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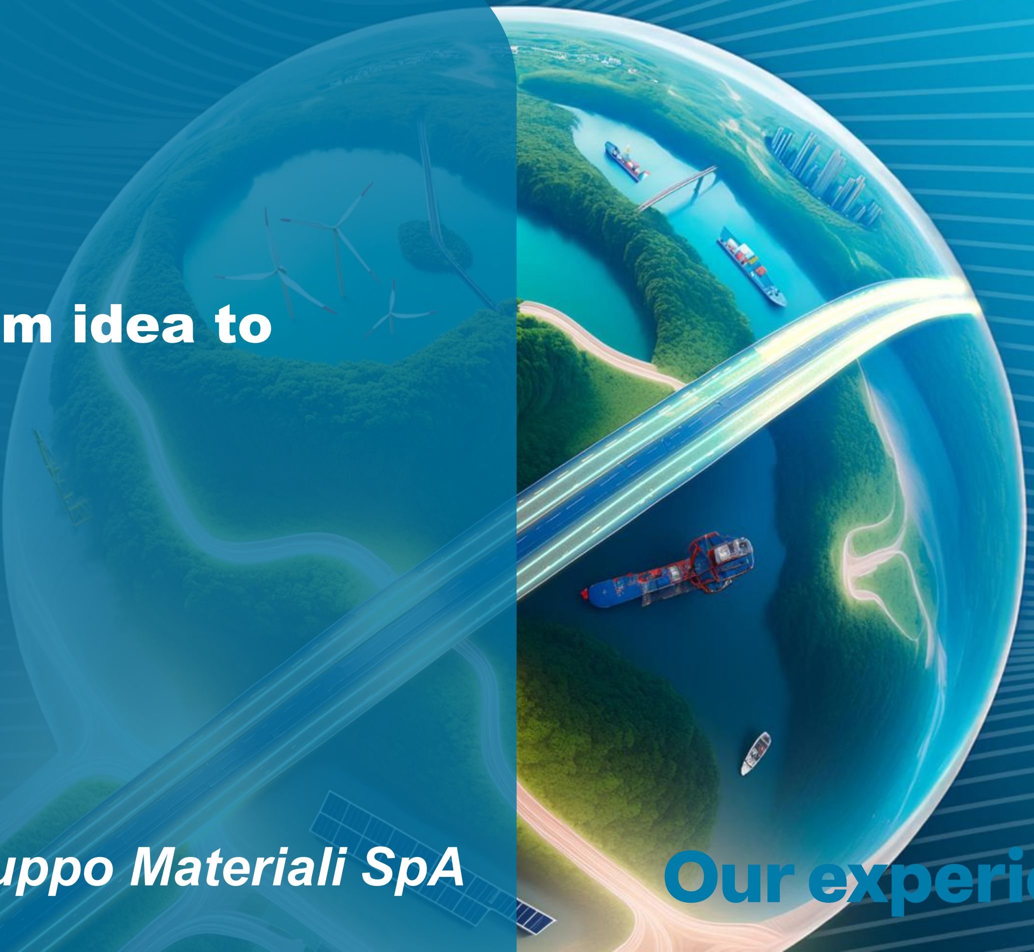
An example of the path from idea to industrial application:

HYDRA Project



Dott. Filippo CIRILLI

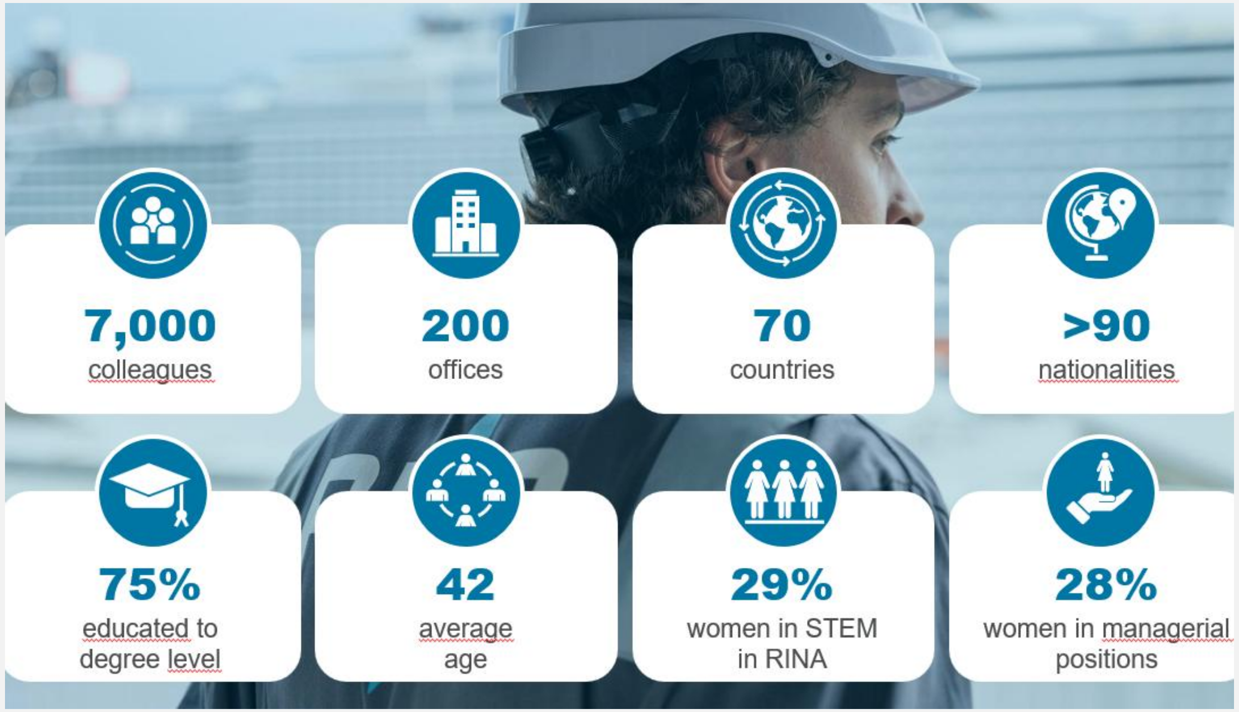
RINA Consulting – Centro Sviluppo Materiali SpA

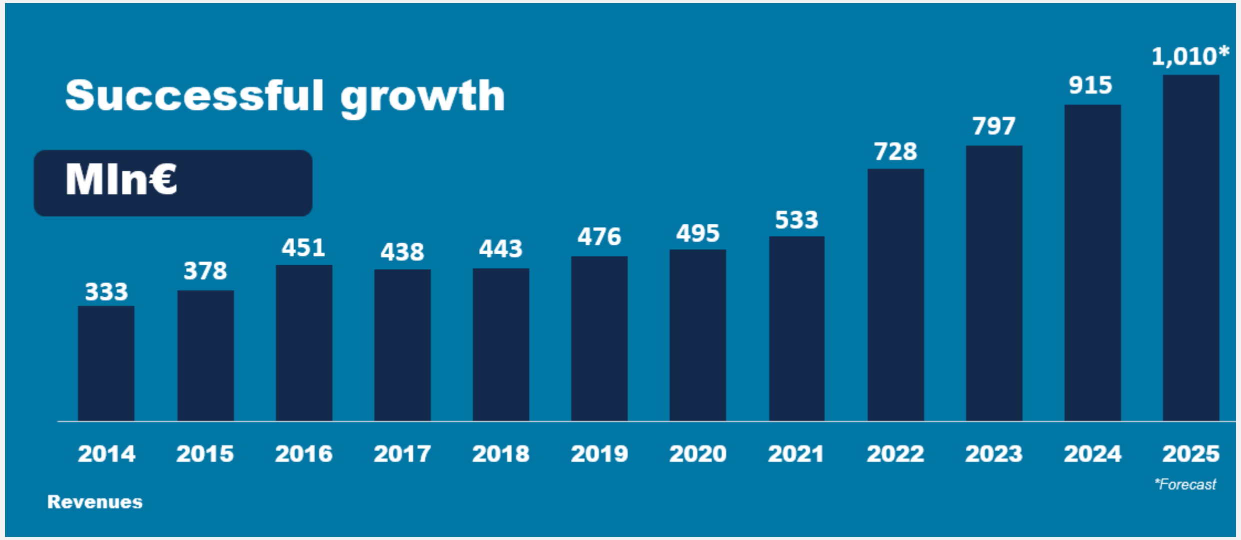
Our experience. Your growth.

Content of the presentation

- Company presentation
- Methodological approach to technological innovation
- Case study: steelmaking decarbonization and HYDRA project
    - Hard-to-abate CO2 emissions
    - Steel production technologies
    - Green Hydrogen
    - Hydrogen production costs
    - Green hydrogen electrolysis
    - HYDRA project

RINA Company





Our business unites

Energy

RINA's energy team offers global expertise in site characterization, advisory, engineering, inspections & supervision, supporting energy projects from development to decommissioning, ensuring safety and efficiency.

Industry

RINA's industry team provides highly qualified services, thank to its multidisciplinary approach and outstanding application expertise across all industrial sectors - including A&D, hard-to-abate industries, management consulting, and cybersecurity.

Infrastructure & Mobility

RINA's infrastructure & mobility team supports the path to the next generation of infrastructures and buildings by ensuring their safety and efficiency.

Marine

RINA's marine team provides ship classification, statutory certification, advisory, digital and technical services for safety, sustainability, and innovation across commercial, naval, and yachting sectors.

Certification

RINA's certification team guides companies on their journey toward continuous improvement and excellence, by certifying organizations' genuine dedication to best practices.

Real Estate

RINA's real estate team supports public and private market operators with innovative services aimed at protecting and enhancing real estate capital value at every stage of the investment.

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RINA CSM

RINA CSM

- The **Rina Industry Business Unit** provides high-added value integrated services with a special focus on manufacturing, steel and heavy industry, aerospace and defense.

- **Whitin this BU, RINA CSM** is the Company devoted to the Steel Industry and manufacturers in sectors such as Oil&Gas, Power Gen and Automotive.

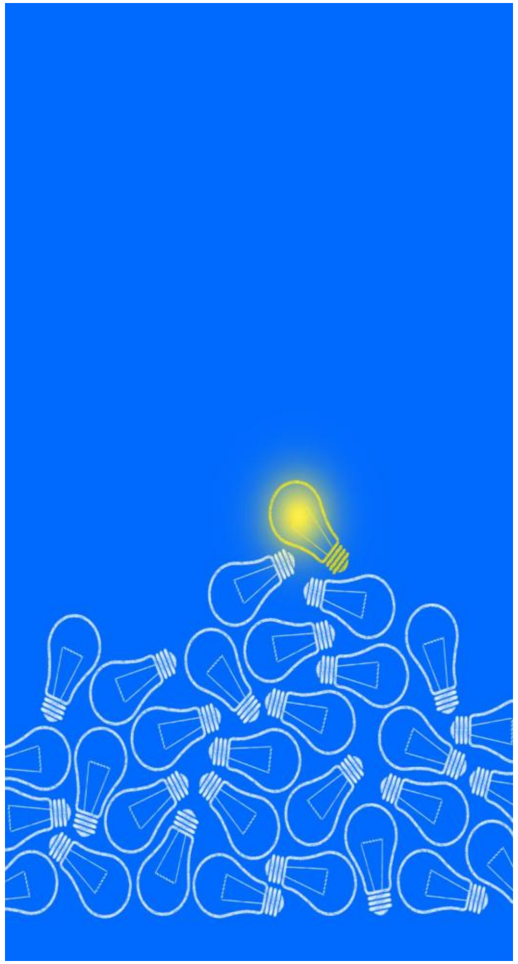
- **RINA CSM** was founded in 1963 by Italian Government and since 2013 incorporated in **RINA Group**.

- More than **270** highly trained and **experienced resources** and **11 laboratories and pilot plants**

- More than **300 R&D projects per year** for the most important European steel makers, plant suppliers, Oil&Gas majors.

Methodological approach to technological innovation

Technical problem definition / Technology choice



Systematic Technology Exploration

Technology scouting involves continuous monitoring of trends, patents, scientific literature to identify innovative solutions.

Internal and External Channels

Scouting leverages internal R&D and external partnerships including suppliers, institutions, and innovation networks.

Technology Assessment Criteria

Technologies are evaluated on maturity, compatibility, scalability, ecosystem strength, and regulatory acceptance.

Outcome and Strategic Value

The scouting output is a curated list of promising solutions with risk profiles

Methodological approach to technological innovation

Theoretical evaluation

Technical Feasibility

Assess if technology delivers required performance reliably in real operating conditions, focusing on maturity and robustness-Modeling.

Economic Feasibility

Evaluate costs, investments, savings, and revenues - Modeling

Environmental and Regulatory Feasibility

Ensure compliance with regulations and assess environmental impacts using lifecycle assessment methods- Modeling

Risk Assessment and Mitigation

Identify and evaluate technical, financial, and strategic risks; propose mitigation strategies for safe innovation progress- Modeling

Methodological approach to technological innovation

Test run in different scale/Stakeholder Engagement

Purpose of small scale and Pilot Testing

Small scale and pilot testing transitions theory to practice by validating technology performance in realistic settings on a limited scale.

Structured Evaluation and Monitoring

Clear objectives, success criteria, and data collection enable measurable and evidence-based pilot evaluations.

Iterative Refinement

Pilot feedback drives iterative improvements addressing challenges like integration, maintenance, and user interaction.

Stakeholder Engagement

Demonstrating pilot results builds stakeholder confidence and informs decisions on scaling or redesigning solutions.

Methodological approach to technological innovation

Pilot-to-Industrial Scale-Up and Technology Deployment Framework

Structured Implementation Roadmap

A clear roadmap outlines timelines, responsibilities, and resources for smooth technology deployment across the organization.

Identification of funding scheme

Careful integration with existing systems and comprehensive training ensure minimal disruption and effective technology use.

Detailed project definition

Detailed project definition, activities, timing, costs and investment needs.

Structured Governance Framework

Defines clear roles, decision-making structures, and accountability across innovation lifecycle.

Key Performance Indicators (KPIs)

KPIs track inputs like R&D and outcomes such as cost savings and adoption rates.

Continuous Improvement Process

Lessons learned are systematically captured and fed back to improve innovation methods.

RINA-CSM
Research/innovation approach

Case Study

Steelmaking decarbonization and HYDRA project

Funded by
the European Union
NextGenerationEU

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Hard-to-abate sectors

Sector	Annual production (Italy)	Specific CO_2 emissions kg/t product	Source
Steel (Blast Furnace route)	3Mt(*)	2330(**)	*Federacciai **Worldsteel
Steel (scrap route - EAF)	18Mt(*)	680(**)	*Federacciai **Worldsteel
Glass	5Mt	379	Sustainability report ASSOVETRO 2023
Cement	12,6 Mt (clinker)	628	Sustainability report Federbeton 2023

Hard-to-abate sectors

- The Hard-to-Abate sector emits about 10,000 million tons of CO_2 equivalent per year globally, (51Mt in Italy), about 25% of total emission
- Net Zero decarbonisation targets can’t be achieved without hard-to-abate sectors transformation
- Decarbonization strategies include electrification, alternative fuels, CO_2 capture and storage, and improved energy efficiency
- The development and use of cutting-edge technologies is an unavoidable step
- **Steel is the world's largest emitter (28% of hard-to-abate producers)**
- **Steel decarbonization strongly rely on green (or low CO_2) hydrogen utilization**

https://www.energy.gov/fecm/articles/scaling-carbon-capture-hard-abate-industries-united-states-and-globally

General framework

- Carbon neutral Steel production requires breaktrough technologies
- **Hydrogen** is recognised as key pillar in steelmaking decarbonization
- Several technologies are available at different TRL.
- The production route based on DRP-EAF fed by hydrogen is recognized as a valuable alternative to BF-BOF based route
- There is a general consensus about decarbonization target at 2050 by many States and Steelmaking Companies

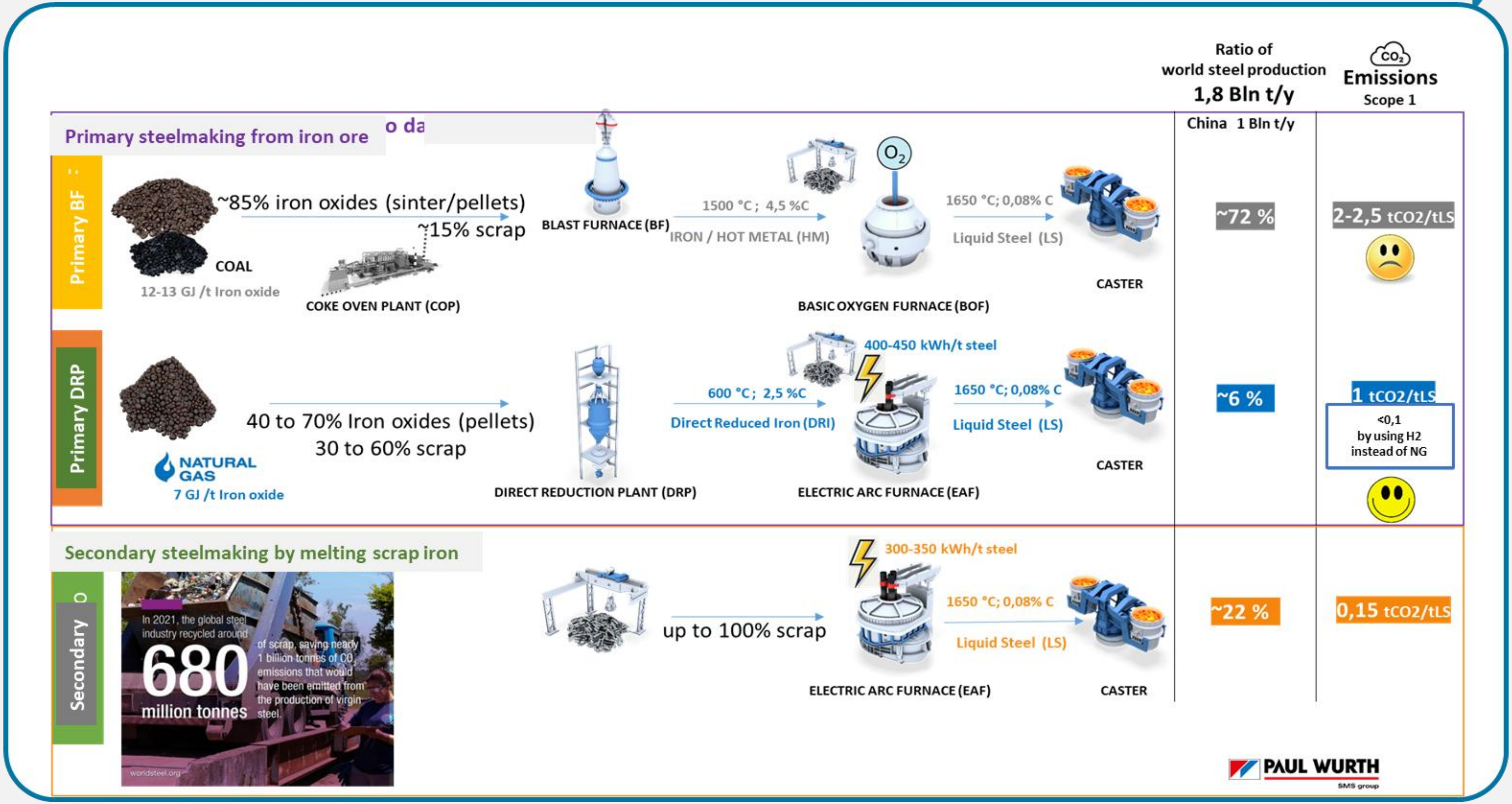
What is green steel

- It is the steel with low amount (or zero) of CO_2 per ton of produced material
- There is not yet an official definition of Green Steel at European and world level
- Proposal has been raised by German Association of Steel producers
- India first country who introduced own definition of Green Steel

General framework
How today steel is made? And CO_2?

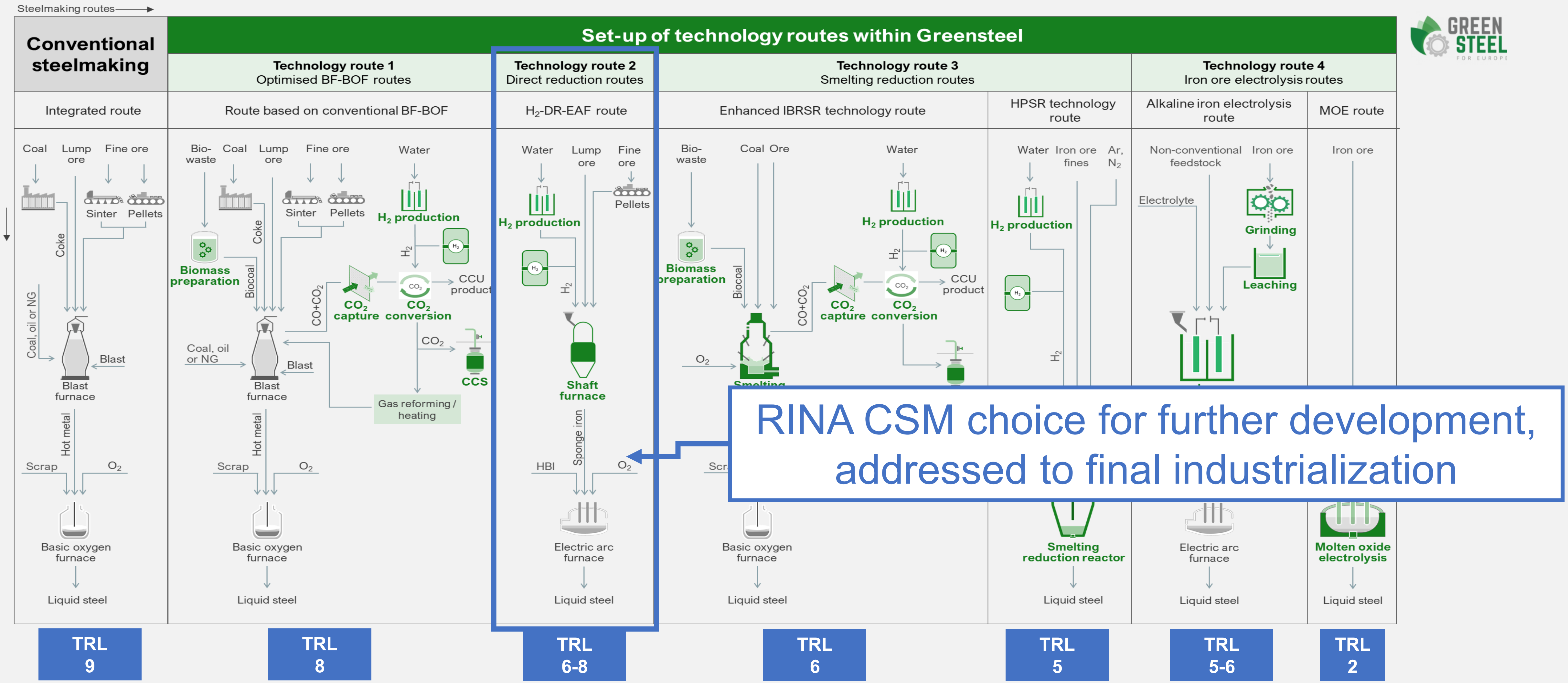
Production from iron ore

Production from scrap

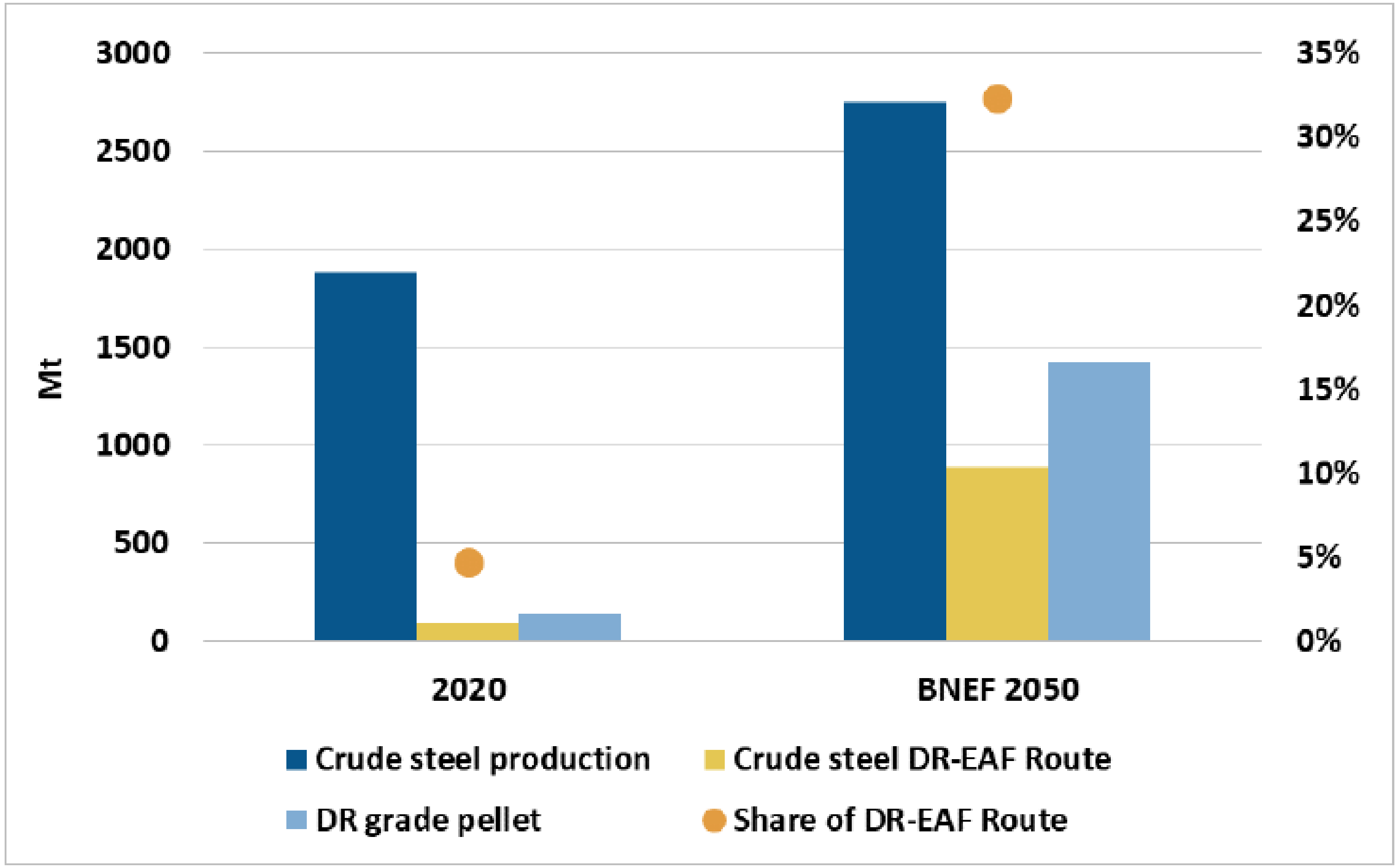


General framework

- Steel production decarbonization requires innovative technologies: scouting of available technologies carried out



General framework



Source: BloombergNEF, Worldsteel, Midrex, IEEFA calculations.

Currently only 6% at world level of steel production is carried out with the DRI-EAF route.

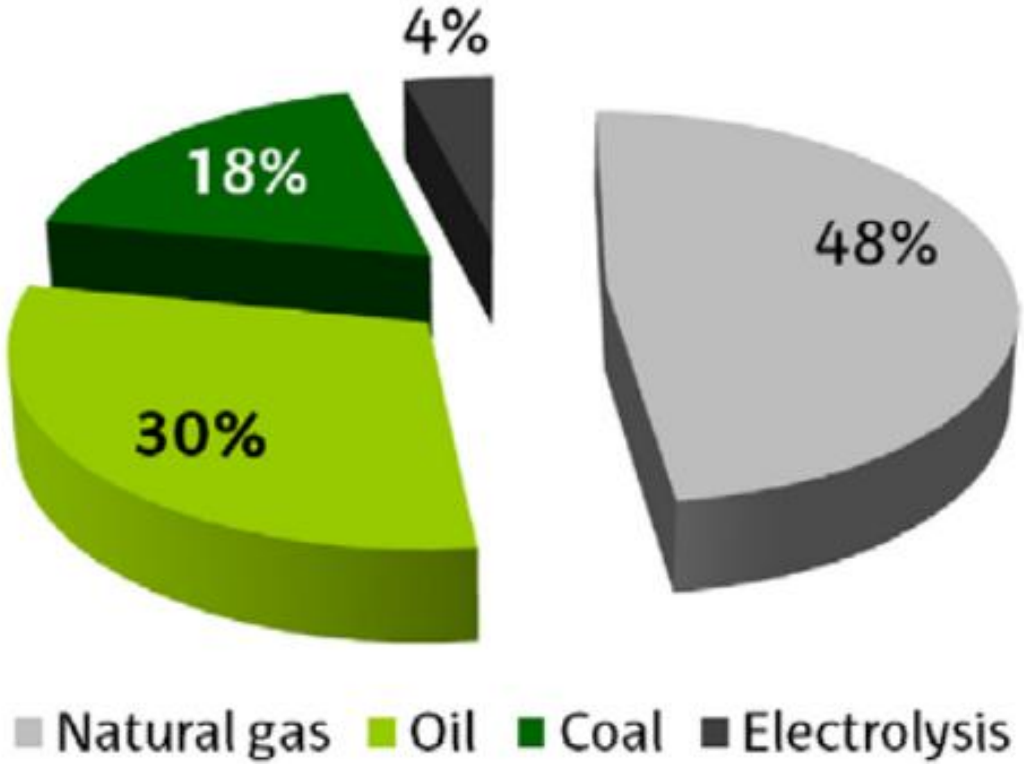
Several available forecast models shows that, in a general frame of increasing global steel production, the production share of DRI-EAF may reach 30% in 2050.

Availability of green hydrogen will allow complete decarbonization

Current Hydrogen demand and production share

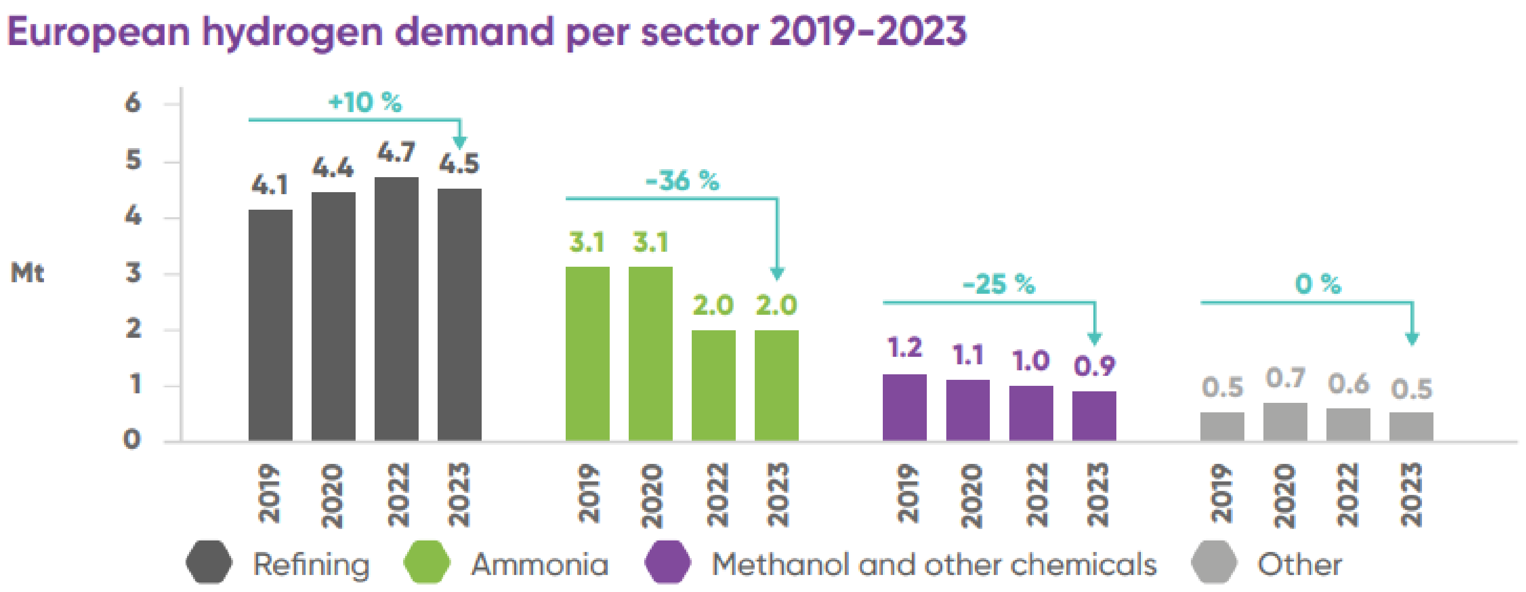
Global hydrogen demand reached 97 Mt in 2023, an increase of 2.5% compared to 2022
Hydrogen production is dominated by fossil sources and a small share of electrolysis

The share of biomass based hydrogen production is currently negligible in the overall production



Arregi, A., Amutio, M., Lopez, G., Bilbao, J., Olazar, M., 2018. Evaluation of thermochemical routes for hydrogen production from biomass: A review. Energy Convers. Manag. 165, 696–719. https://doi.org/10.1016/j.enconman.2018.03.089

Current Hydrogen demand and production share



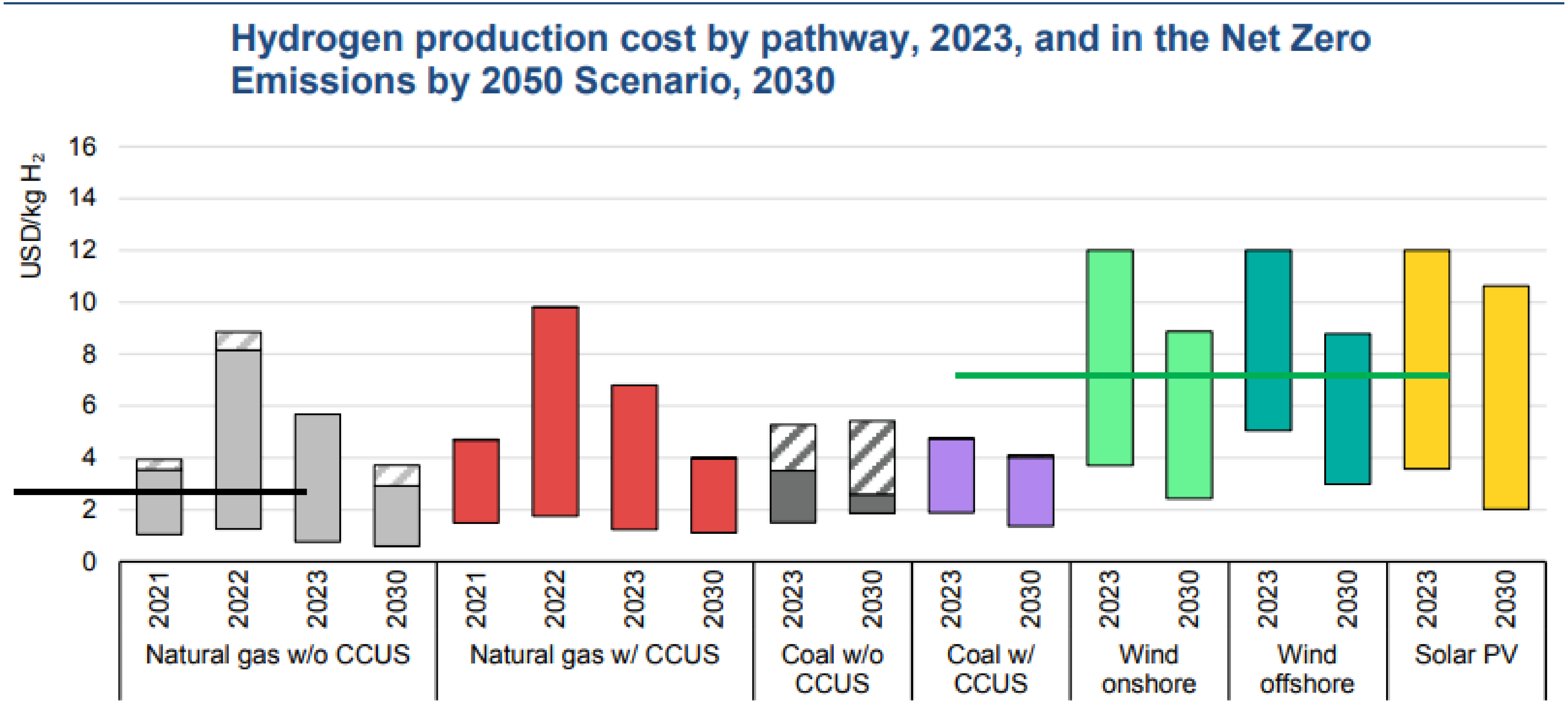
Hydrogen demand in Europe was 7.9 Mt in 2023, a 3% decrease compared to the 8.2 Mt reported for 2022 and close to a 15% fall since 2020 *(source Hydrogen Europe)*

Assuming 50 kg/t* of H_2 as average demand for steel production

6Mt/y of H_2 necessary for 120Mt of European steel production

**https://www.europarl.europa.eu/RegData/etudes/BRIE/2020/641552/EPRS_BRI(2020)641552_EN.pdf*

Hydrogen production costs

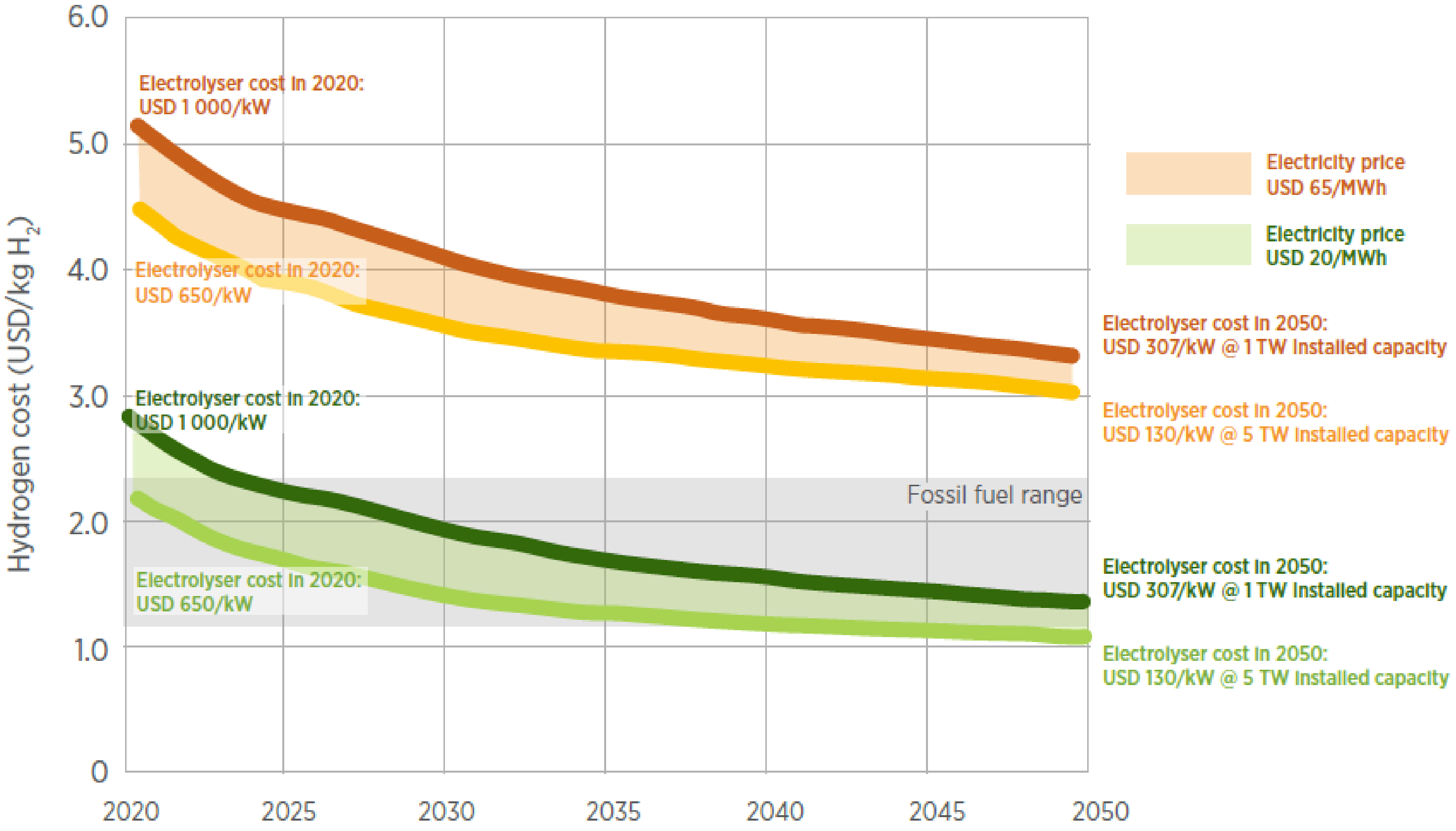


How much will it cost to produce green hydrogen?

The most important components influencing the cost of green hydrogen production are the cost of the **renewable electricity** needed to power the electrolyzer unit and the **electrolyzer** itself.

VARIABLES and ASSUMPTIONS

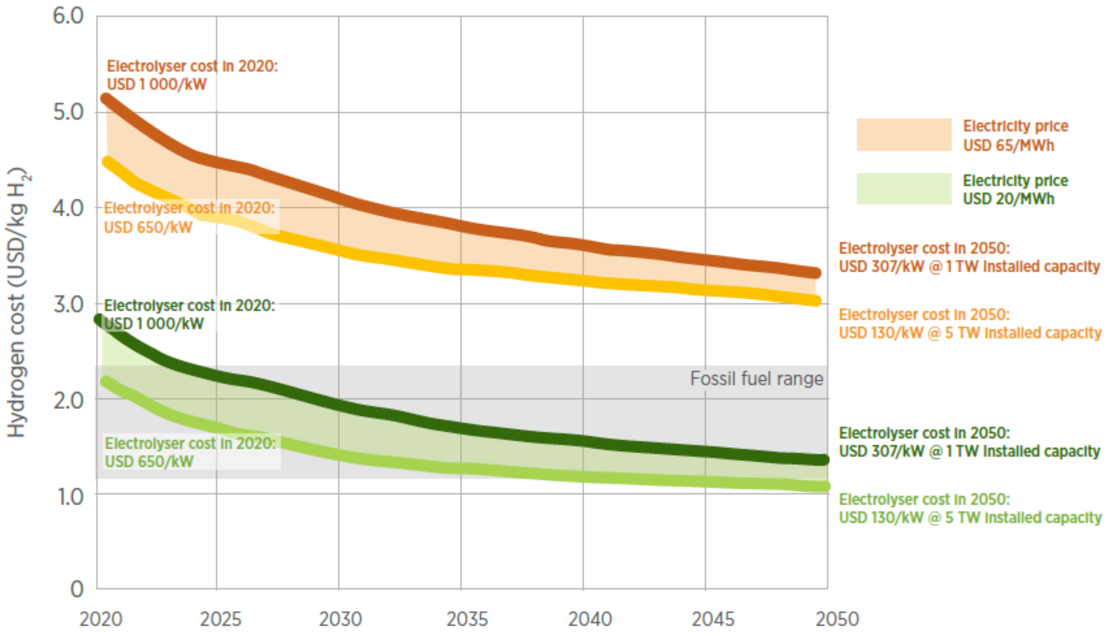
- ✓ Time interval: 2020 to 2050 - cost reductions in 2050 include efficiency improvement and the electrolyzer cost guaranteed by scale effect for the capacity deployment increase
- ✓ Renewable electricity price: 20 USD/MWh (low-cost) and 65 USD/MWh (average cost)
- ✓ Electrolyzer cost:
  - in 2020: 650 USD/kW and 1000 USD/kW
  - in 2050: 130 USD/kW and 307 USD/kW
- ✓ Electrolysis deployment: 1 TW and 5 TW
- ✓ Only bare technical production costs are considered: conversion/transport cost to demand centers are not included



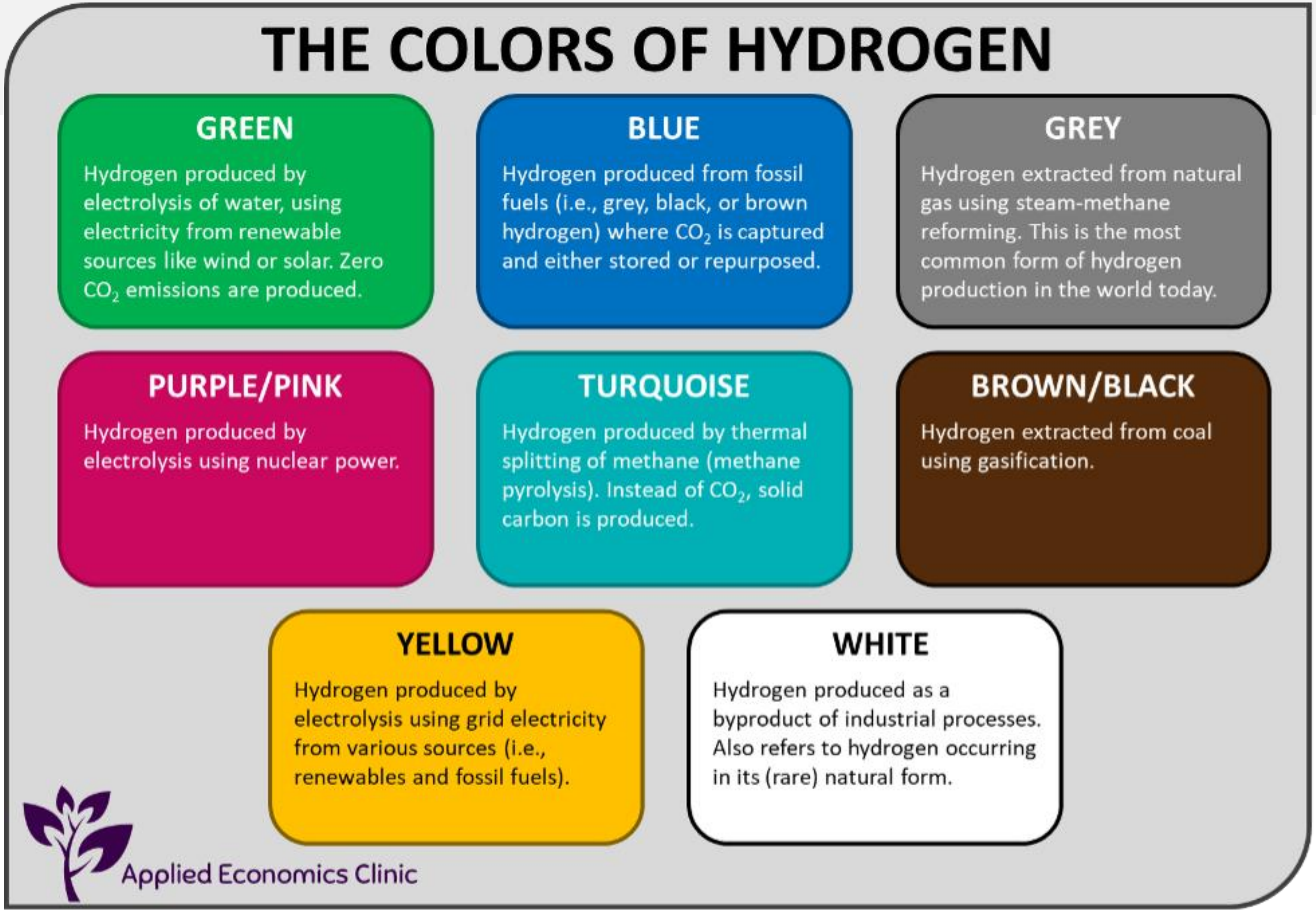
Source: *IRENA 2022 Green hydrogen cost reduction - Scaling up electrolyzers to meet the 1,5 °C climate goal*

How much will it cost to produce green hydrogen?

- Low costs of electricity are a necessary condition for producing competitive green hydrogen (green area).
- Cost reductions in electrolysers cannot compensate for high electricity prices.
- Combined with low electricity cost, an aggressive electrolyser deployment pathway (5TW) can make green hydrogen cheaper than any low-carbon alternative (i.e., < USD 1/kg), before 2040. If rapid scale-up takes place in the next decade, green hydrogen is expected to start becoming competitive with blue hydrogen by 2030 in a wide range of countries, where the electricity prices is ab. 30 USD/MWh



What is Green Hydrogen: the colours of hydrogen



What is Green Hydrogen: the colours of hydrogen

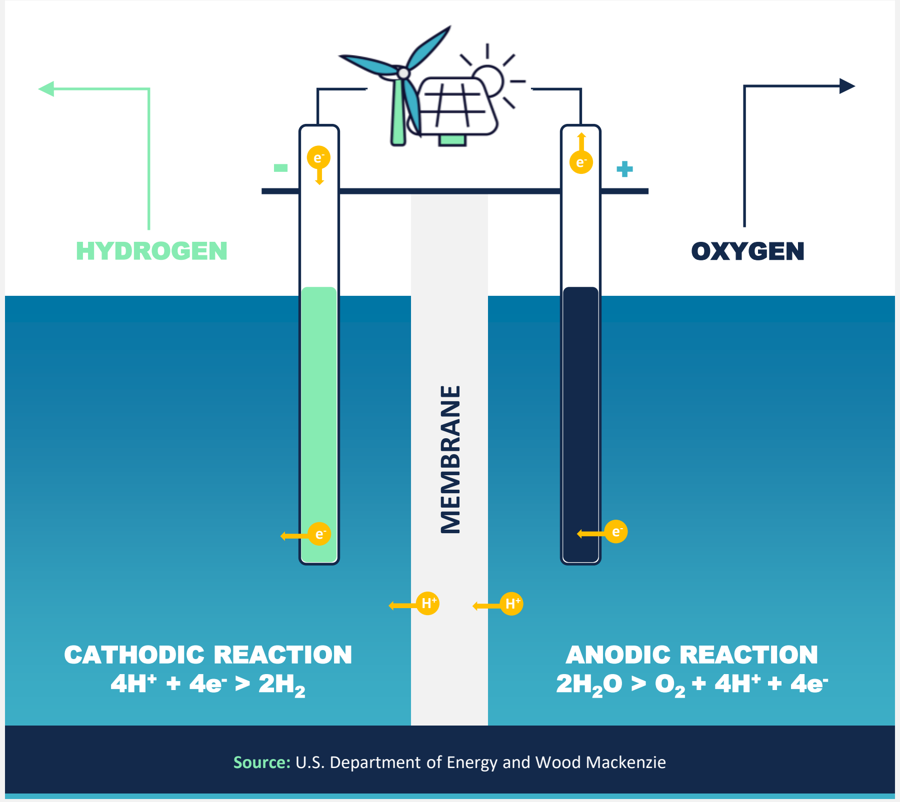
	Inspired by Global Energy Infrastructure (GEI) 2021 DIRECT: emissions for H2 production process INDIRECT: emissions by feedstock and energy supply chains	Hydrogen Council (2021) and Energy Transition Commission (2021)
GREY HYDROGEN	9,5 – 15 Kg CO_2/Kg H_2 DIRECT: 9 – 11 INDIRECT: 0,5 – 4	2020: 0,7 - 2,1 USD/kg 2030: 0,8 – 2,1 USD/kg
BLUE HYDROGEN	1 – 11 kg CO_2/Kg H_2 DIRECT: 0,5 - 4 INDIRECT: 0,5 - 7	2020: 1,6 – 2,6 USD/kg 2030: 1 – 2,1USD/kg
GREEN HYDROGEN	> 0 kg CO_2/Kg H_2 DIRECT: 0 INDIRECT: >0	2020: 3,2 – 5,3 USD/kg 2030: 1,8 – 2,7 USD/kg
PINK HYDROGEN	> 0 kg CO_2/Kg H_2 DIRECT: 0 INDIRECT: >0	NA
TURQUOISE HYDROGEN	NA	NA
YELLOW HYDROGEN	< 1 – 30 kg CO_2/Kg H_2 DIRECT: 0 INDIRECT: <1 – 30 depending on the grid mix	NA

Electrolyzers: the working principle

Water electrolysers are electrochemical devices used to split water molecules into hydrogen and oxygen by passage of an electrical current.

The core of an electrolyzer is the *electrolytic cell*, where electrochemical reactions take place. According to basic principles of *electrochemistry*, the electrolysis of water occurs when a *direct current* is passed between two *electrodes immersed in an electrolyte* giving rise to *reactions* at the electrodes where the product gases are released: hydrogen and oxygen.

Once the products are released a physical separation is needed to avoid the mixture.



An electrolytic CELL

Available electrolyzers today: some figures

$$2\,H_2O \rightarrow 2H_2 + O_2$$

Water required to produce 1 kg of hydrogen* (high water purity required: 99.8% to 99.9998%)	9 l/kg of hydrogen: stechiometric value 10 - 11 l/kg of hydrogen: de-ionized water 20 - 25 l/kg of hydrogen: tap water
Energy required to produce 1 kg of hydrogen *	about **50 kWh/kg** of hydrogen
Hydrogen energy density: • Lower heating value • Higher heating value	 **33.33 kWh/kg** of hydrogen (3.00 kWh/Nm³ - 120,1 MJ/kg) 39.39 kWh/kg (3.54 kWh/Nm³ - 141,9 MJ/kg)
Electrolyzer system efficiency (BoP included)*	55% - 75%
Hydrogen density	0,089 kg/m3 @ 0°C, 1 bar: a volume of ab. **11 m³** to store **1 kg** of H_2 0,081 kg/m3 @ 25°C, 1 bar

* Data refer to the most mature electrolyzers in the market, Alkaline and Proton Exchange Membrane electrolyzers.
They are closely dependent on the electrolysis type and system design

How to select the best electrolyzer

	**ALKALINE (AEL)**	The ideal project environment is **large-scale industrial installations** requiring a **steady H2-output** at **low pressure levels**. In this scenario, the electrolyzer is typically **grid-connected**, operated at **high utilization and steady load**. H_2-production is often located **close to the demand center** with no need for high compression.
	**PROTON EXCHANGE MEMBRANE (PEM)**	Well suited for **off-grid installations** powered by **highly variable renewable energy sources** (e.g., wind turbines, PV plants). The co-location, close to the renewable power plant and dynamic operation mode, often entails a **need for compression** to transport and store hydrogen. The high load variability combined with the demand for elevated output pressure, the **small footprint** and **low maintenance needs**, make the PEM the ideal candidate for the **offshore environment**.
	**SOLID OXIDE (SOEC)**	They work very well when coupled with exothermal reactions, in locations where waste heat is available: for example, in the methanation processes of Power to Hydrogen to Gas, ammonia plants, refineries, etc

Overwiev of (other) H_2 production technologies

- Steam methane reforming: main technology
- Methane partial oxidation: secondary (but operating) technology
- Biomass gassification: secondary (but operating) technology
- Methane pyrolysis: available at pilot level
- Photocatalysis: Available at small scale level

Details in ANNEX

Hydrogen utilization in steelmaking

HYDRA
An open R&D platform for steel decarbonisation

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NextGenerationEU

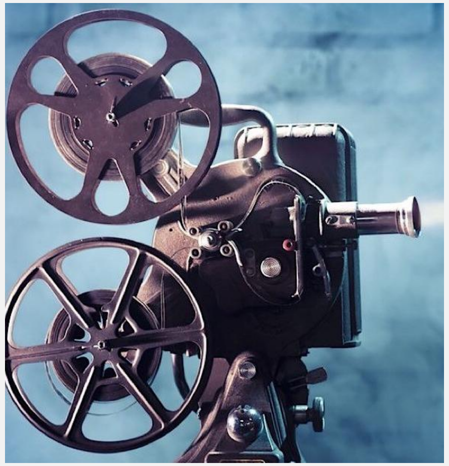
Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the granting authority. Neither the European Union nor the granting authority can be held responsible for them.

Scope of the project

The project foresees the setup of *hydrogen-based steel production*, in an integrated framework, including hydrogen management in the steel factory, direct reduction of iron ore, utilization of hydrogen in electric arc furnace and decarbonization of steel reheating and thermal treatment furnaces

Implemented under the IPCEI funding scheme (**I**mportant **P**rojects of **C**ommon **E**uropean **I**nterest) and approved by European Union and financially supported by Italian Ministry of Enterprises and Made in Italy

Started on January 1st, 2023, will be completed by December 31st, 2028



Project description

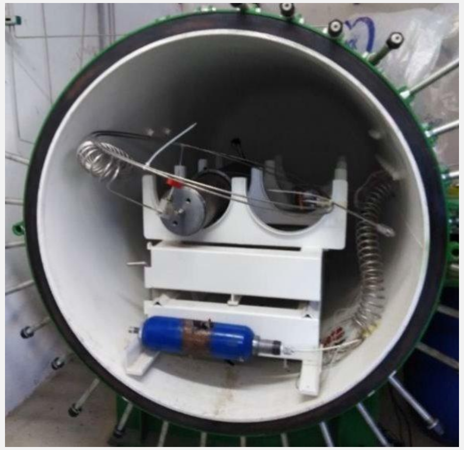
The project is divided into 4 lines of activity (global approach), which have been called *Work Packages* (WP):

- **WP1:** labs to study and development methodologies for testing and qualification of materials and components in hydrogen environment;
- **WP2:** the construction and development of the hydrogen-fed direct reduction pilot plant and process (DRP);
- **WP3:** the construction and development of an EAF for DRI melting obtained with hydrogen;
- **WP4:** the study and development of the 'downstream' use of hydrogen in reheating and heat treatment furnaces and its impact on steel quality.

Project description

WP1 is focused on the **Development of green hydrogen use in iron and steelmaking**, aiming to:

- define the guidelines and procedure for a safe and reliable use of H_2 within the industrial steelmaking plants
- give confidence to the steelmakers about the feasibility of introducing H_2 in the industrial steelmaking process
- evaluate the impact of H_2 percentage in a CH_4/H_2 blended mixture on the industrial steelmaking plant (targeting 100% H_2)
- make deeper knowledge and to upgrade the standards and regulation framework for the design and realization of dedicated hydrogen components in the steel making plant, with the HSE related issues.
- provide training support (training HUB)



Project description

WP2 is focused on the **Direct Reduction process** in a pilot plant

The pilot plant has been designed to investigate phenomena governing the Direct Reduction process, simulating in a reliable scale what occurring in industrial plants

DRP tower of about 30 m height

100 kg/h DRI produced (about 2 t per day)

Gas input by wagon tank (slot for four tanks foreseein)

Gas treament line equipped with CO2 capture

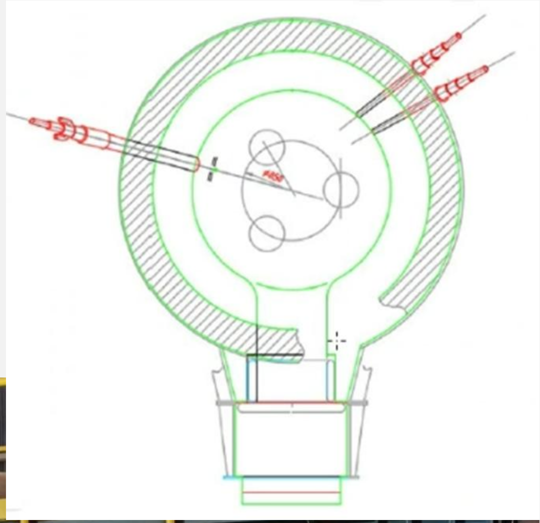
NG injection in the lower part of the furnace

Project description

WP3 is focused on the DRI melting will be investigate with a state- of-the-art electrical furnace pilot plant, of capacity of **7 t/heat**.

Main characteristics of the furnace are:

- 7 t capacity, with 4 m^3 internal volume
- AC three electrodes
- Scrap and DRI charge
- Continuous charging of DRI
- Injection of solid materials (additive, coal, alternative carbonaceous materials)
- KT lance working as Hydrogen burner or Oxygen injector
- Furnace shell refractory insulated



Project description

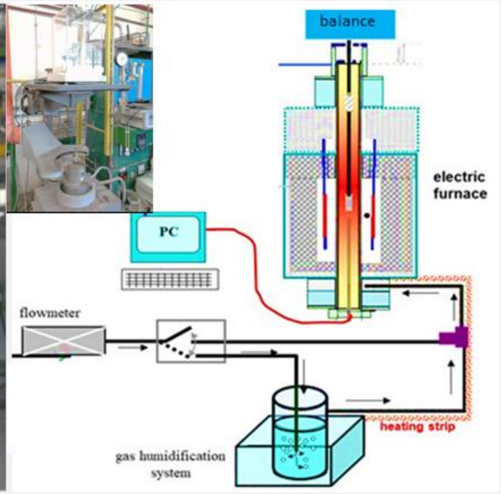
WP4 is focused on the use of hydrogen in furnaces for re-heating and treatment of the steel
This stream of activities uses the already existing facilities (experimental combustion station in Dalmine and high temperature labs in Rome

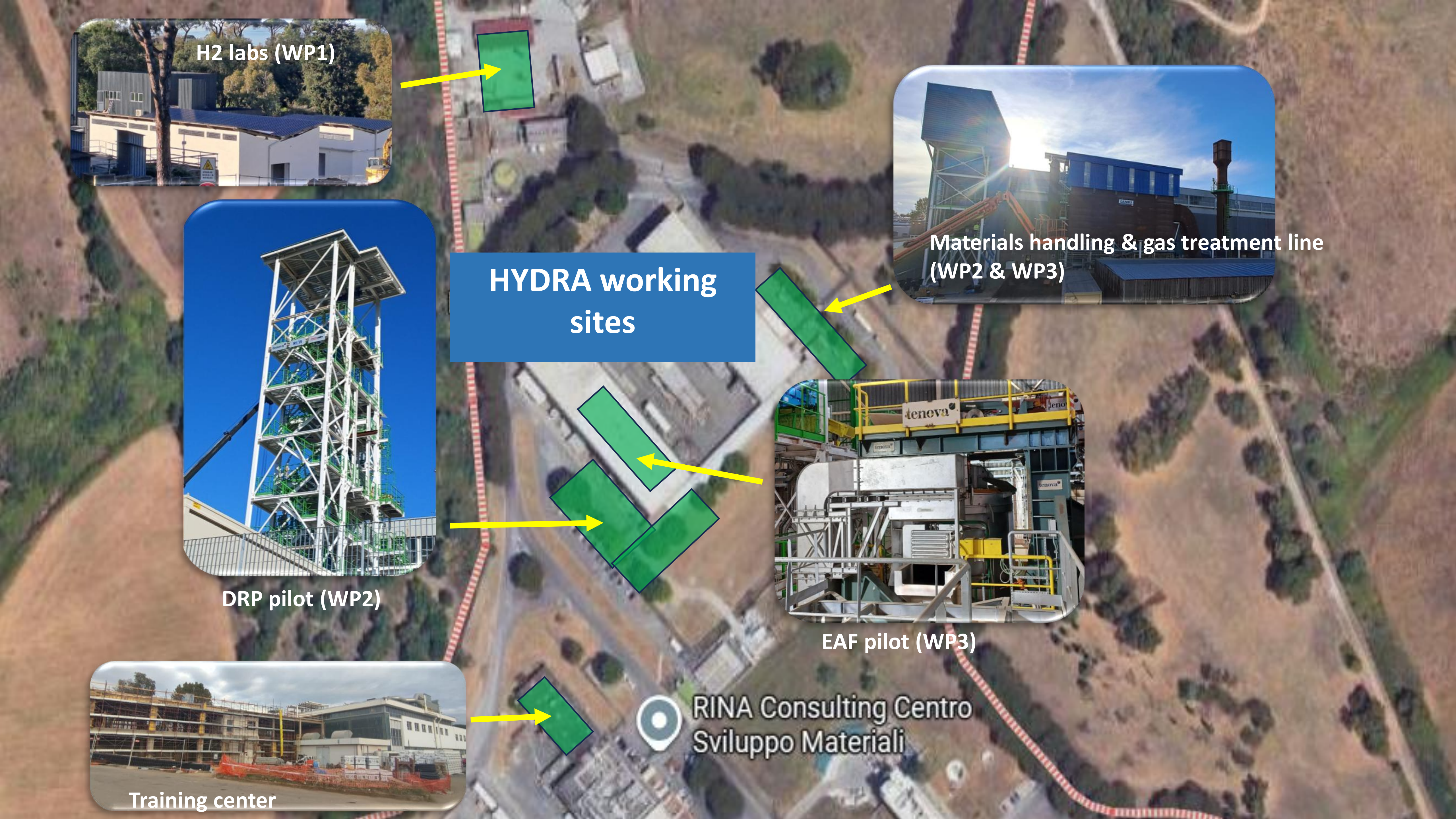
The aim of WP4 is to support the diffusion of the technology and investigating the effect of H_2 combustion both on the products quality and performance/life of the plant components


Horizontal furnace for annealing simulation


Combustion station

TGA to simulate steel oxidation




HYDRA working sites
H2 labs (WP1)
Materials handling & gas treatment line (WP2 & WP3)
DRP pilot (WP2)
EAF pilot (WP3)
Training center
RINA Consulting Centro Sviluppo Materiali

HYDRA – DRI & EAF H2 based steel production – further application of experimental platform

Interaction with grid and coupling with plant production scheduling

Hydrogen production technologies: electrolysers, testing and performances under variable conditions, Methane pyrolysis, Biomass and waste gasification, blending with biogas

Flexible management of CO2 capture unit

Testing of innovative sensors and control technologies

Testing of new plant components and refractories

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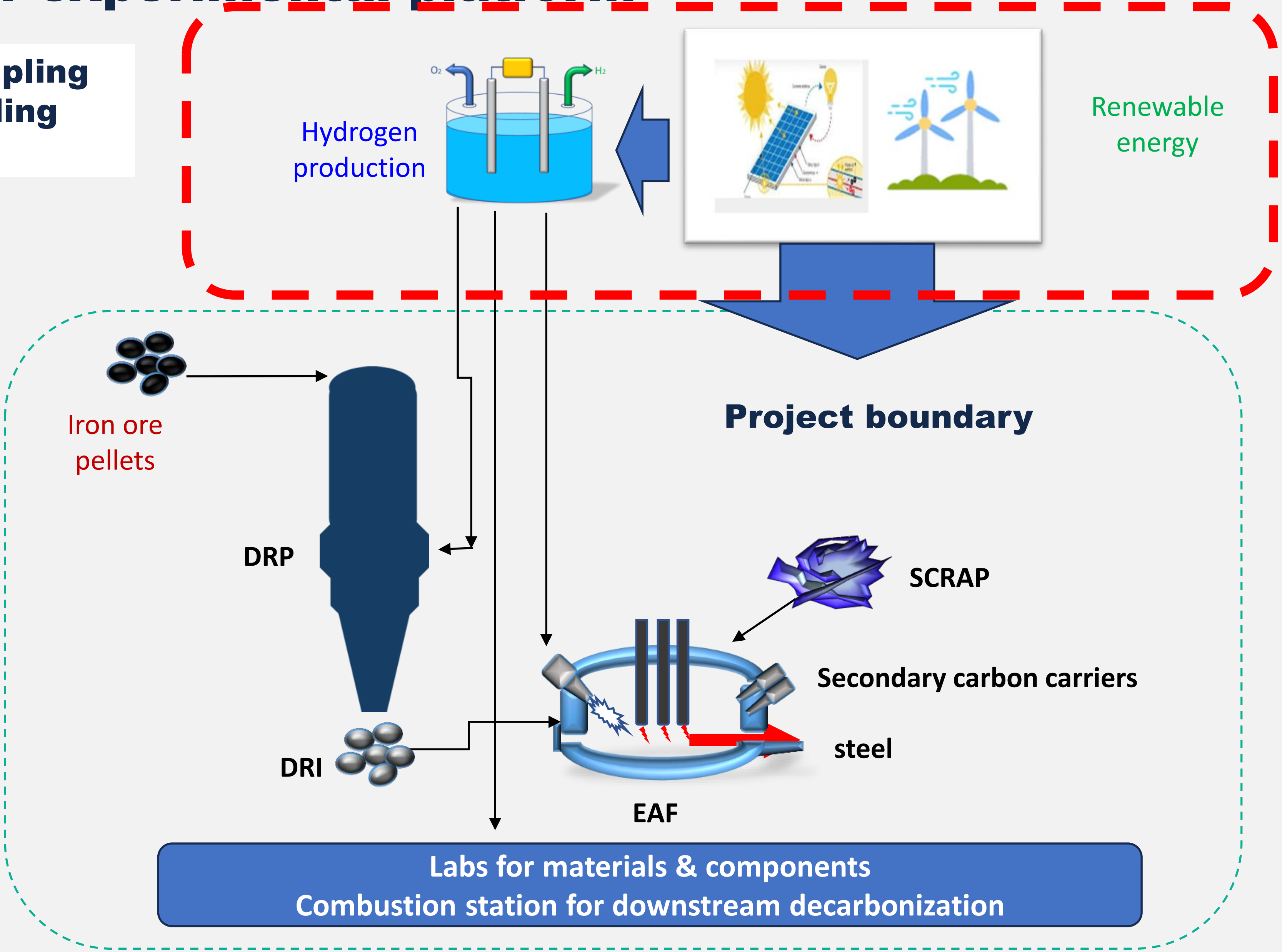


HYDRA – DRI & EAF H2 based steel production – services for steelmaking

Decarbonization roadmap of existing plants

Decarbonization plans

Support to technology scouting

Pilot tests to support operating practice definition, impact on productivity, steel quality, definition of new slag practices

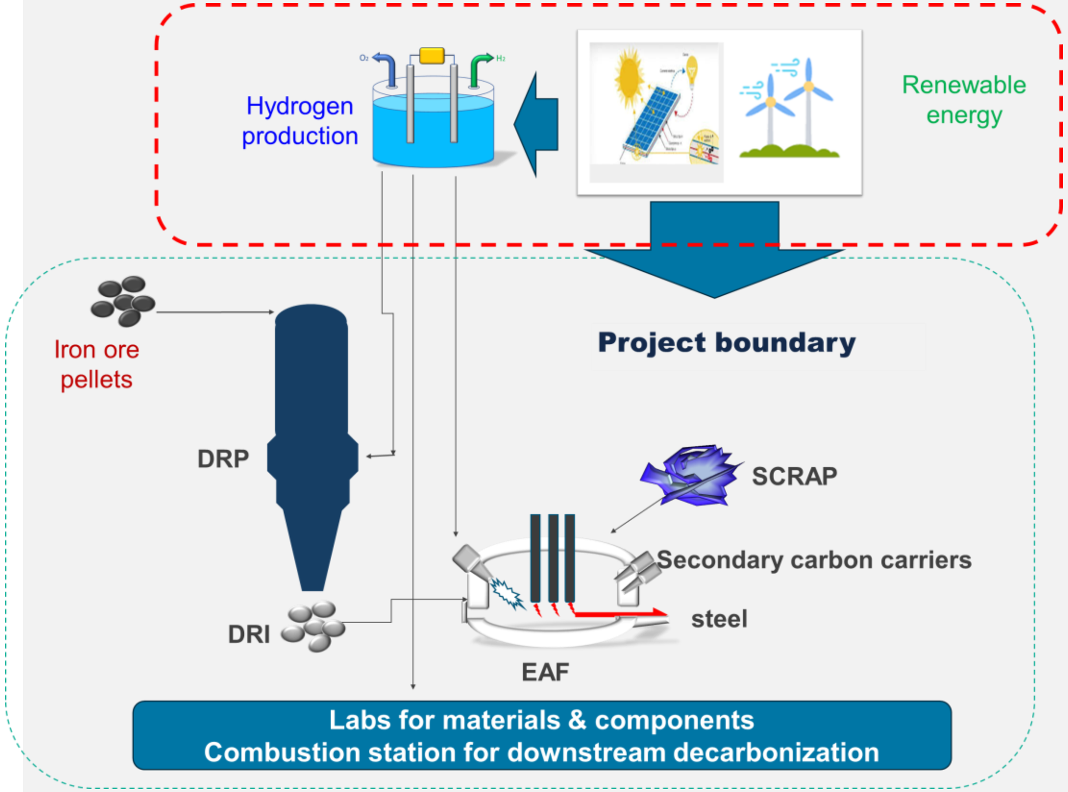
Qualification of materials and components under hydrogen containing atmospheres

Engineering services

Testing and integration of hydrogen production technologies

Integration of steel plant with Renewable energy production

Carbon Capture (CCS)



General conclusions

- The HYDRA project is aimed to support steel decarbonization with integrated approach linking pilot plants and labs

- The experimental facilities will be in operation in 2026

- Possibility to visit the facility during tests and to discuss results and performances

- Fully open to technical interactions with steelmakers and technology providers and to perfom tailored experimental campaign at European and International level

Thank you for your attention!

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RINA Consulting – Centro Sviluppo Materiali S.p.A.

ANNEX
Hydrogen production technologies

Steam methane reforming

SMR is the most common method for hydrogen production.

CH4 reacts with H2O under 3–25 bar pressure in the presence of a catalyst to produce H2, CO, and a relatively small amount of CO2. Steam reforming is endothermic.

In a second step CO and H2O are reacted using a catalyst to produce carbon dioxide and more hydrogen. In a final process step called "pressure-swing adsorption," carbon dioxide and other impurities are removed from the gas stream. Steam reforming can also be used to produce hydrogen from other fuels, such as ethanol, propane, or even gasoline.

Steam-methane reforming reaction

$$CH_4 + H_2O \text{ (+ heat)} \rightarrow CO + 3H_2$$

Water-gas shift reaction

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

Steam methane reforming

The typical steam methane reforming process has four main units: the desulfurizing unit, the reforming unit, the shift reactor, and the separation unit. The desulfurizing unit removes sulfur from the supplied natural gas, mainly to avoid the production of sulfur oxides, which are environmentally harmful, and which can contaminate the reformer catalysts, damaging the separation unit if a hydrogen Pd-alloy membrane is used.

SMR has emissions of CO2 of approximately 7 kg per kg of hydrogen produced.

Steam methane reforming

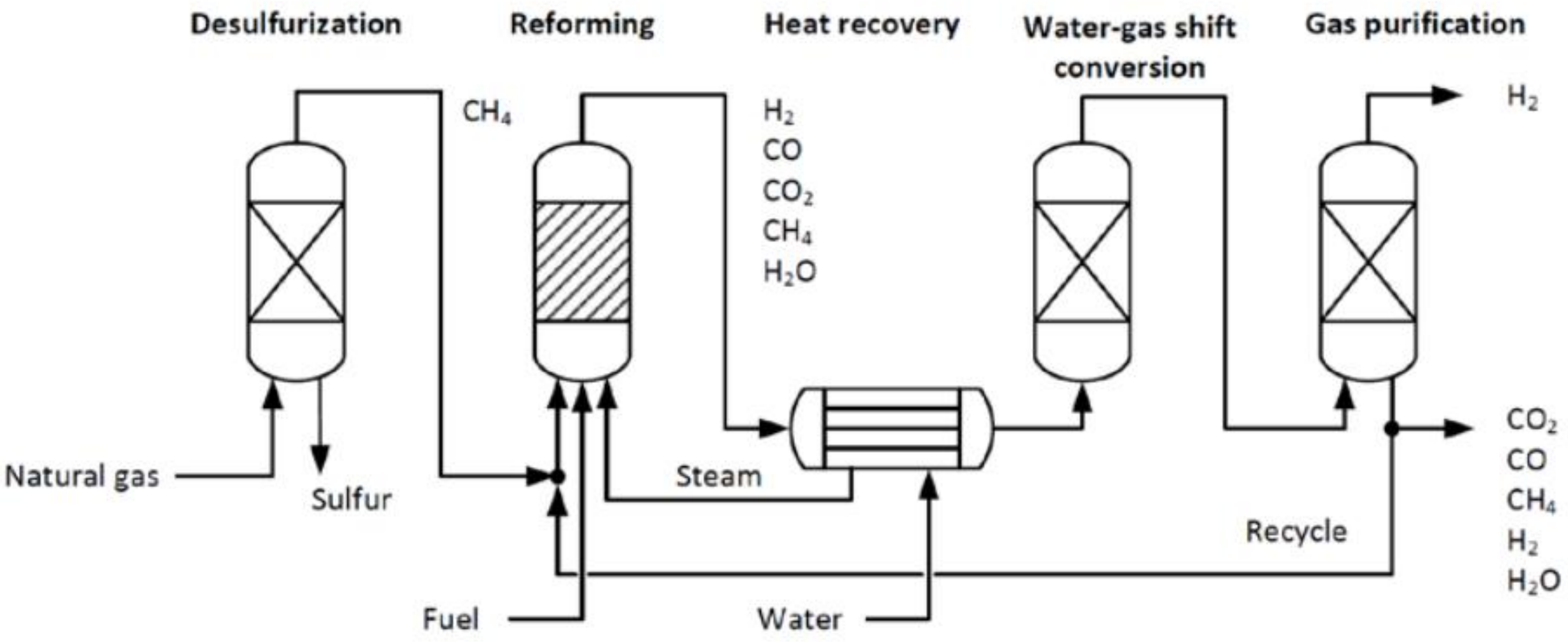


Figure 13: Hydrogen production using the steam reforming (SR) process with its process steps. (Díaz Pérez, 2013)

Díaz Pérez, N.F., 2013. Hydrogen separation from producer gas generated by biomass steam gasification (PhD thesis). TU Wien, Vienna

Methane partial oxidation

Methane and other hydrocarbons in natural gas react with a limited amount of oxygen (typically from air) that is not enough to completely oxidize the hydrocarbons to carbon dioxide and water. With less than the stoichiometric amount of oxygen available, the reaction products contain primarily hydrogen and carbon monoxide.

Partial oxidation is an exothermic process. The process is, typically, much faster than steam reforming and requires a smaller reactor vessel but produces less hydrogen per unit of the input fuel than is obtained by steam reforming of the same fuel.

Partial oxidation of methane reaction

$$CH_4 + \frac{1}{2}O_2 \rightarrow CO + 2H_2 \text{ (+ heat)}$$

Water-gas shift reaction

$$CO + H_2O \rightarrow CO_2 + H_2 \text{ (+ small amount of heat)}$$

Biomass gasification

Thermochemical routes, based on fossil fuels, are state of the art for industrial scale H2 production.
Renewable hydrogen via thermochemical methods can be achieved using biomass as the feedstock.

Hydrogen production from hydrocarbons such as fossil fuels and biomass involves conversion technologies such as reforming, gasification, and pyrolysis.

Biomass gasification

Simplified example reaction

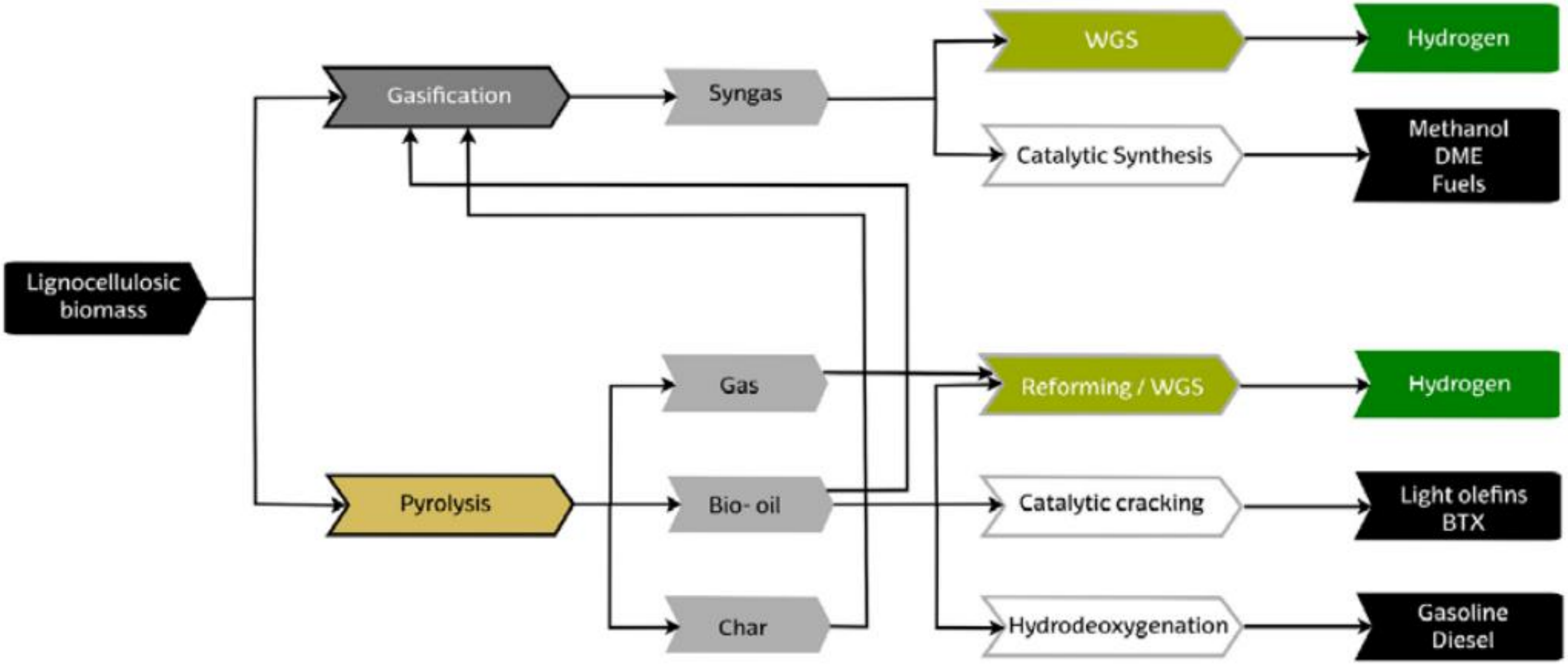
$C_6H_{12}O_6 + O_2 + H_2O \rightarrow CO + CO_2 + H_2$ + other species

The above reaction uses glucose as a surrogate for cellulose. Actual biomass has highly variable composition and complexity with cellulose as one major component.

Water-gas shift reaction

$CO + H_2O \rightarrow CO_2 + H_2$ (+ small amount of heat)

Biomass gasification



Biomass gasification

Biomass gasification is a mature technology pathway that uses a controlled process involving heat, steam, and oxygen to convert biomass to hydrogen and other products, without combustion.

Net carbon emissions of this method can be low, especially if coupled with carbon capture, utilization, and storage in the long term.

Gasification is a process that converts organic or fossil-based carbonaceous materials at high temperatures (>700°C), without combustion, with a controlled amount of oxygen and/or steam into carbon monoxide, hydrogen, and carbon dioxide. The carbon monoxide then reacts with water to form carbon dioxide and more hydrogen via a water-gas shift reaction. Adsorbers or special membranes can separate the hydrogen from this gas stream.

Methane pyrolysis

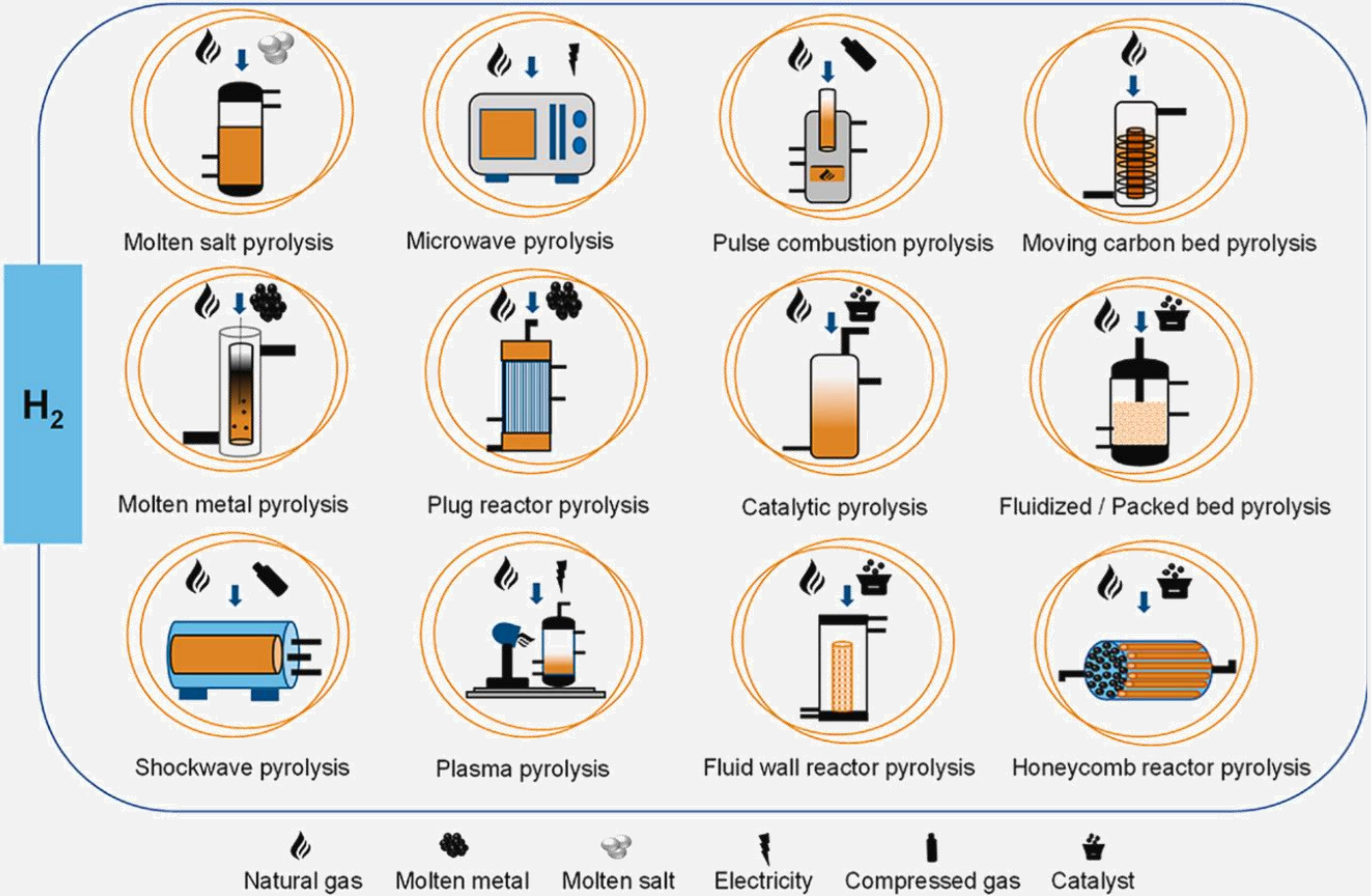
Methane pyrolysis is a technology that can produce low-cost, low-emission hydrogen. In the absence of oxygen, this process can use endothermic reactions that split C–H bonds to produce gaseous hydrogen and solid carbon.

Thermodynamically, methane pyrolysis **produces a lower amount of GHG emissions compared to steam methane reforming (SMR)and it requires high temperatures (800–1600 °C) or catalyst to overcome activation energy barriers.**

The technology is currently available at relatively low TRL and several configurations of reactors are under investigation (see next slide).

$$CH_4 \rightarrow C\,(s) + 2H_2$$

Methane pyrolysis



Methane pyrolysis

Similar to methane, natural gas can be pyrolyzed to generate hydrogen and solid carbon. Natural gas residues can affect the efficiency and purity levels of pyrolytic hydrogen production. For example, impurities in natural gas can form intermediate species and increase the energy required for cleaning hydrogen.

Solid carbon is the byproduct of the methane pyrolysis reaction is easy to store and use in other applications, e.g., tire and rubber manufacturing. The main issues to be solved related to solid C produced are:

1) The amount, 3 kg of C are formed per each kg of H2 produced
2) C is formed as fine powder, difficult to be handled
3) C may be polluted by catalyst

Methane pyrolysis

Methane pyrolysis not cause any CO_2 emissions.
Pyrolysis is considerably more efficient than other processes, with a specific energy demand of 37.8 kJ/mol H2 compared with 63.3 kJ/ mol H_2 for steam reforming or 285.9 kJ/ mol H_2 for hydrogen production by electrolysis

Hycamite (https://hycamite.com/) is constructing Europe's largest methane-splitting hydrogen plant in Finland. The next ones will be built in the USA.

Tulum Energy, a pioneering methane pyrolysis startup, has successfully closed a $27 million venture financing round. This significant investment, led by CDP Venture Capital (through its Green Transition Fund) and TDK Ventures and a global consortium of prominent investors (https://www.cdpventurecapital.it/en/news.page?contentId=COM50945).

Exxon is erecting a demo plant in USA (ready in 2029, 2000t/y and an industrial plant is under designing (expected in 2030, 50-100 kt/Y

Photocatalysis

Photocatalytic water splitting is a multistep process that is used to obtain hydrogen and oxygen by using irradiation with solar light as the only source of energy to initiate the reaction. The energy band gap of materials that serve as photocatalysts should be aligned with reduction and oxidation redox potentials. Overall, the water splitting is ascribed *via* the following steps:

- light with energy higher or equal to band gap should be used, as it leads to the appearance of electrons and holes in the conduction and valence bands of a photocatalyst, respectively
- the charge carriers move to the surface, where they initiate reactions with adsorbed water molecules. This reaction is described as the combination of two half-reactions associated with oxidation and reduction steps. They are called as **oxygen evolution reaction** (OER) and **hydrogen evolution reaction** (HER):

Oxidation half-reaction: $2H_2O+4h^+ \rightarrow O_2+4H^+$

Reduction half-reaction: $4e^-+4H^+ \rightarrow 2H_2$

Overall reaction: $\mathbf{2H_2O \rightarrow O_2+4H^+(aq)+4e^- \rightarrow 2H_{2(g)}+O_{2(g)}}$

Thank you for your attention!

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