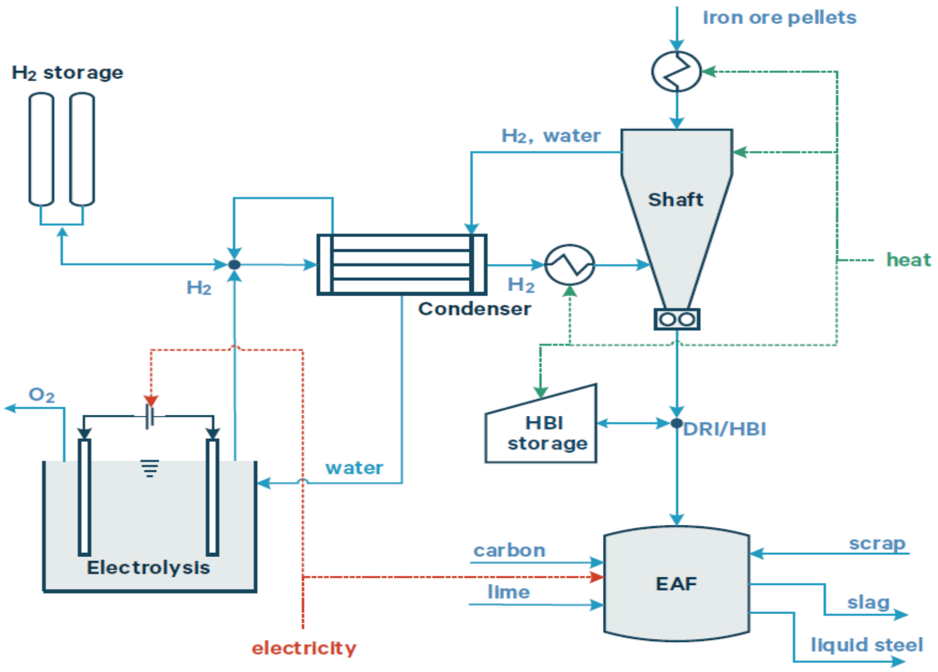


**Figure 14.** Flow-sheet for hydrogen direct reduction process under HYBRIT project.

In practical production, the reducing gas contains about 90vol% hydrogen and 10vol% other gases (i.e., CO, $CO_2$, $H_2O$, and $CH_4$), which are mainly used to control the appropriate furnace temperature and ensure the carburization of DRI [13]. In 2019, ArcelorMittal commissioned Midrex Technologies at Hamburg site, produce steel with hydrogen, demonstrate large-scale production, and use DRI made of 100 vol% hydrogen as a reductant. In the future, the plant will produce about 100000 t of DRI per year initially with gray hydrogen sourced from NG.

***Hyl-ENERGIRON Process [14]***

Tenova HYL has developed a new coal-based HYL technology (also known as Energiron HYL technology, Figure 16) by combining a coal gasification technology with HYL. The original HYL technology relied on natural gas.

The reactor and its peripheral systems and the principles of operation for the coal-based HYL processare thesameas for the gas-based HYL process in which oxidematerial is fed fromthe top and is reduced by a countercurrent flow of $H_2$- and CO-containing gas.

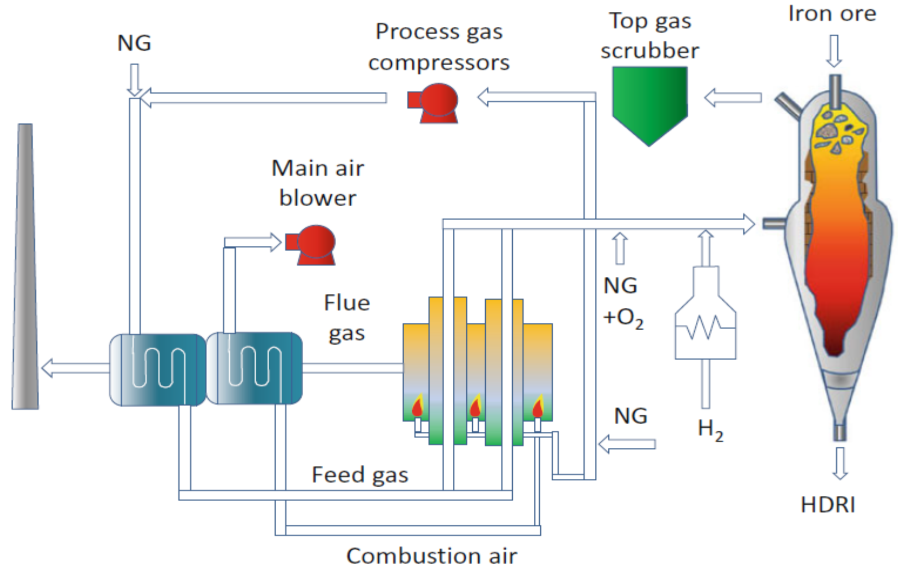


**Figure 15.** MIDREX process with H2 addition.

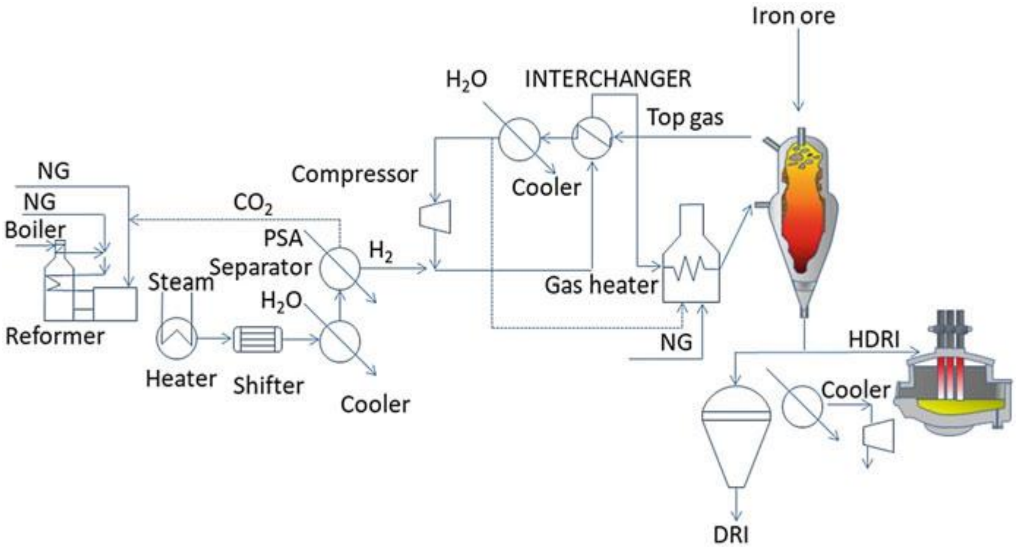


**Figure 16.** Hyl-ENERGIRON process.

 

Becausethe HYL reactor is designed to work with high-$H_2$-content reducing gas, and the gasfrom the gasifier contains considerable amounts of CO, a gas shift reactor is requiredto convert CO into $H_2$ by the reaction

$$CO + H_2O \rightarrow CO_2 + H_2$$

Both energyconsumption and $CO_2$ emissions are comparable with those belonging to theMIDREX process.

**Hydrogen injection in Blast Furnace**

***Hydrogen injection by ThyssenKrupp Stahl AG [15]***

ThyssenKrupp Stahl AG initiated a project that involves the replacement of coal with hydrogen as a reducing agent inBF to reduce or completely avoid $CO_2$ emission in steel production. At the initial stage, hydrogen is injected to BF through a tuyere in a Duisburg steel plant and gradually expanded to all tuyeres.

***$H_2$ enriched COG injection for ROGESA BFs [16]***

ROGESA Roheisengesellschaft Saar mbHhas awarded Paul Wurth to design and supply COG injection systems for BF Nos. 4 and 5 located in Dillingen/Saar, Germany. Initially COG partially replaces pulverized coal and metallurgical coke as reducing agents in the BF process. According to the project schedule, by the end of 2020, COG is permanently injected into all the tuyeres of both furnaces. This application will be a bold step toward hydrogen-based iron-makingin the future.

***Hydrogen reduction iron-making by POSCO [17]***

Hydrogen reduction iron-making developed through public–private cooperation by POSCO in Republic of Korea involves threesteps: start of the trial operation in a test furnace in 2025; productionof two BFs in 2030 to decrease $CO_2$ emission by1.6%; complete hydrogen reduction iron-making in 12 BFs in2040 to further decrease $CO_2$ emission by 8.7%. The program consists of six projects:

- Heat recovery from hot sinter;
- $CO_2$ absorption using ammonia solution;
- Slag utilization
- Hydrogen production using COG and wastes;
- Iron ore reduction using hydrogen-enriched syngas;
- Carbon-lean version of the FINEX process.

***$H_2$ reduction iron-making in Japan [18]***

Hydrogen-rich reduction in iron making is introduced underCOURSE50 project shown in Figure 17. Nippon Steel built a 12 $m^3$ experimental BF with a productivity of 35 t/d and confirmed the project emission reduction target of 10% reduction by hydrogen reduction iron-making and 20% reduction by $CO_2$ recovery; thus, the overall emission reduction target is 30%.

- Development of reaction control technologies to reduce iron ore using hydrogen (producing $H_2O$ rather than $CO_2$ in the blast furnace off-gas stream),
- Increase of hydrogen content in Coke oven gas (Figure 18), and
- High strength and reactive coke for hydrogen reduction blast furnaces.

In hydrogen reduction iron-making, a portion of coke is replaced with hydrogen to reduce $CO_2$ emissions during BF process. The adjustable position in the stack and raceway of BF and the preheating of $H_2$ beforeinjection are conducted to ensure the maximum reduction performance and a stable inner temperature because of the small density of $H_2$ and endothermic reactions accompanying hydrogen reduction.

 

During the injection of hydrocarbon fuels- deoxidizing agents into tuyeres, particular technological impacts approve themselves (Figure 19), such as:

- Control of RAFT temperature;
- Change of lower zone permeability in the lower part of the blast furnace (Bosh Zone);
- Reduction of the slag specific amount;
- Change of intensity of fuel combustion;
- Reduction of coke specific consumption.

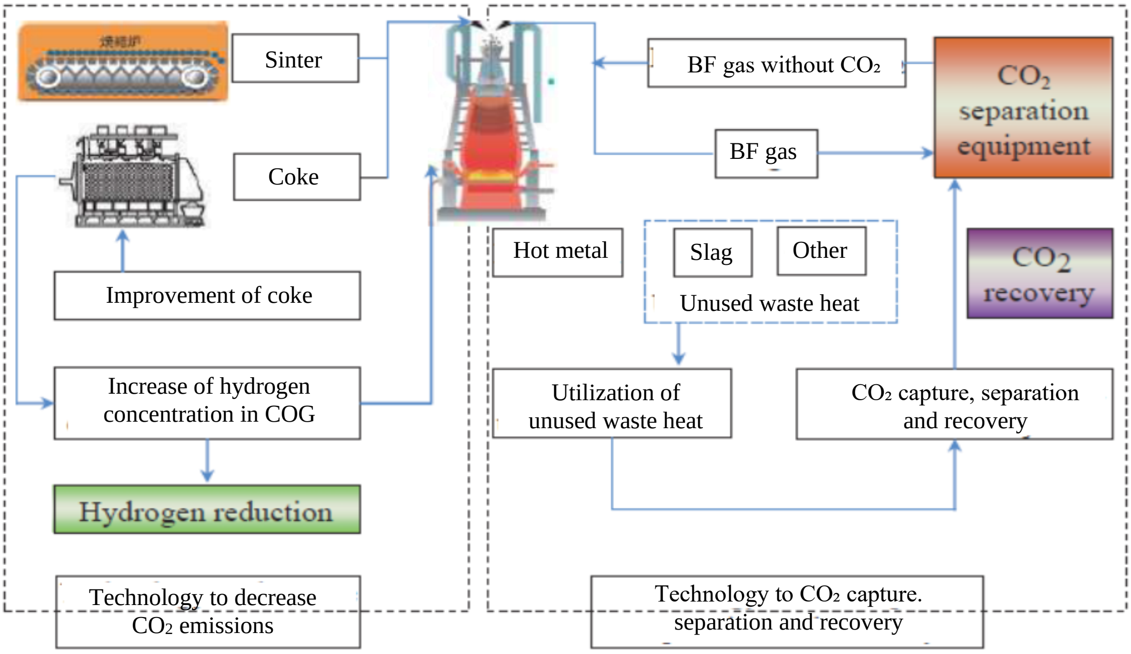


**Figure 17.** Route of the COURSE50 project.

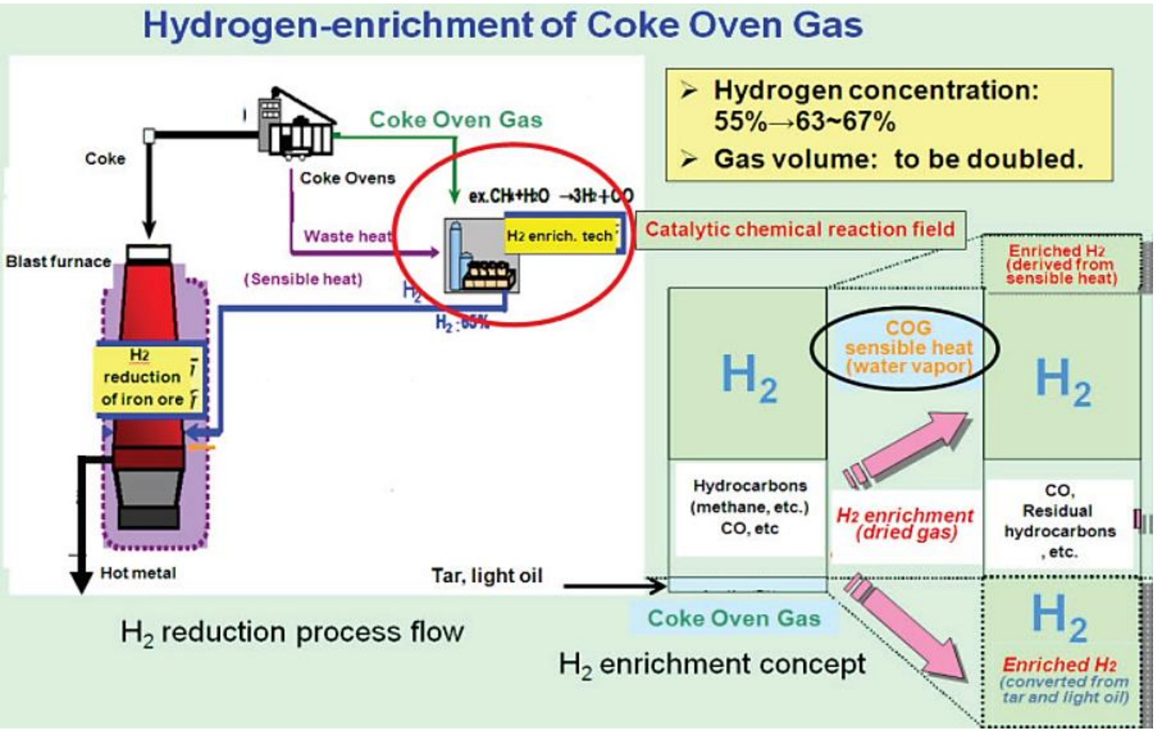


**Figure 18.** Hydrogen enrichment of Coke oven gas (COG).

 

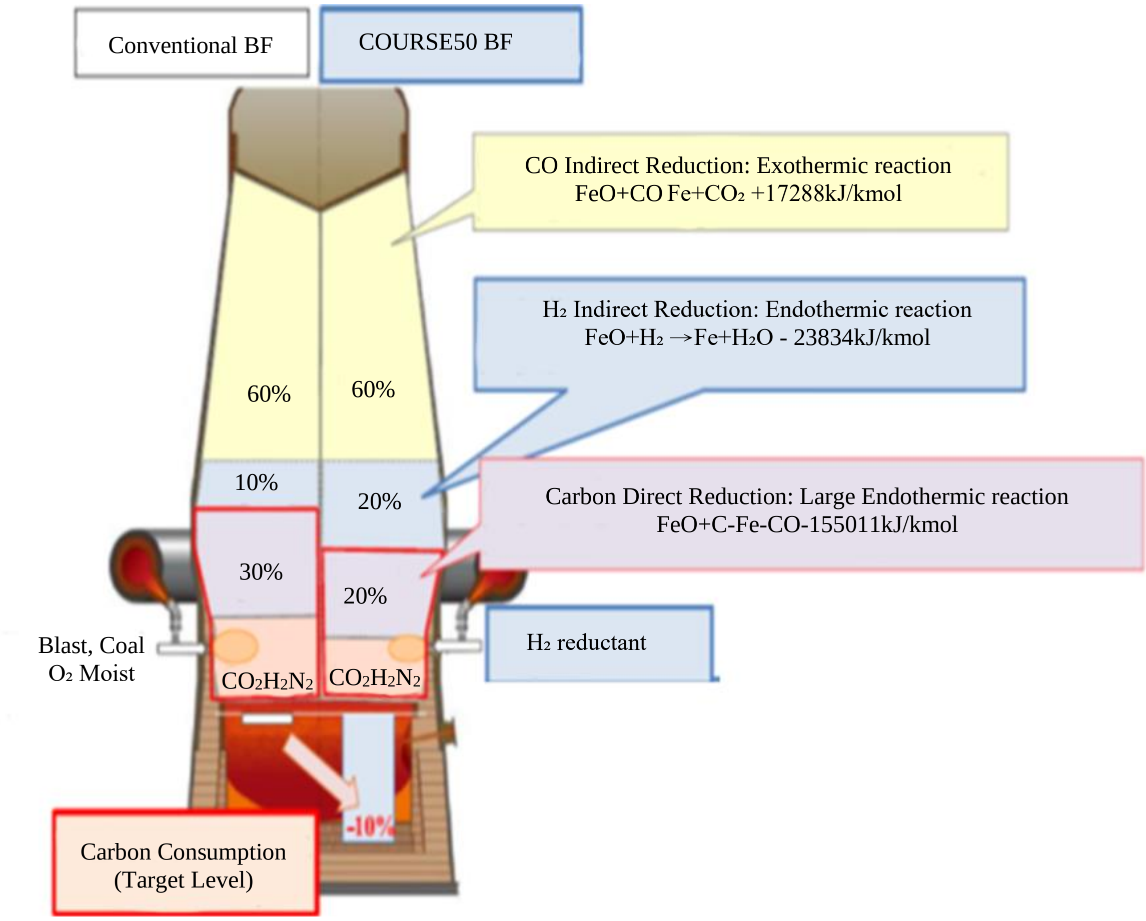


**Figure 19.** Concept of increased iron ore reduction by hydrogen in the blast furnace [19].

## HYDROGEN DEMAND FOR LOW CARBON SCENARIO

hydrogen indeed has significant potential in various sectors. In heavy-duty and long-distance transportation, hydrogen fuel cells can offer advantages in terms of range, refueling time, and zero-emission operation, making them particularly suitable for these applications. In the power sector, while hydrogen might play a minor role currently, it could serve as a valuable long-term storage medium for renewable energy, helping to address intermittency issues associated with sources like solar and wind power.

Beyond 2050, there will likely be a greater need for green hydrogen, which is created by electrolysis using renewable energy sources.

Industries such as steel production, which currently rely heavily on carbon-intensive processes, are exploring hydrogen as a clean alternative fuel or reducing agent. Green hydrogen holds promise as a way to decarbonize such sectors, contributing to global efforts to combat climate change. About 40 Mt of green hydrogen, a seven-fold increase from today, may be needed to achieve a net-zero aim by 2060[20].

## HYDROGEN PRODUCTION

With the increasing consumption of fossil fuels and thedeterioration of global climate conditions, developing thehydrogen economy tends to be a new competitive field in the21$^{st}$century due to the numerous advantages of hydrogenenergy. In general, the feedstock for hydrogen productionis mainly classified into two major categories: fossilfuels and the renewable sources, such as water and biomass.

 

**Hydrogen-from-Coal Process (HYCOL)/Coal Gasification**

The Hydrogen-from-Coal Process (HYCOL) is a gasification technology that utilizes an entrained bed system. Pulverized coal is gasified with oxygen under high pressure and temperature conditions in this process.

The result of this gasification is the production of a medium calorific gas that is rich in hydrogen and carbon monoxide. The technology is called the"HYCOL process." Through the shift reaction, the gas yieldscarbon monoxide and converts steam to carbon dioxide andhydrogen. After separating the carbon dioxide, the gas is purifiedto become high-purity hydrogen.

**Hydrogen from COG**

Coke oven gas (COG) contains a substantial amount of hydrogen, making it a valuable resource for hydrogen production, particularly in industries like steel manufacturing where hydrogen is increasingly sought after as a cleaner alternative to traditional carbon-intensive processes. Pressure swing adsorption (PSA) technology is an efficient method for separating hydrogen from COG due to its ability to selectively adsorb hydrogen molecules.

By installing a PSA unit, steel plants can recover hydrogen from COG for onsite use in various processes, such as direct reduction of iron ore or annealing, or for separate sale to other industries. This not only reduces the carbon footprint of steel production but also presents an opportunity for additional revenue generation through the sale of excess hydrogen. Overall, leveraging COG for hydrogen production via PSA technology aligns well with sustainability goals and economic viability in the steel industry. (Figure 21).

The steel industry can become more environmentally friendly and self-sufficient by installing such COG utilization units within coking facilities. Table 5 lists the data from US plant studies that demonstrate the possibility of producing hydrogen from COG by using PSA facilities [20].

However, although the processhas achieved the high degree of automation for generatinghigh pure hydrogen (90-99%), there are also some disadvantageswhich cannot be ignored.

- Complexity of operation and high pressure and oxygen removal from product gas. High investment and payback period.
- Other components except for hydrogen in COG can’t be fully utilized, making the low hydrogen production rate of unit COG, appropriately 0.45 $Nm^3$ per $Nm^3$ COG.

**Steam Methane Reforming**

Hydrogen production process from Natural Gas is a commercializedmature technology, which accounts for appropriately 50% ofhydrogen production in the world. At present, the main methods ofhydrogen production from methane include steam reforming,partial oxidation reforming, carbon dioxide reforming andauto-thermal reforming, and their advantages and disadvantagesare listed in Table 6[21]. Among them, the steamreforming for hydrogen production with efficiency of 65-75%is currently the least expensive and most common method.

**Electrolysis of Water**

Being a commercially mature and promising technology forhydrogen generation, electrolysis of water is a process wherewater is split directly into hydrogen and oxygen by adoptingelectricity and relevant electrolysis equipment, which accountsfor about 4%-5% of the world’s total hydrogen production [22]. With the constant depravation of the globalclimate, electrolyzing water for hydrogen production withrenewable energy such as wind energy and solar energy, hasbecome a hot topic. At present, there are tworelatively mature and common types of electrolysers: one isalkaline electrolysis system of taking potassium hydroxide orsodium hydroxide aqueous solution as electrolyte; the other isthe proton exchange membrane (PEM), which employs a solidpolymer membrane electrolyte [23].

 

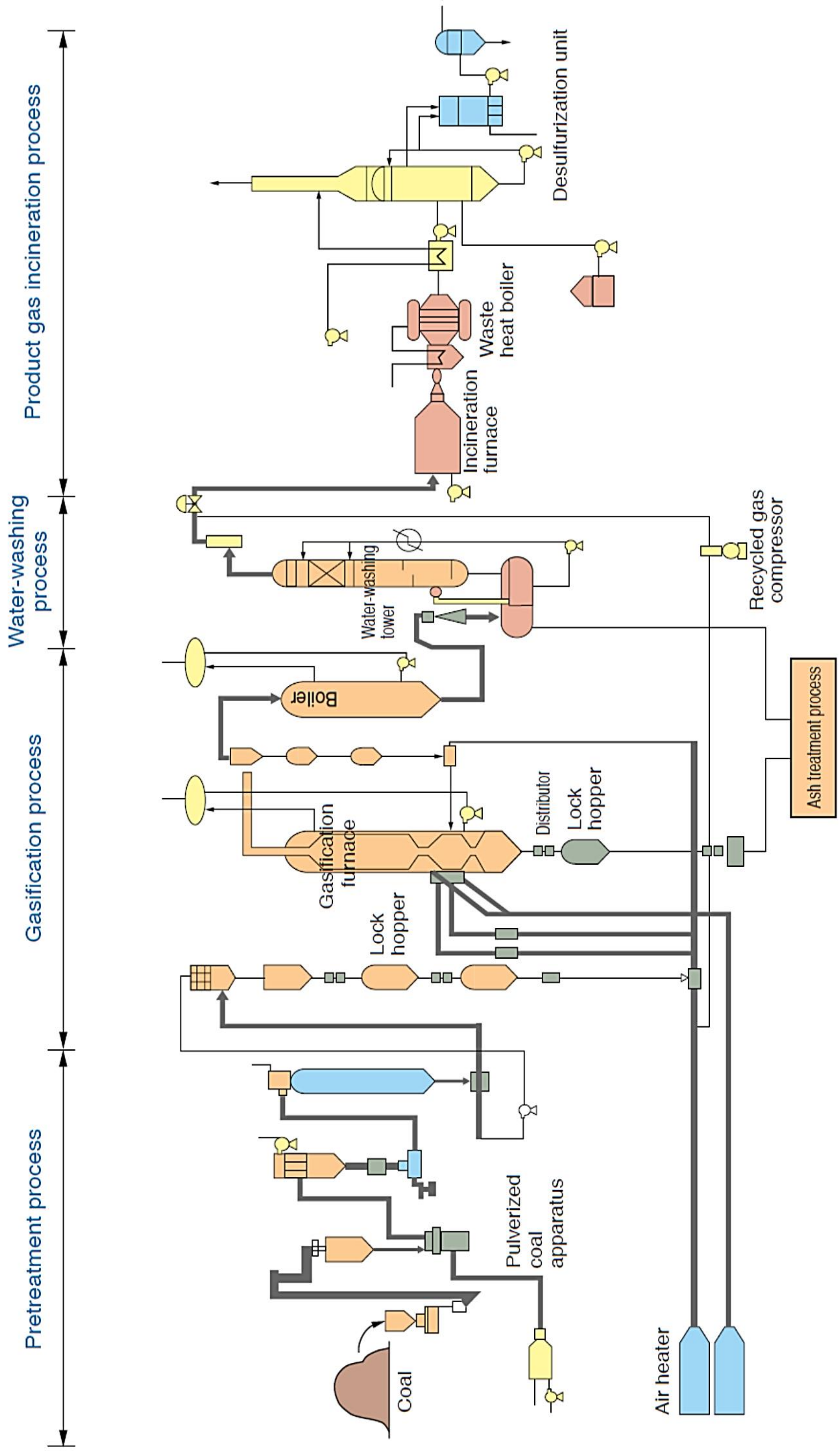


**Figure 20.** Hydrogen-From-Coal Process (HYCOL).

**Table 5.** Production ratio of coke vs coal,
COG Vs Coke , $H_2$ Vs COG.

| Production | Ratio |
|---|---|
| Coke/Coal (t/t) | **0.72** |
| COG/Coke ($m^3$/t) | **0.50** |
| H2/COG (g/$m^3$) | **0.034** |

**Table 6.** Comparison of four hydrogen productionmethods by NG.

| Methods | Advantages | Disadvantages |
|---|---|---|
| Steamreforming | • No oxygen consumption,<br>• Lower temperature<br>• High ratio of H2/CO<br>• High efficiency<br>• More mature technology andextensive application | • Additionalheating<br>• required<br>• High CO2emissions<br>• Complexsystem<br>• High requirementsFor NG quality |
| Partialoxidation reforming | • No catalyst required<br>• High conversion efficiency<br>• Simple system<br>• Small scale production<br>• Low desulfurization demand | • OxygenRequired<br>• Low ratio of H2/CO<br>• Highertemperature<br>• High pressureof dust treatment |
| Auto-thermal reforming | • Lower temperature than partial oxidation reforming<br>• High conversion efficiency<br>• Lower oxygenconsumptionthan partial oxidationreforming | • Oxygenrequired<br>• Less industrialProduction |
| Carbondioxide reforming | • CO2 as raw material<br>• Low reforming temperature | • Additionalheatingrequired<br>• Low ratio of H2/CO<br>• Underinvestigation |

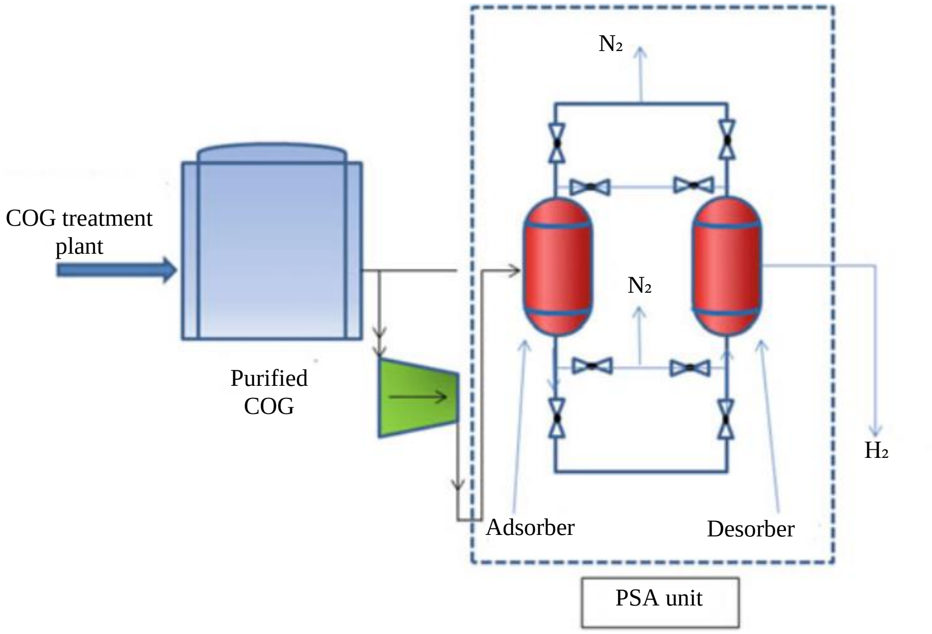


**Figure 21.** Separation of Hydrogen from coke oven gas.

 

Although the extremely pure hydrogen with a purity of99.99% can be obtained through the technology of water electrolysis, some disadvantages keep still unresolved. Forexample, the present application is limited to small scale forhydrogen production due to the energy limitation, and theoverall costs and energy demands are too high, hindering thedevelopment of hydrogen production by water electrolysis.

**Hydrogen production using biomass**

In recent years, biomass as a clean and renewable energy hasbeen widely concerned and also shows the promising foregroundto generate hydrogen due to significantamounts ofhydrogen existed in them, such as wood, forestry, agriculturalresidues and so on. The biomass conversion technologiesmainly include thermochemical and biological forhydrogen production. The detail methods involved in thesetechnologies are shown in Figure 22. Among them, biomassgasification and biomass pyrolysis draw the most attentionrecently. However, the hydrogen content in the syngas generatedfrom the biomass gasification and pyrolysis is usually 40%- 60%, and the stability and recyclability of catalysts are still abig challenge in future scaled-up application

**TECHNO-ECONOMIC FEASIBILITY**

BF-BOF (blast furnace-basic oxygen furnace) and even BF-CCS (blast furnace with carbon capture and storage) routes might indeed face profitability challenges as coal prices rise and stricter regulations on carbon emissions are enforced, particularly with increasing prices for CO2 allowances.

Transitioning to hydrogen-based direct reduction (H2-DR) processes becomes increasingly attractive as renewable energy sources become more prevalent and prices for CO2 allowances rise further. However, you rightly point out the significant barriers to immediate adoption, including high investment costs and dependency on electricity prices.

To make H2-DR economically viable before 2030, additional subsidies or incentives may be necessary to offset these barriers. Governments, industry stakeholders, and research institutions can collaborate to develop policies and strategies that support the transition to hydrogen-based steel production. This could include subsidies for investment in H2-DR technology, incentives for renewable energy adoption, and support for research and development to drive down costs and improve efficiency.

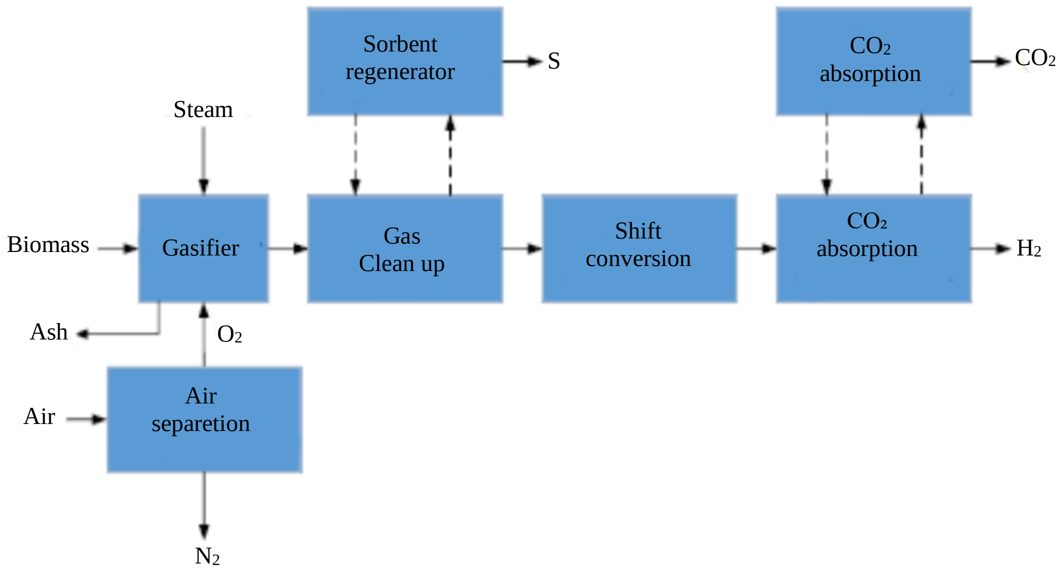


**Figure 22.** Flow diagram of the biomass gasification process.

 

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Overall, while the transition to H2-DR may face challenges in the short term, it represents a promising pathway towards more sustainable and profitable steel production in the long run. Replacing Carbon with Hydrogen required one addition facilities i.e. Hydrogen generation units. Direct reduction of hydrogen Per tonne of liquid steel produced, the steel industry uses 3.48 MWh of electricity, mostly for the electrolyser hydrogen production.There will be almost no emissions from the process if renewable electricity is employed. The cost of power and the quantity of scrap used are major factors that affect the overall manufacturing costs, which range from $400 to $650 per ton of steel. A $50/MWh power cost in an integrated steel factory makes hydrogen direct reduction economically viable.

When switching to hydrogen-based direct reduction (H-DR) processes, there are a number of important factors to take into account. These are especially important when considering India's steel sector:

**Production Cost**

In general, the H-DR method has higher production costs than the conventional BF/BOF approach, but in the event of a low electricity price, it may become competitive.

This underscores the importance of ensuring access to low-cost, low-carbon electricity to support the economic viability of hydrogen-based steel production.

**Water Requirements**

Electrolysis, which is a common method for producing hydrogen, requires a significant amount of fresh water. While the water requirements for electrolysis may seem substantial, they represent only a small fraction of India's total water supply. However, it's essential to manage water resources sustainably to avoid depletion, especially considering the challenges posed by overuse and climate change.

**Low Carbon Electricity Requirements**

Meeting India's future hydrogen demand through electrolysis would necessitate a substantial increase in low-carbon electricity production. This demonstrates the necessity of making large investments in infrastructure for renewable energy sources, like solar photovoltaics, in order to supply the electricity required for the creation of hydrogen.

**Raw Material Constraints**

The construction of electrolyzers for hydrogen production requires significant amounts of raw materials, including unalloyed steel, nickel, and copper. While India may have sufficient domestic reserves of steel and copper to meet these demands, there may be uncertainties regarding nickel supply, especially considering the growing demand for nickel-based batteries in electric vehicles. Efficient recycling practices and proactive engagement with mining companies will be essential to address potential raw material constraints.

Overall, transitioning to hydrogen-based steel production presents both challenges and opportunities. Addressing these considerations will require coordinated efforts from policymakers, industry stakeholders, and research institutions to ensure the sustainability and economic viability of hydrogen-based processes in the steel industry.

**Investment Cost Analysis**

Estimated investment requirement for 1Mt steel production capacity for integrated green field project:

**Energy**

The relationship between achievable metallization in the shaft and overall energy consumption in the steelmaking process is crucial for optimizing efficiency. Metallization refers to the extent to which iron ore pellets are reduced to metallic iron in the direct reduction shaft furnace.

 

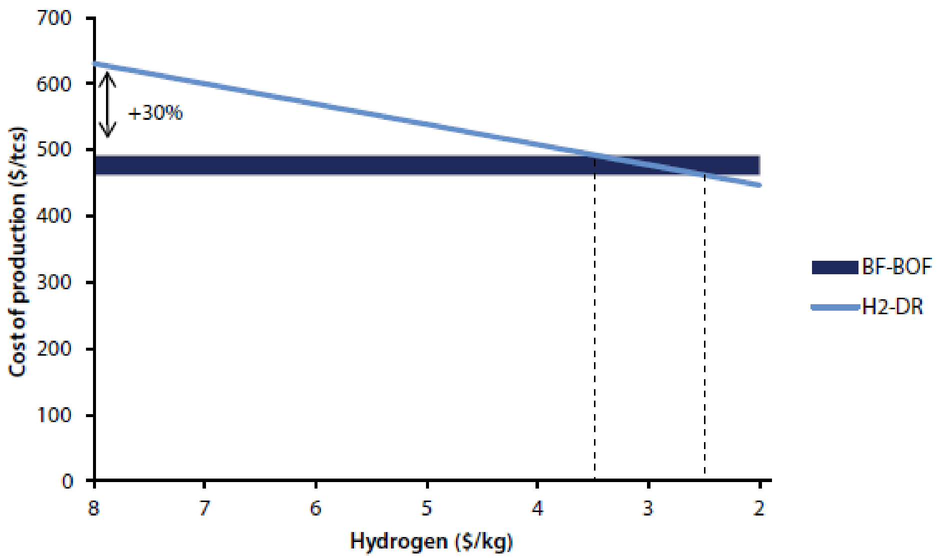


**Figure 23.** Cost of production:$H_2$-DRI Vs BF-BOF Process [24].

**Table 5.** Comparison of Investment costs for various process lines ($/t cs) [20,24-26].

| **Primary Energy** | **Coal** | **Natural gas** | **Hydrogen** | **Hydrogen** | **Hydrogen** |
|---|---|---|---|---|---|
| Process Route | ***BF-BOF*** | ***DRI-EAF*** | ***Shaft F/c-EAF*** | ***Hyl-EAF*** | ***Fluid Bed-EAF*** |
| Hydrogen Plant/ Electrolyser | - | - | 190 | 190 | 190 |
| Coke Oven | 100 | - | - | - | - |
| Ore preparation | 50 | 50 | 50 | 50 | 30 |
| Gas reformation | - | 40 | - | - | - |
| BF | 150 | - | - | - | - |
| DRI/HBI | - | 80 | 90 | 90 | 110 |
| BOF | 150 | - | - | - | - |
| EAF | - | 160 | 160 | 160 | 160 |
| Total | 450 | 330 | 490 | 490 | 490 |

**Table 6.** Raw Material consumption pattern (kg/t cs).

| **Primary Energy** | **Coal** | **Natural gas** | **Hydrogen** | **Hydrogen** | **Hydrogen** |
|---|---|---|---|---|---|
| Process Route | *BF-BOF* | *DRI-EAF* | *Shaft F/c-EAF* | *Hyl-EAF* | *Fluid Bed-EAF* |
| Iron Ore | 1370 | 1190 | 1190 | 1190 | 1190 |
| Ore Fines | 1250 | - | - | - | 850 |
| Lump Ore | 350 | 400 | 400 | - | - |
| Pellets | | 400 | 400 | 700 | - |
| Processed Scrap | 125 | 710 | 710 | 710 | 710 |
| Flux | 270 | 270 | 270 | 270 | 270 |
| Coking Coal | 780 | - | - | - | - |
| Natural Gas * | - | 225 | - | - | - |
| Hydrogen * | - | - | 600 | 600 | 600 |

*($m^3$/tcs)*

 

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In the case of hot-briquetted iron (HBI), low metallization means that not all the iron ore pellets have been reduced to metallic iron. This situation can lead to increased energy consumption in the electric arc furnace (EAF) because more energy is required to further reduce the remaining iron oxide to produce steel. However, despite this increase in energy consumption in the EAF, the total specific energy consumption (SEC) of the process can be reduced if the metallization is low enough to compensate for the additional energy required in the EAF.

The specific energy consumption of the hydrogen-based direct reduction (H2-DR) process is influenced by several factors, including the amount of excess hydrogen supplied to the shaft and the heat lost between the shaft and the arc furnace. Figure 24 [26]. likely illustrates how the specific energy consumption of the H2-DR process varies with the amount of scrap charged into the EAF. This relationship is crucial for understanding the energy efficiency of the steelmaking process and optimizing operational parameters to minimize energy consumption while maintaining product quality.

Tentative material flow diagram is shown in Figure 25 for the proposed Hydrogen based Iron and Steel industry

## CHALLENGES FOR HYDROGEN BASED IRON & STEEL MAKING

### Cost of Hydrogen Production:

***Steam Methane Reforming (SMR)***

While SMR is a widely used method for hydrogen production, especially in industries like petrochemicals, its reliance on natural gas makes it less economically viable for the steel industry due to the high cost of natural gas. Additionally, SMR produces carbon dioxide as a byproduct, which can pose environmental challenges.

***Coal Gasification***

India's abundant coal reserves make coal gasification an attractive option for hydrogen production. However, the infrastructure and logistics required for coal transport and storage add complexity and cost to this method.

***Electrolysis***

With India's significant potential for renewable energy generation, particularly from wind and solar sources, electrolysis presents a promising route for hydrogen production. Water must be electrolyzed in order to separate its hydrogen and oxygen, and using renewable electricity sources helps reduce its negative effects on the environment.

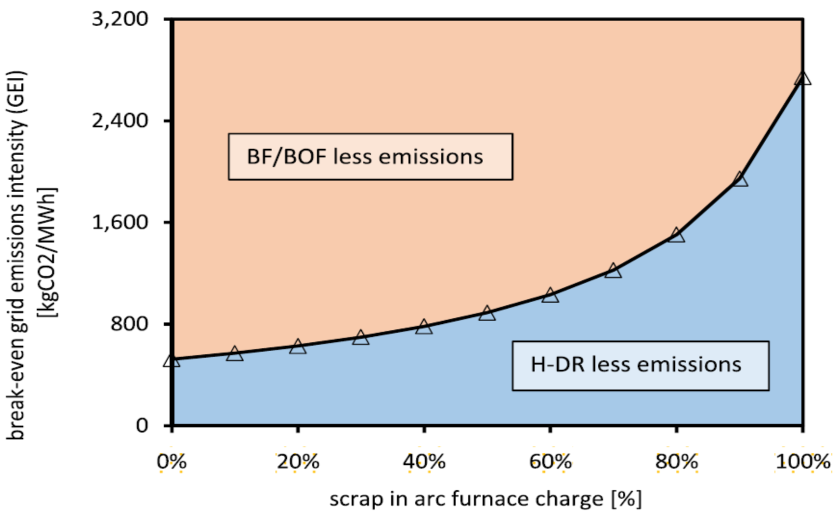


**Figure 24.** The H-DR process's specific energy consumption (SEC) as a function of the scrap charged into the EAF is expressed as MWh/tLS [27].

 

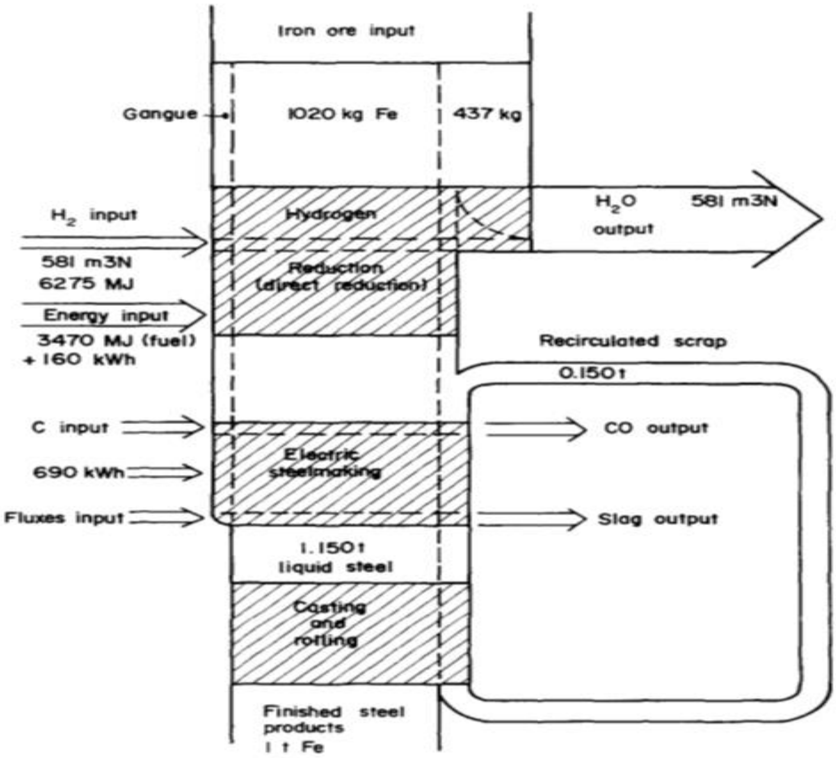


**Figure 25.** Flow sheet of $H_2$ based Iron and Steel Plant [28].

However, electrolysis is capital-intensive and water-intensive, posing challenges in water-scarce regions like India. Maximizing water recycling can help address this issue.

**High Capital Costs of Electrolysers**

The high capital costs associated with electrolyzers necessitate high capacity utilization factors to ensure cost-effectiveness. Running electrolysers at maximum capacity can help spread out the initial investment over a larger volume of hydrogen production, reducing the per-unit cost of hydrogen. However, achieving high capacity utilization requires consistent demand for hydrogen or storage infrastructure to accommodate fluctuations in demand. This underscores the importance of careful planning and market analysis when implementing electrolysis-based hydrogen production facilities in the steel industry or any other sector.

**Flexibility of Operation**

- Electricity demand flexibility and grid balancing services as $H_2$ based DR process required a large additional electricity demand (3.5 TWh per million tonne steel).
- The H2-DR process allows for flexibility in the overall amount of electricity used by adjusting the amount of scrap charged to the electric arc furnace. Numerous operational strategies can be pursued by combining these possibilities.

**Hydrogen Transportation &storage**

Hydrogen production and transportation in India can be approached through two primary models:

***On-Site, Distributed Production Model***

In this model, hydrogen production occurs at or near the point of useBecause users and production assets are located in the same location, this strategy reduces the need for a large transportation infrastructure.

 

### *Production Hub and Grid Model*

This model is akin to the current natural gas infrastructure, where hydrogen is produced in centralized hubs and then transported to various locations via a dedicated grid.

### *Global Hydrogen Production and Consumption*

- *On-Site Production:* Currently, about 85% of the hydrogen produced globally is consumed on-site. This reduces the need for transportation but requires production facilities to be near the point of use.
- *Transportation:* The remaining hydrogen is transported via trucks or pipelines. This includes the use of Liquid Organic Hydrogen Carriers (LOHCs), ammonia, methanol, and hydrogen in liquid form.

### *Transportation Challenges*

- *Liquid Hydrogen:* Transporting hydrogen as a liquid requires it to be cooled to –253˚C. This process involves significant energy losses, typically around 25–35%, due to the refrigeration and regasification required.
- *Alternative Carriers:* To mitigate these energy losses, hydrogen can be transported as ammonia, methanol, or using LOHCs. These carriers can be more efficient for long-distance transport.
- *Storage Technologies:* For large-scale hydrogen storage and transportation, the industry primarily relies on two technologies:
- *High-Pressure Gaseous Storage:* Hydrogen is stored in high-pressure tanks, which is suitable for shorter-term and flexible storage needs [29,30].
- *Cryogenic Liquefied Storage:* Hydrogen is stored at very low temperatures in a liquid state, which is more suitable for long-term storage and bulk transportation.

### Benefits of Hydrogen Storage

- *Detachment of Electrolyser:* Hydrogen storage allows the electrolyser to operate independently from the rest of the process, acting as a buffer.
- *Continuous Operation:* By storing hydrogen, parts of the hydrogen-dependent processes can continue to operate even when production fluctuates, ensuring a more stable and continuous supply.

In summary, the effective production, transportation, and storage of hydrogen involve a combination of on-site and centralized production models, various transportation methods including alternative carriers, and advanced storage technologies to ensure efficiency and reliability in the hydrogen supply chain.

### Operational Challenges

The specific gravity of hydrogen is low, and the density of hydrogen is only 1/20 of that of CO. As a result, the entering hydrogen molecule rapidly escapes upward and un-utilized. Hydrogen is an extremely flammable and explosive substance, and the shaft furnace needs highly efficient and long-term stable production. If the shaft furnace system is allowed to work for a long time under the ultimate conditions of high temperature and high pressure, safety cannot be guaranteed, so required attention on metallurgical process re-designs.

### Hydrogen in steel: Quality aspect

Hydrogen, even in 2 ppm dissolved in steel, are undesirable as it's presence in steel can catastrophically failed during services. Hydrogen induced/ dissolved steel required low stress level for crack initiation and propagation resulting in embrittlement effect.

 

According to Sievert's law, a di-atomic gas reacts with a metal and is dissolved into atomic form. Figure 26.

In the instance of hydrogen solubility, Figure 26 provides a pictorial representation. As a result of hydrogen's reduced solubility at lower temperatures, during rapid cooling, a buildup of H2 pressure will occur in the steel matrix.

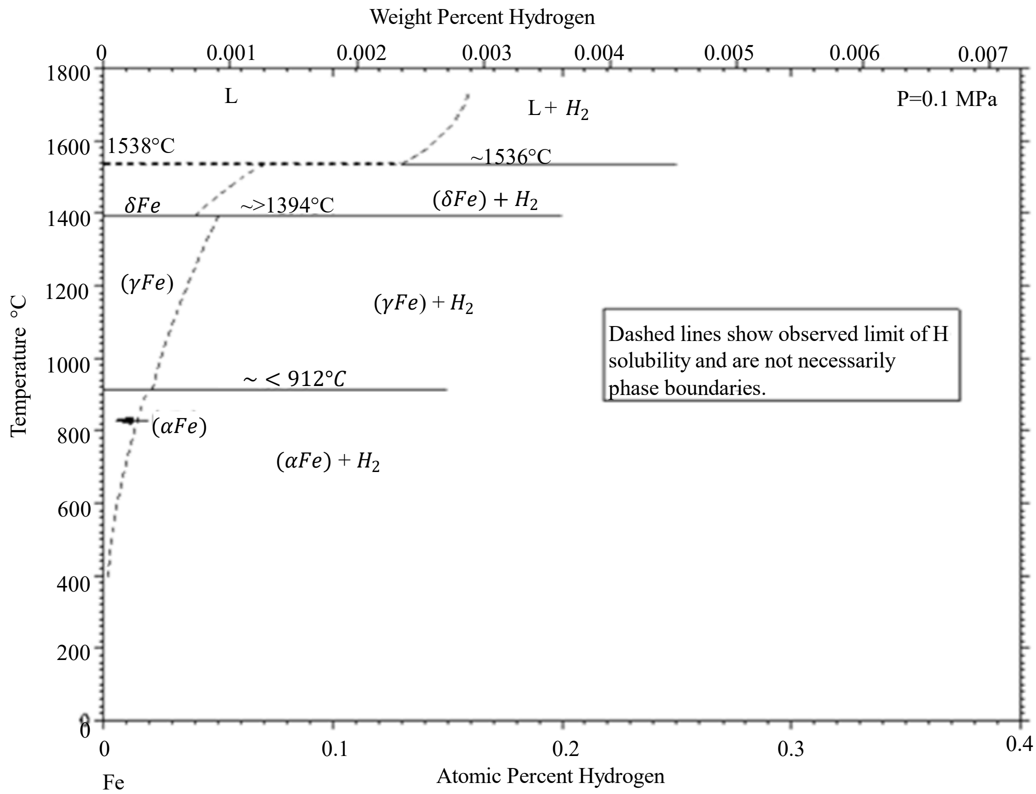


**Figure 26.** Fe-H phase diagram.

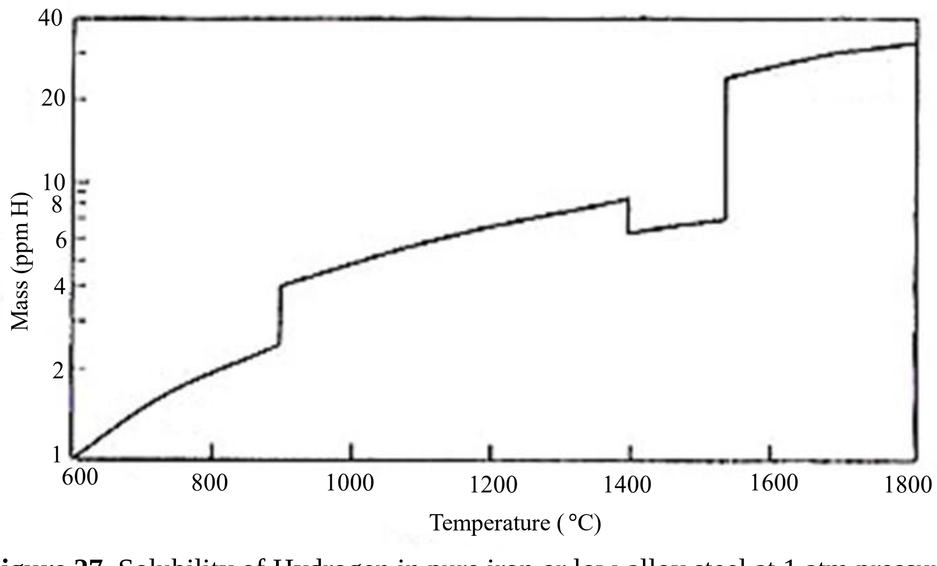


**Figure 27.** Solubility of Hydrogen in pure iron or low-alloy steel at 1 atm pressure of $H_2$.

Therefore, critical application, when hydrogen is more than 2 ppm, the steel slab or billet slowly cooled with very slow cooling rate (with sand-witch cooling) so that induced hydrogen diffuse out from surface.

## CONCLUSION

Although many authoritative metallurgical experts emphasized the benefits of hydrogen metallurgy, the technological and economic value of shaft furnaces with pure hydrogen should still be considered and discussed.

Strategies to capture, store, utilize, or avoid CO2 in steel production are crucial for reducing the carbon footprint of this energy-intensive industry. The production of low-carbon hydrogen ($H_2$) depends heavily on the availability of renewable electricity, which is a prerequisite for these techniques. The technique for using H2 as a reductant in the steel-making process is still in its infancy. To convert hematite to iron, 0.6 t CO2/t of liquid steel would be produced stoichiometrically throughout the carbon-based steelmaking process. The heat requirement of the different processes combined with the thermodynamic equilibrium between C, CO, and CO2 raises these emissions to 1.9 t CO2/t liquid steel for a reference steel plant.

Large scale use of hydrogen for iron ore reduction is not realistic at present. The supply of hydrogen is limited and the cost is not competitive in most countries. Today's fossil sources involve considerable CO2 formation during hydrogen production.

Hydrogen-based steel-making, while promising for long-term decarbonization, is not considered a short-term option due to several challenges and constraints. Iron ore reduction with hydrogen is feasible from thermodynamics and kinetics, although difficulties in processing may originate from the minimum effect, from insufficient gas utilization and sticking of ore fines. Such phenomena need more R&D for a deeper understanding. Future developments will lead to a larger supply of low-carbon hydrogen.

## Declaration

*Conflict of Interest:* The author declares no conflict of interest.

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