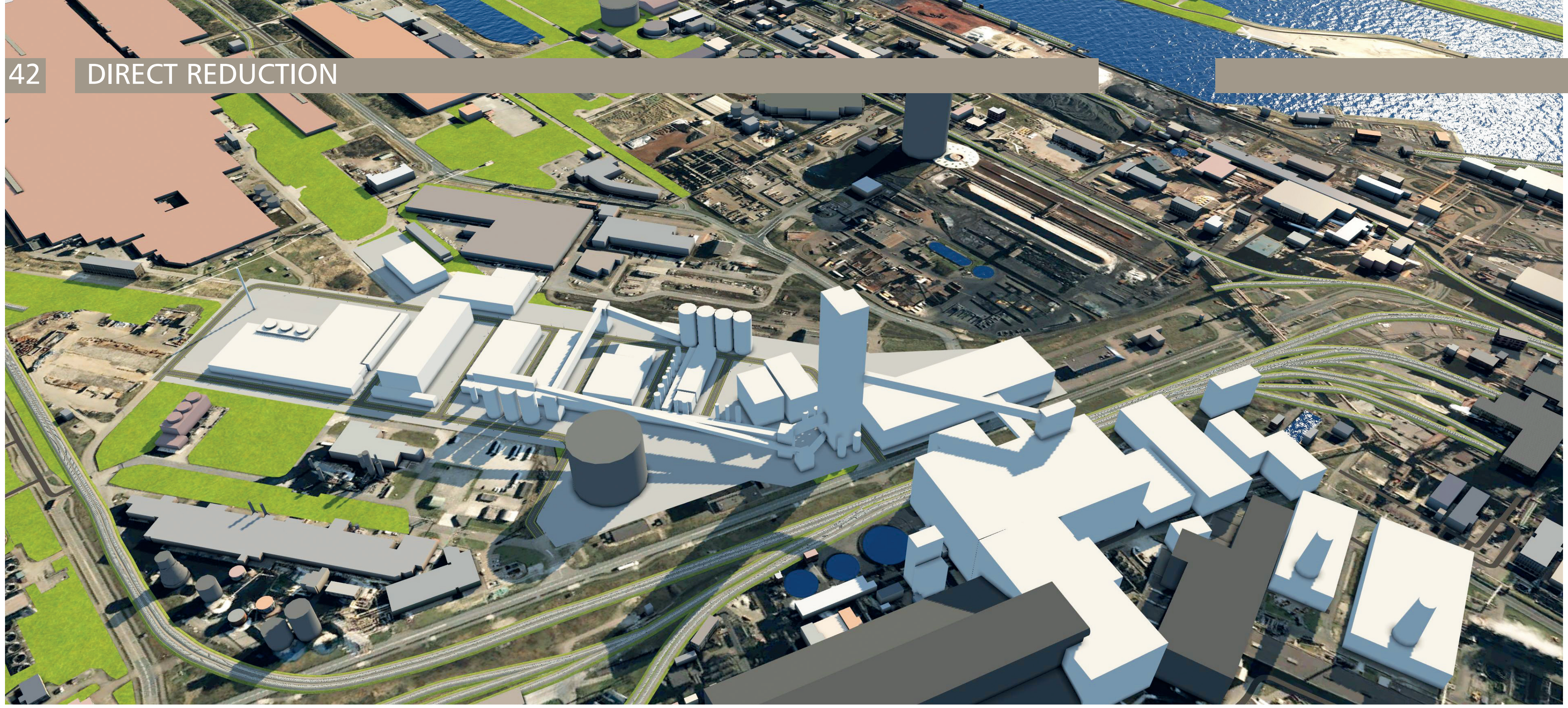

Technological pathways to decarbonization

Decarbonizing the steelmaking industry, which accounts for around 11% of global CO_2 emissions, is crucial for achieving the near-zero emissions target. One option is carbon capture, utilisation, and storage (CCUS), which could help manage residual emissions from traditional coal-based blast furnace (BF) operations. On the other hand, existing proven technologies have the potential to significantly reduce CO_2 emissions in steel production. In this context, the current trend in reducing the carbon footprint of steelmaking involves replacing the ironmaking BF in integrated BF-BOF installations with gas-based Direct Reduction (DR) units. By **Jorge Martínez[1], Leonardo Tamez[2], Pablo Duarte[3]**

THE Direct Reduction (DR) process, which uses natural gas (NG), results in a reduction of approximately 50% in CO_2 emissions compared to the BF-BOF route and facilitates the gradual transition from NG to hydrogen (H_2) that paves the way for further decarbonization. Understanding the characteristics of DR systems is essential for defining the most effective pathway for decarbonising the steelmaking industry using currently available technologies.

Traditional steelmaking routes

There are three conventional basic processes for steel production:

(1) Coal-based blast furnace–basic oxygen furnace (BF–BOF),

(2) Scrap-electric arc furnace (EAF), and

(3) NG-based direct reduced iron (DRI) + electric arc furnace (EAF)

While being the most effective approach in terms of circular economy and minimal CO_2 emissions (depending on the carbon intensity of electricity), the scrap-EAF process is limited in its ability to produce high-grade steels due to the concentration of trace elements in the recycled scrap.

Direct Reduced Iron (DRI), used as feedstock for EAF in the production of high-quality steels, relies on NG and/or H_2 as the primary energy source to reduce iron oxides. This is the current technological pathway for replacing the coal-based BF-BOF process for decarbonization. As the composition and amount of gangue in the iron oxide can affect both the operation and economics of the EAF, high-quality iron ores are necessary for DRI production to optimise operating costs and/or steel quality.

An alternative and transitional approach for decarbonizing BF-BOF installations involves replacing the BF system with a gas-based DR plant coupled with an electric melter, while maintaining the BOF downstream steelmaking facilities in operation.

In this system, the DR plant, using NG and H_2 along with low-grade iron ore pellets, produces hot DRI (HDRI), which is fed into the electric melter to produce hot metal, with the required % of carbon (C) content, as feedstock for the existing BOFs. To meet the decarbonization needs of integrated steelmakers, Tenova offers the iBLUE® scheme, which includes energy recovery from off-gases to be utilised as fuel in the DR plant (**Fig 1**).

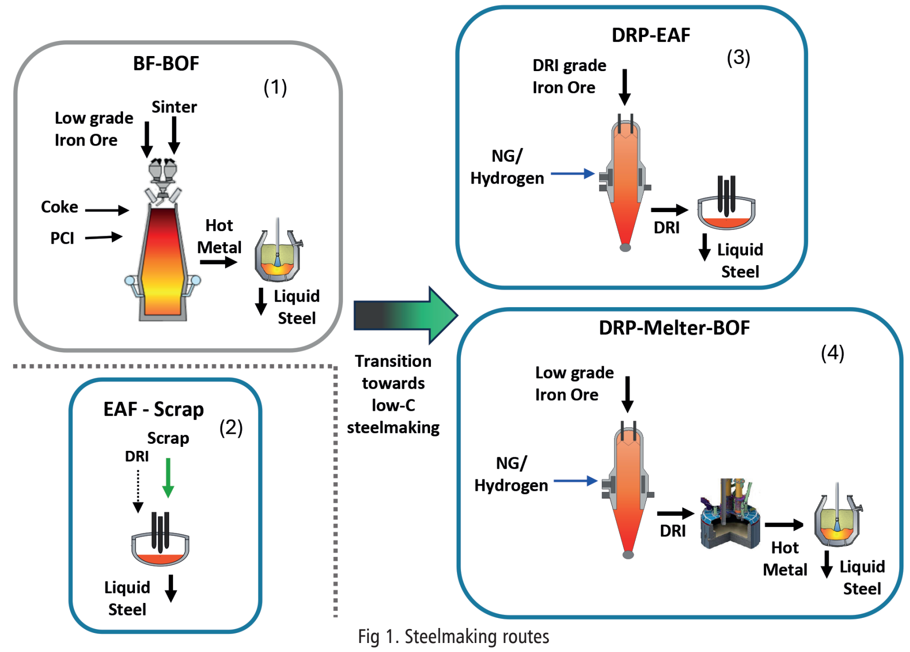

Fig 1. Steelmaking routes

DRI process configurations

The DRI-EAF and DRI-Melter-BOF configurations allow the production of a wide range of steel qualities. The DR plant is based on the use of NG (and/or H2) as the primary energy source for reduction and fuel, which is converted to H_2 and CO through hydrocarbons reforming (CH4 → CO + $2H_2$), for reduction of the iron ores, with final by-products consisting of CO_2 and H2O, instead of coal (C → CO_2). The CO_2 emissions are ~50% or less compared to those of the BF-BOF scheme.

There are two main methods for the direct reduction of iron ores using NG:

1) The direct injection of NG into the reduction loop of the DR plant, where *in-situ* reforming takes place within the reduction shaft to produce the required reductants for the reduction process.

2) Employing an NG reformer, an integral and essential component of the reduction process, to generate the reductants H_2 and CO.

Method 1 is exemplified by the ENERGIRON process, which features the same core configuration for any reducing gas source, operating at a higher pressure. This innovative technology, jointly developed by Tenova and Danieli, includes an efficient and selective CO_2 removal system, an inherent part of the process, supported by waste energy from top gas heat recovery. It incorporates a process gas heater (PGH) to raise the reducing gas temperature to the required levels, along with oxygen injection when necessary. The CO_2 removal system enables the capture of approximately 60% of total CO_2 emissions for CCUS, while optimising the recycling of unreacted H_2 and CO back into the reduction shaft. The tail gas serves only for inert gas purging and pressure control within the system. As shown in **Fig 2**, the plant can operate with any combination of NG and H_2, simply by adjusting operating modes.

Method 2, on the other hand, is an optimised configuration designed for 100% NG use. It includes the NG reformer, a heat recovery system with partial recycling of top gas through the reformer, and the use of tail gas as fuel, whose primary function is a non-selective carbon purge from the process via the flue gases. However, it lacks inherent capabilities (aside from capturing from the flue gases or tail gas, which would demand extra energy) for efficient CO_2 removal. For other reducing gases, different configuration schemes will need to be adapted for each specific case.

The advantages of ENERGIRON DR technology in the transition to green steel

When choosing the approach for DRI production, the following scenarios should be considered:

a) The DR plant will operate with 100% NG and a certain proportion of H_2 for a period, with the ultimate goal of transitioning to 100% H_2 use in the foreseeable future.

b) The DR plant will operate exclusively with 100% H_2 from the start.

For the first scenario, if the scheme includes a catalytic NG reformer and progressively replaces NG with H_2, there are several considerations. These include the use of the reformer as an H_2 heater, operating it whenever NG is used, diverting valuable H_2 as fuel for the overall energy balance, or potentially exporting energy, depending on the NG/H_2 ratio and overall energy efficiency. Ultimately, when nearing 100% H_2 usage, the reformer may become an inefficient heater or could be replaced with a heater.

In this instance, the ENERGIRON

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(2) After sales and marketing manager, Tenova HYL (3) Partner/consultant, Penguin Engineering

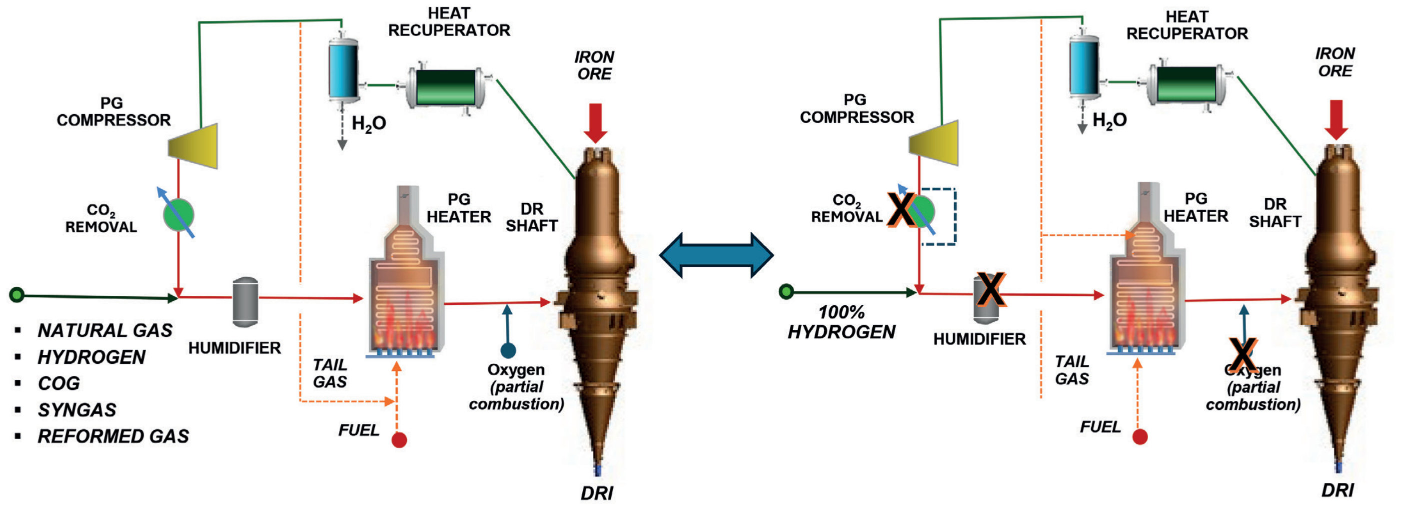

Fig 2.Nucor ENERGIRON DR plant at Nucor Steel, Louisiana, USA with CCUS, which has achieved a worldwide record of combined 330tons/hr productivity with DRI @96%Mtz and 3.3%C.

scheme presents unique benefits in terms of reduction of CO_2 emissions, energy optimisation, NG/H2 use and operational flexibility.

As illustrated in **Fig 2**, the ENERGIRON plant offers the unique flexibility to operate with any combination of reducing gases, utilising the same process scheme and equipment. This flexibility is demonstrated by DR plants using ENERGIRON technology, including the Hybrit plant in Sweden, which operates with 100% H_2, and the Baowu plant in China, which uses NG, COG, and H_2 (**Picture 1**). The DR plant can handle any mix of NG (and other gases) with H_2, up to 100% H_2, by adjusting process parameters and bypassing certain equipment, depending on the operational mode (**Fig 2**).

When using mixtures of NG/H_2, the plant offers the flexibility to accommodate variations in H_2 supply as well as the ability to transition between 100% NG and 100% H_2, or any ratio in between, at any given time. This can be achieved in a short time span simply by adjusting operating conditions, based on predictive process algorithms, without compromising plant productivity and DRI quality. The carbon %in the DRI will vary depending on the proportion of H_2 used.

As mentioned earlier, the ENERGIRON DR scheme already incorporates an inherent CO_2 removal system as part of the process configuration, without any additional energy requirements (thus avoiding implicit extra CO_2 emissions). This enables the process to reduce approximately 60% of CO_2 emissions from the DR plant, without the need for a low-carbon H_2 feed, provided CCUS is available. This is equivalent to using low-carbon H_2 derived from NG via steam methane reforming with carbon capture and storage, or blue hydrogen. **Picture 2**.

Picture 1. ENERGIRON DR Plant at Baowu, China, using NG, COG & H_2

As shown in **Fig 3**, the CO_2 emissions from the DR plant are nearly identical in the cases of NG without CCUS + 55% H_2 (% energy), and NG with CCUS. Notably, the NG with CCUS + 30% H_2 scenario results in lower CO_2 emissions compared to NG without CCUS + 55% H_2. Additionally, it can be observed that when the H_2 exceeds 70%, CO_2 removal is no longer required and can be bypassed. This allows for the flexibility to achieve substantial emissions reductions and associated savings, depending on the specific costs and/or availability of effective CCUS options or low-carbon hydrogen use.

In the second scenario, provided that the DR plant operates exclusively with 100% H_2, as shown in **Fig 2**, the ENERGIRON scheme can be simplified by omitting the CO_2 absorption system, oxygen injection and the humidifier, as the latter is only necessary to control the %C in the DRI when a high %NG is used.

In this context, while other systems adopt the same process configuration by substituting the NG reformer with a heater, the ENERGIRON system provides substantial advantages:

- Due to the high operating pressure (6-8 barA at top gas), the reduction shaft diameter is smaller for a high-productivity plant, offering greater flexibility when processing high %H_2. For lower gas molecular weight/density, gas velocity and distribution can be adjusted by both volumetric flow and operating pressure,

Picture 2. Nucor ENERGIRON DR Plant at Nucor Steel, Louisiana, USA, which has achieved a worldwide record of combined 330 t/h productivity with DRI @96%Mtz & 3,3%C

which is not at the lower limit and can be optimised for the required pressure drop (ΔP), enhancing H_2 recycling. In contrast, a low-pressure scheme with a wider shaft diameter for the same capacity needs much higher H_2 flow to offset the lower ΔP and maintain proper gas distribution.

- Regarding operating pressure, recycling unreacted H_2 from the top gas to the reduction shaft results in lower power consumption with higher suction pressure at the compressor, for the same ΔP. For comparison, with the same flow and ΔP, the power consumption of the recycling gas compressor in a lower-pressure scheme with 100% H_2 is approximately four times higher than that of the ENERGIRON compressor, in addition to requiring higher volumetric flow in the wider shaft.
- The above improves the energy optimisation of the ENERGIRON scheme with just 8,3 GJ/tDRI, including fuel, or about 6,6 GJ/tDRI for process only, and power demand of only 35 kWh/tDRI (core plant).Depending on the carbon intensity and costs of grid/renewable electricity and H_2, an electric PGH can replace the direct-fired heater.

Conclusion

The ENERGIRON process offers unique flexibility for processing NG, H_2, and other reducing gases in any combination, all within the same plant, ensuring efficient and seamless operation.

Regardless of the proportion of H_2 used, the process configuration and operating conditions result in highly optimised thermal and electrical energy consumption.

Key advantages of monetising selective CO_2 capture from the ENERGIRON DR plant:

- The ENERGIRON process provides the flexibility to consider selective CO_2 capture for effective CCUS, either as a bridging alternative or in conjunction with the use of low-carbon H_2, equivalent to approximately 55% H_2 feed.
- There are no additional energy requirements or capital expenditure for the CO_2 captured in the reduction loop, which is ready for CCUS, as is currently the case with several ENERGIRON DR plants in operation.
- Even when accounting for costs associated with CO_2 storage (around 80 US\$/t) or utilisation (around 60 US\$/t), which equates to approximately 0,80 US\$/kgH_2 and 0,55 US\$/kgH_2, respectively [IEA, *Global Hydrogen Review 2023*], these costs remain lower than those of low-carbon H_2 produced from SMR with CCS and are significantly less than H_2 produced via water electrolysis. However, it is important to note that the long-term environmental impacts of CO_2 storage are still very much under analysis. ■

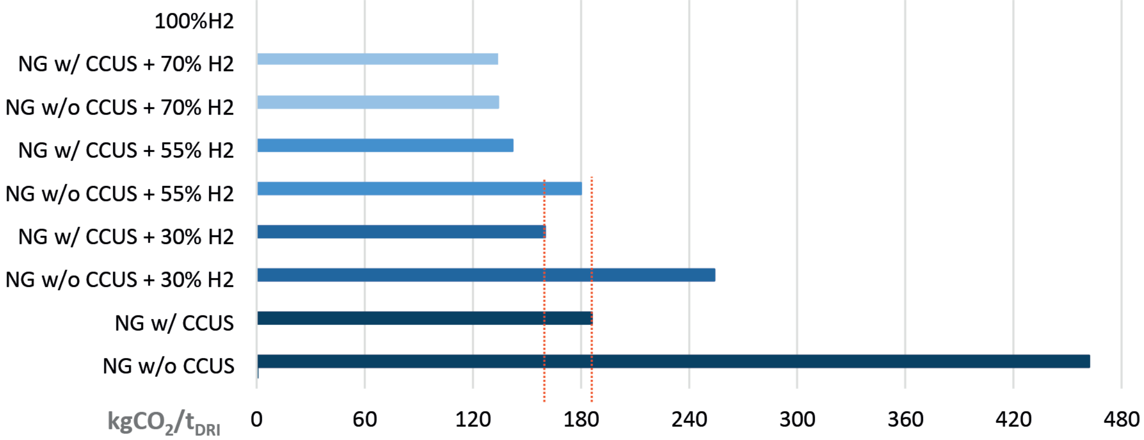

Fig 3. Direct CO_2 emissions from ENERGIRON DR plant under different CCUS/H_2 use scenarios

- *NG w/CCUS refers to CCUS applicable to selective and available CO_2 capture in the ENERGIRON DR plant*
- *The analysis is based on only direct CO_2 emissions, without including carbon footprint from Low-C H_2. The difference between Low-C H_2 from SMR w/CCS (@93% capture) and Green-H_2 from water electrolysis powered by renewable energy, is about 1,1-2,7 $kgCO_2/kgH_2$, including upstream/midstream emissions.*