Steel Industry Transformation: From Carbon to Green

Turquoise Hydrogen, a new path to low carbon industry

Organized by AIST Association for Iron & Steel Technology MENA

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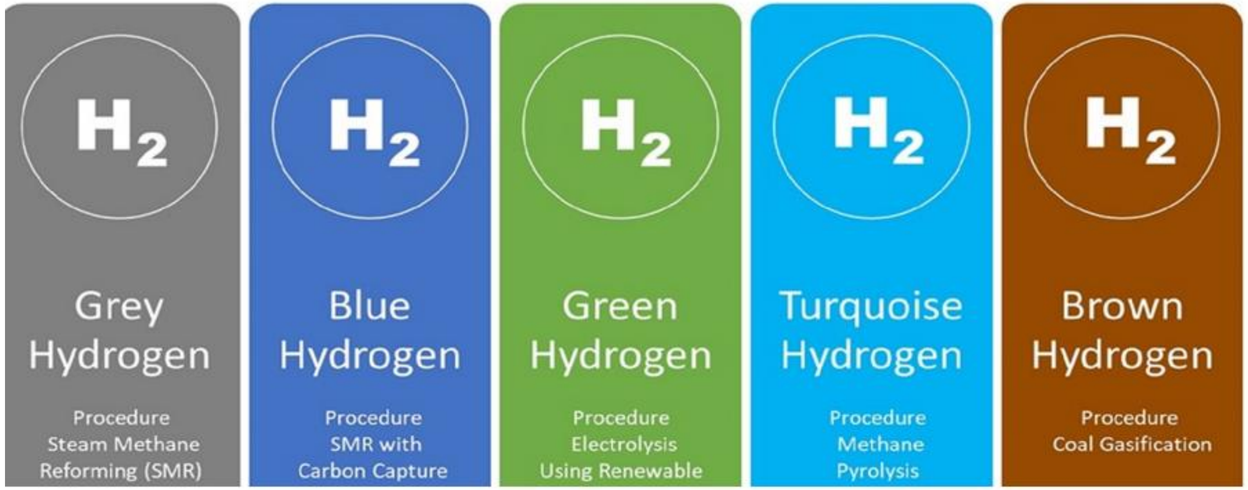
Types of Hydrogen



While Green Hydrogen is the targeted color to be produced, the Turquoise Hydrogen could be an **economical option** (less energy demand) for some industries when Brown Hydrogen and also Grey Hydrogen is not preferred any more.

Production Process and H2 Source

	Gray Hydrogen	Blue Hydrogen	Turquoise Hydrogen	Green Hydrogen
Process	Steam methane reforming or gasification	Steam methane reforming or gasification with carbon capture (85-95%)	Pyrolysis	Electrolysis
Source	Natural gas or coal	Natural gas or coal	Natural Gas	Renewable electricity
Product	H_2 & CO_2	H_2 & CO_2	H_2 & C (solid)	H_2 & O_2

Figure reproduced from IEA report

What is Turquoise hydrogen

Turquoise hydrogen is produced by **methane pyrolysis**, a process that heats natural gas to a high temperature in the absence of oxygen to break it down into hydrogen and solid carbon. This method is considered a low-emission or carbon-neutral hydrogen production pathway because it avoids creating carbon dioxide emissions, instead producing **solid carbon**, which can be stored or sold for industrial uses.

Main technologies for methane cracking

The main technologies for methane cracking (CH_4) to hydrogen (H_2) and carbon (C) are:

1. Thermal Cracking, e.g. direct heating of methane, or catalytic thermal cracking

2. Molten Salt or Molten Metal Bath

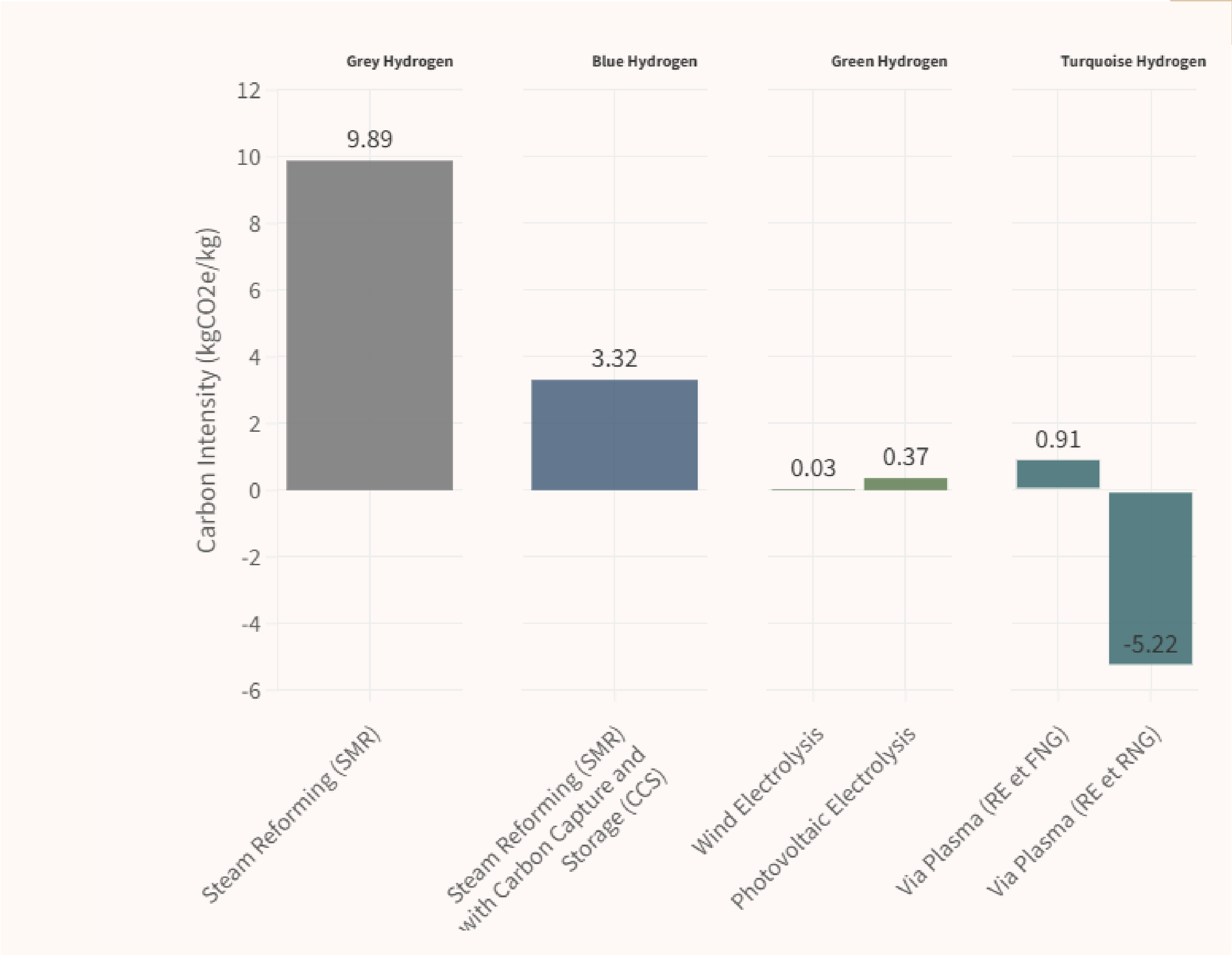
3. Plasma Cracking, can be used both as a heat source and as a way to generate reactive species that accelerate the reaction. This technology is considered the most mature with the highest technology readiness level (TRL) currently.

Solid Carbon

Solid carbon from **Turquoise Hydrogen** production can be used in industries like:

- ❑ Tire and Rubber Manufacturing
- ❑ Batteries,
- ❑ Construction
- ❑ Electronics

Carbon Intensity



*FNG: Fossil Natural Gas,
RNG: Renewable Natural Gas

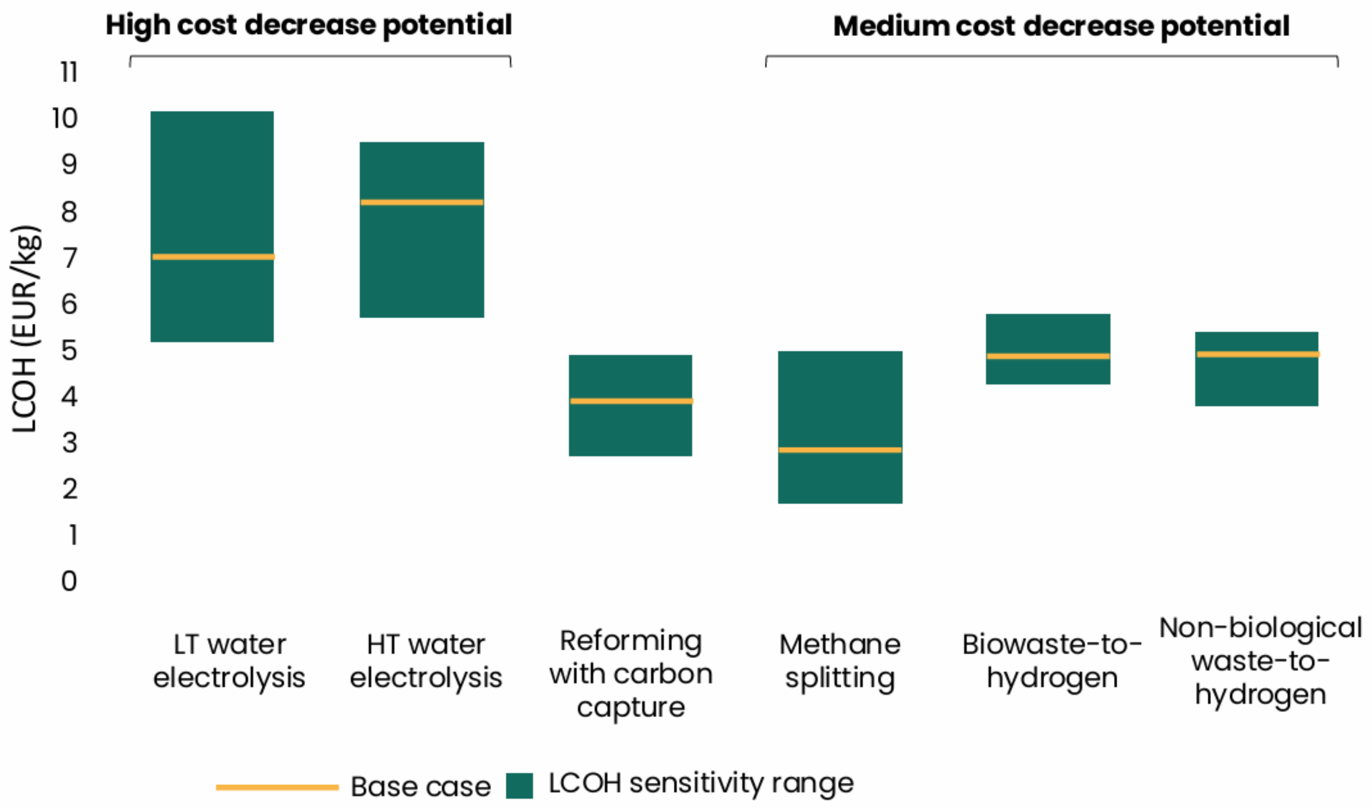
Source: Turquoise hydrogen takes a step towards the next level, , Laurent Fulcheri, MINES-ParisTech

Electrical Energy

Producing **green hydrogen** requires approximately **55 kWh electricity per kg H2**, while current **turquoise hydrogen** production needs approximately half the amount, i.e., **25 kWh electricity per kg H2**. The difference is because green hydrogen is produced by electrolyzing water, which is more energy-intensive, whereas turquoise hydrogen is made from methane pyrolysis, a process that requires less energy.

Aspect	Green Hydrogen (Electrolysis)	Turquoise Hydrogen (Methane Pyrolysis)
Process	Splits water (H_2O) using an electric current	Thermally cracks methane (CH_4)
Primary energy	Large amounts of electricity	Thermal energy and smaller amount of electricity
Energy use	~50–55 kWh per kg H_2	~10–35 kWh per kg H_2
Primary byproduct	Oxygen (O_2)	Solid carbon (C)
Feedstock	Water	Natural gas
Carbon emissions	Zero direct emissions if renewable electricity is used	Zero direct carbon emissions, but solid carbon waste must be managed

Levelized Cost of Hydrogen



Source: CLEAN HYDROGEN PRODUCTION PATHWAYS, REPORT 2024, hydrogeneurope.eu

Overview of TRL 6-8 projects pursuing various methane splitting technologies

Company	Status	Technology
Monolith	Commercial plant (13 t/d) in Nebraska in 2020, expansion to 165 t/d in 2026.	High temperature electric heating - plasma
Hazer Group	Demo plant (275 kg/d) in Perth in 2024, commercial plant (7 t/d) in Canada 2025.	Low temp fluid bed iron ore catalytic pyrolysis
C-Zero	Pilot plant (400 kg/d) planned for 2024, commercial plant (6 t/d) 2025.	Bubble column molten metal / salt pyrolysis
Huntsman Nanocomp	Bench scale (1 kg/d), pilot plant (25 kg/d) in Texas in 2023, commercial demo plant (1 t/d) in 2026.	Thermocatalytic pyrolysis
H-Quest	Pilot plant (250 kg/d) in 2023, with commercial target of 1 t/d.	Microwave plasma pyrolysis
Hycamite	Bench scale, pilot plant (5.5 t/d) planned for 2024 (Finland).	Thermocatalytic pyrolysis
Hiiroc Hydrogen	2 demo plants in operation (UK), pilot plant (400 kg/d) planned for 2024.	Vortex plasma torch and molten metal pyrolysis
Modern Hydrogen	2 micro demo plants (5 kg/d) 2023, pilot plant (500 kg/d) in 2024.	High temp pyrolysis
Ekona Power	Bench scale reactor (200 kg/d), pilot plant (1 t/d) in Alberta planned for 2025.	Thermal pulsed methane pyrolysis
Levidian	Demo plants (27 kg/d) in Scotland and demo plant (55 kg/d) planned for 2025 in UAE.	LOOP - microwave plasma methane cracking
Plenesys	Demo plant (150 kg/d) in Australia planned for 2024 with commercial target of 275 kg/d and 2.7 t/d units.	Hyplasma (AC plasma arc)
Graforce	Demo plant in Austria in 2024.	Plasmalysis
Sakowin	Small demo launched in 2022 in Switzerland (4 kg/d). Industrial demo planned for 2024 (72 kg/d).	Plasmalysis

Source: CLEAN HYDROGEN PRODUCTION PATHWAYS, REPORT 2024, hydrogeneurope.eu

Three Ironmaking Examples Suited for Integration with Methane Pyrolysis (Turquoise Hydrogen)

1. SuSteel Hydrogen Plasma Smelting

Process:
Natural Gas → Thermal Plasma Methane Pyrolysis → H_2 + Carbon Black → Liquid Iron

Advantages
- Highest technological synergy
- Direct use of H_2 in the smelting reduction of iron ore

Challenge
- Plasma scale-up & energy demand
- Handling of carbon Black

2. HYFOR + Hy4Smelt

Process:
Natural Gas → Methane Pyrolysis → H_2 → HYFOR (fine ore reduction) → Electric Smelter → Liquid Iron

Advantages
- Fine ore feed (no pelletizing)
- Near-commercial pathway
- Lower electricity demand than thermal plasma

Challenge:
Process Upscale

3. Hydrogen DRI (MIDREX / Energiron)

Process:
Natural Gas → Methane Pyrolysis → H_2 → Shaft Furnace → DRI → EAF

Advantages
- Commercially mature
- Lowest technical risk
- First large-scale market for turquoise H_2

Limitations
- Separate routes of turquoise hydrogen production and ironmaking

Source: Reichel, E.K. (2024). *Model-based Control of Electric-arc Plasma in the HPSR Process for Zero-emission Iron-ore Reduction*. Presented at the ESTEP Annual Event 2024, Linz, Austria, 29 October 2024. K1-MET GmbH; Midrex; Energion

Summary

While Green Hydrogen is the targeted color worldwide to be produced, the investment in the various technology production processes of the Turquoise Hydrogen and enhancing its technology readiness level is worth the consideration.

Turquoise Hydrogen could be a better option than the Green Hydrogen for the natural gas producing countries.