Water Electrolysis

Technological aspects and use case of plants for hydrogen production

Pietro Fiorentini

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Pietro Fiorentini

Figures for the Group, constantly evolving

Pietro Fiorentini is now one of the largest industrial companies in the North East of Italy, with its main headquarters at **Arcugnano, near Vicenza.** The Group has more than thirty-five production sites and commercial offices both in Italy and abroad, employing around 2,800 people worldwide.

More than **2.800 collaborators** around the world

20 production facilities:

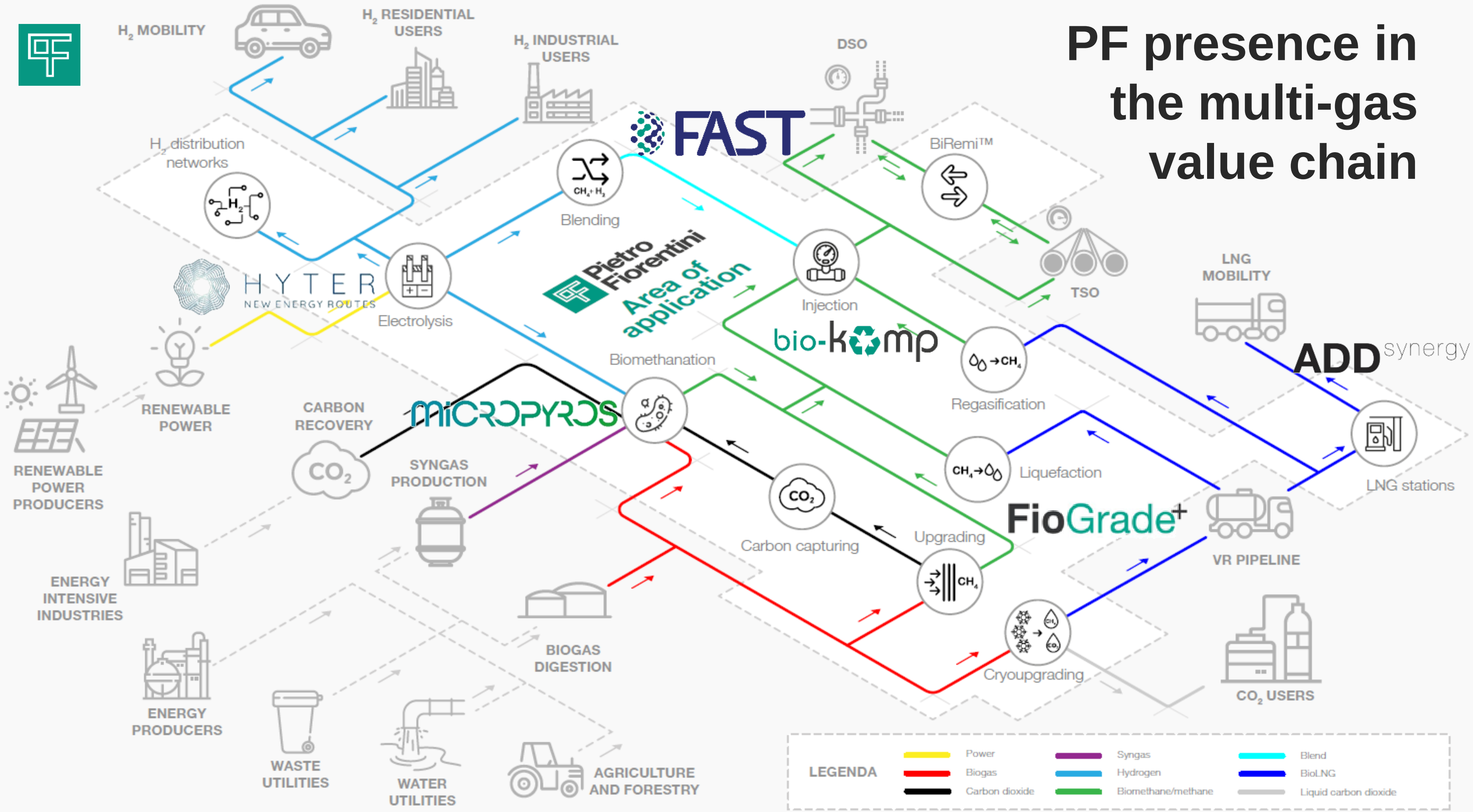
10 in Italy and **10** abroad

Offices in **Europe**, **America**, **Africa** and **Asia**

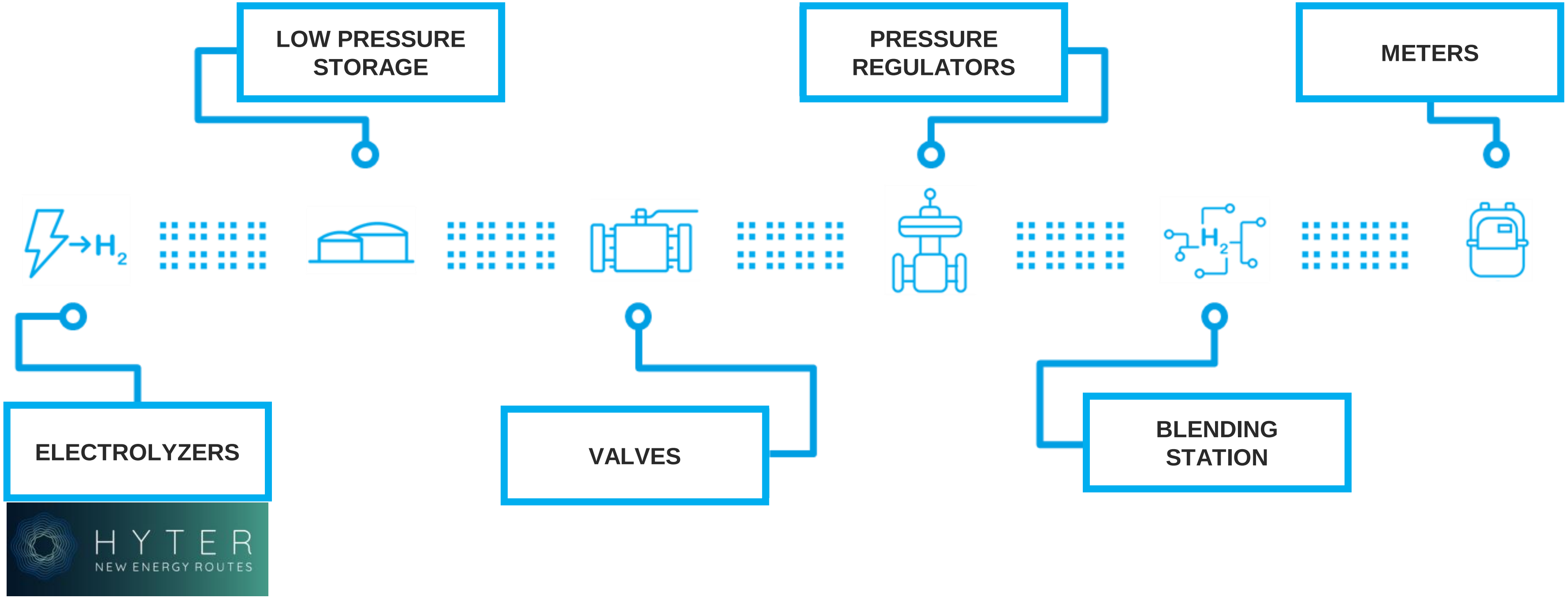
Group turnover **≈ 550 € mln**

Services **to over 100** countries

PF presence in the multi-gas value chain



Our current portfolio for the hydrogen value chain



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Why hydrogen?

Hydrogen properties

Property	Hydrogen	Natural Gas
Density (gas phase)	0.09 kg/m3 (@ 0°C, 1 bar)	0.72 kg/m3 (@ 0°C, 1 bar)
Density (liquid phase)	70.8 kg/m3 (@ -253°C, 1 bar)	489.9 kg/m3 (@ -180°C, 1 bar)
Boiling point	-253 °C (@1 bar)	-163 °C (@1 bar)
Heat of combustion	286 kJ/mole	890 kJ/mole
Higher Heating Value	12.7 MJ/Nm3	39.7 MJ/Nm3
Higher Heating Value	141.1 MJ/kg	55.5 MJ/kg

- Light
- High energy content per unit mass

- Low boiling point
- Low energy content per unit volume
- Molecule not available in natural reservoir

Hydrogen rainbow

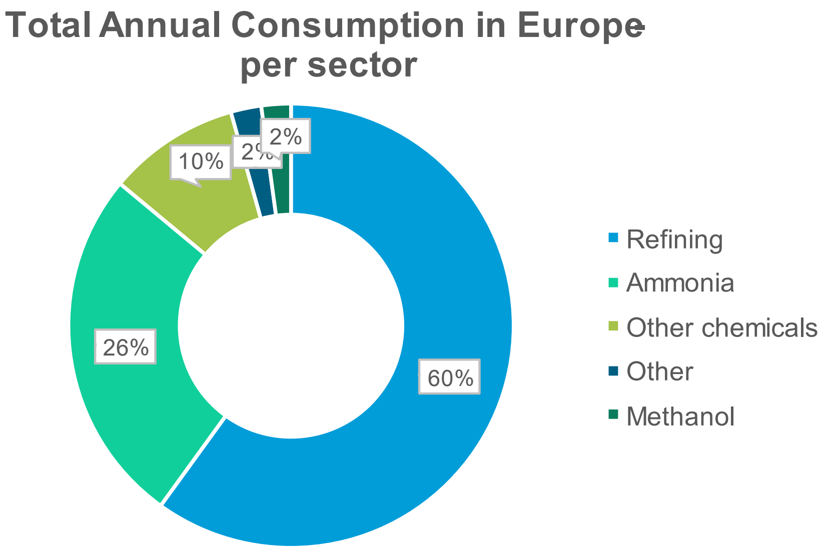
- Hydrogen colour classification based on feedstock and conversion process

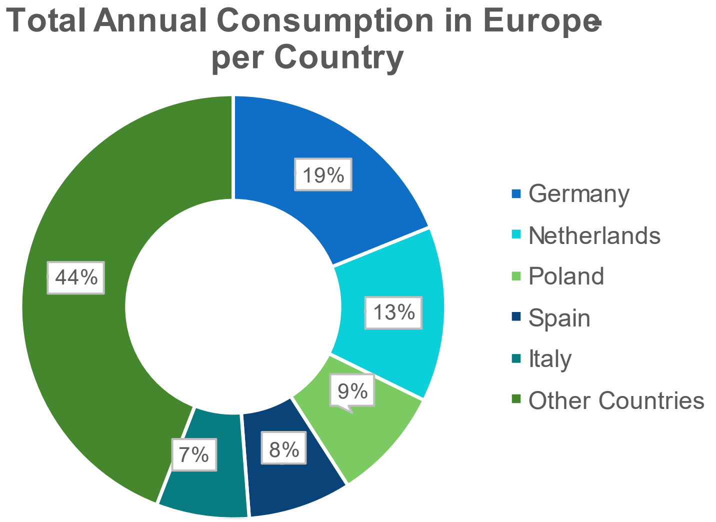
	BLACK/ BROWN hydrogen	GREY hydrogen	BLUE hydrogen	TURQUOISE hydrogen	YELLOW hydrogen	PURPLE hydrogen	GREEN hydrogen
Feedstock	Coal	Fossil fuels	Fossil fuels	Natural gas	Water	Water	Water
Conversion process	Gasification	Steam (methane) reforming	Steam (methane) reforming coupled with CCUS	Pyrolysis	Electrolysis (using solar power)	Electrolysis (using nuclear power)	Electrolysis (water splitting) using renewable electricity
Output	H_2 & CO_2	H_2 & CO_2	H_2, CO_2 (captured)	H_2 & C (solid)	H_2 & O_2	H_2 & O_2	H_2 & O_2
Market share	45%	45%	4%	<1%	2%	1%	2%
H2 cost	1.5 €/kg	3.3 €/kg	4.12 €/kg				6.7 €/kg

Skillen et al. (2022)

Hydrogen demand in Europe

- Overall hydrogen demand in Europe is 7.9 Mton/year (2024)

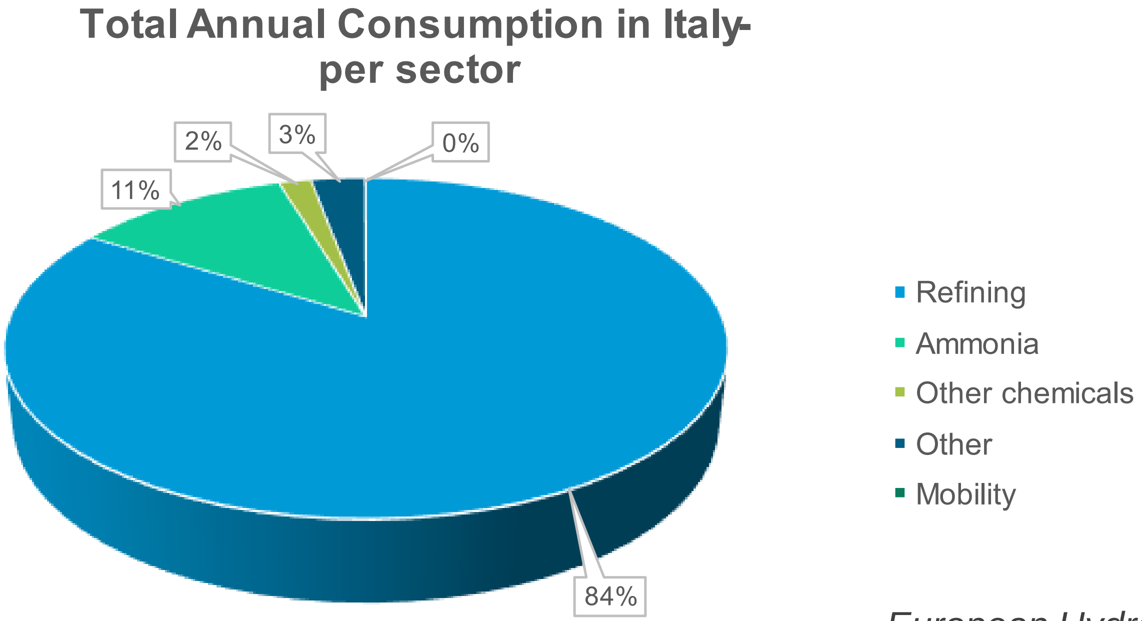




European Hydrogen Observatory

Hydrogen demand in Italy

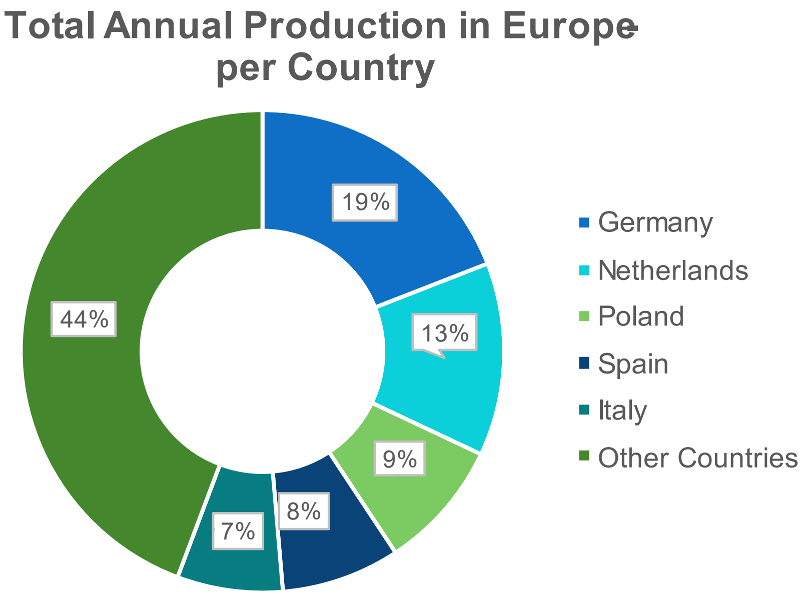
- Overall hydrogen demand in Italy is 0.55 Mton/year, 7% of total Europe (2024)

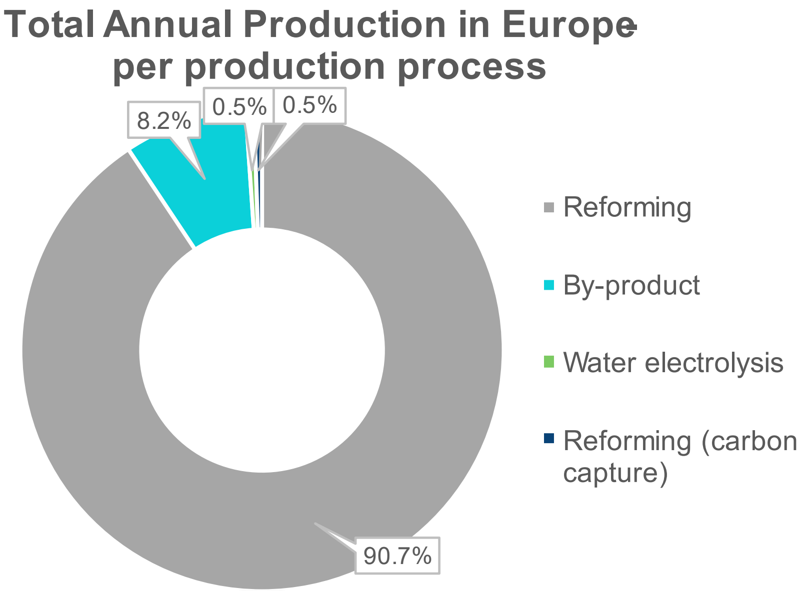


European Hydrogen Observatory

Hydrogen production in Europe

- Overall hydrogen production in Europe is 7.86 Mton/year (2024)

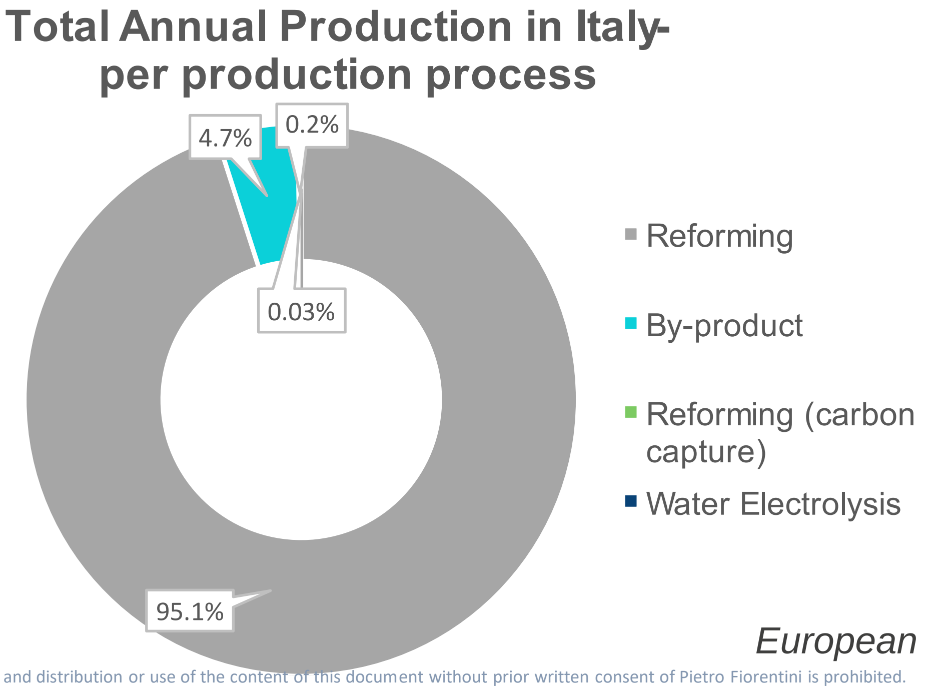




European Hydrogen Observatory

Hydrogen production in Italy

- Overall hydrogen production in Italy is 0.55 Mton/year (2024)



European Hydrogen Observatory

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Electrolysis

Hydrogen production by electrolysis

- Hydrogen can be produced by water electrolysis, i.e. splitting of the water molecule by an electrochemical process:

$$H_2O + energy \rightarrow \frac{1}{2} O_2 + H_2$$

ACIDIC ENVIRONMENT

Cathode (reduction): $2H^+(aq) + 2e^- \rightarrow H_2(g)$

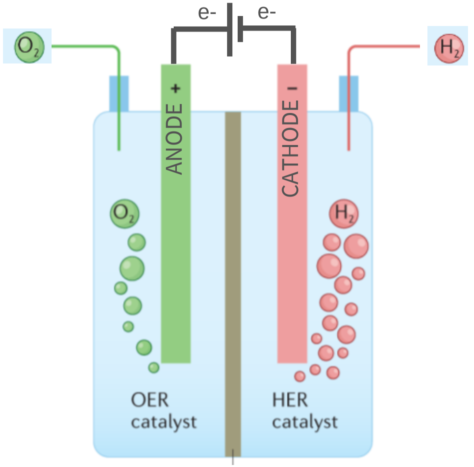
Anode (oxidation): $H_2O(l) \rightarrow 1/2\ O_2(g) + 2\ H^+(aq) + 2e^-$

BASIC ENVIRONMENT

Cathode (reduction): $2\ H_2O(l) + 2e^- \rightarrow H_2(g) + 2\ OH^-(aq)$

Anode (oxidation): $2\ OH^-(aq) \rightarrow 1/2\ O_2(g) + H_2O(l) + 2\ e^-$

- To produce 1 Nm3 of H2 (and 0.5 Nm3 of O2), 0.8 kg of water are consumed. The energy depends on the specific electrolysis technology.
- The minimum voltage to achieve the splitting of water molecule: 1.23 V
- The thermoneutral potential is at **1.48 V** (electrolyser neither releases heat to the environment nor absorbs heat from the environment).



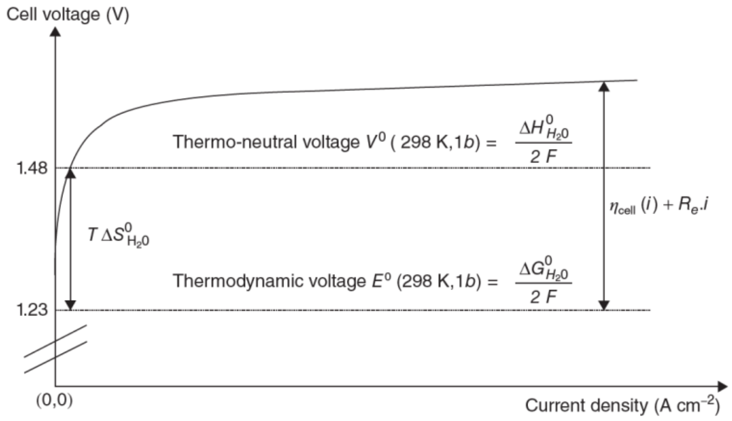
Hydrogen production by electrolysis

- The **electrolysis efficiency** is defined as the ratio between the ideal voltage and the real voltage:

$$\eta = \frac{V_{ideal}}{V_{real}}$$

- We could also consider the **specific consumption**, i.e. energy required to produce the unit of mass (or volume) of hydrogen:

$$Specific\ consumption = \frac{Energy\ consumed}{kg\ H2}$$



- The energy to produce hydrogen mostly depends on electrolyser efficiency, which is directly related to **cell voltage**: the closer it is to 1.48 V, the higher the electrolyser efficiency is.
- Cell voltage increases at high current density and at low temperature; hydrogen production is proportional to current

$$Q = \int_0^{\Delta t} I(t)dt$$

Technological solution for electrolysers

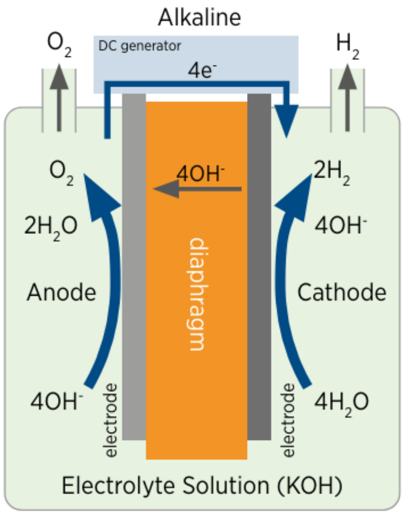
- Several electrolyser types are available; some of them are available on the market, others are at the research and development stage. Among low temperature application we find:

	Alcaline Electrolysers (AEL)	Proton Exchange Membrane Electrolysers (PEM)	Anion Exchange Membrane Electrolysers (AEM)
TRL	9	8-9	6-7
Spread	Large scale	Growing	Few applications

Alcaline Electrolysers (AEL)

- AEL is the **most mature technology** for hydrogen production; it has been already used in ammonia plants for usage at a constant load.

- Electrodes are immersed in an **alkaline solution** and separated by a **porous diaphragm**, which is permeable to OH-.
- The temperature of operation is low and it can work at Pmax=30 bar. It does not require noble metals.
- Electrolite is an aqueous solution of KOH 25-30%, which is recirculated on both sides of the electrolysers.
- It suffers from **safety issues when the electrical load is not constant**, and especially at low electrical load, because gases can diffuse inside the diaphragm (hydrogen crossover!)
- Electrode area is up to 3 m2.
- It has **low efficiency**.



Anode: $4OH^- \leftrightarrow 2H_2O+O_2+4e^-$

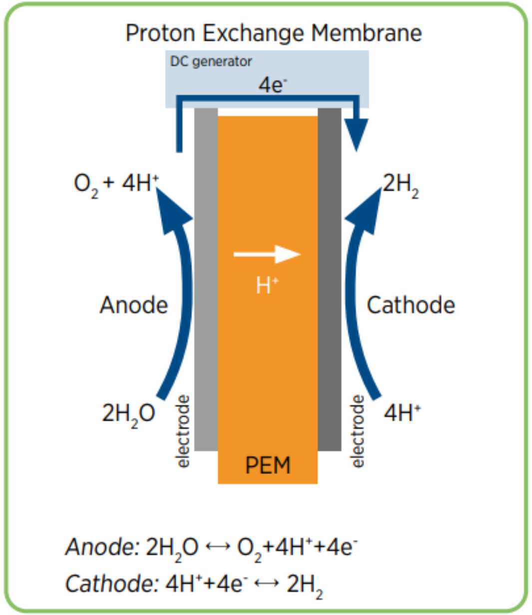
Cathode: $4H_2O+4e^- \leftrightarrow 2H_2+4OH^-$

IRENA, 2020

Proton Exchange Membrane El. (PEM)

- PEM technology is a **more recent technology** compared to AEL. PEM plants have slightly less power than AEL plants but the average plant size is increasing.

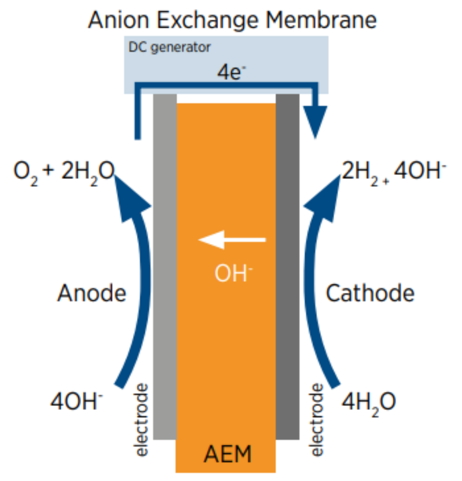
- The temperature of operation is low (70-80 °C) and they can work up to 30-40 bar. The water solution **is highly purified water** (impurities are catalyst poisons).
- Compared to AEL, they have higher efficiency and they are more compact; moreover, they have higher **operational flexibility** also with variable electrical load.
- They **require noble metals**: iridium and platinum.
- The electrodes are separated by a thin polimeric membrane, permeable to H+.
- Electrode area is up to 2000 cm2, current density up to 3 A/cm2.



IRENA, 2020

Anion Exchange Membrane El. (AEM)

- AEM technology is the **most recent technology** among low temperature electrolysers. There are still few producers worldwide.
- The temperature of operation is low (40-60 °C) and they can work up to 35 bar. The electrolyte solution is a **water solution with 5% KOH**.
- This technology merges the advantages of AEL (alkaline environment) and PEM (simplicity).
- They require only platinum at the cathode side.
- The electrodes are separated by a **thin polimeric membrane**, permeable to OH-.
- Electrode area is up to 200 cm2, current density up to 0.5 A/cm2.



Anode: $4OH^- \leftrightarrow 2H_2O + O_2 + 4e^-$

Cathode: $4H_2O + 4e^- \leftrightarrow 2H_2 + 4OH^-$

IRENA, 2020

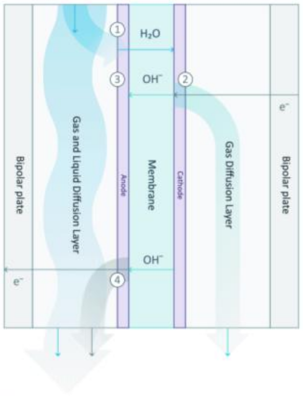
Electrolyser comparison: material and operative conditions

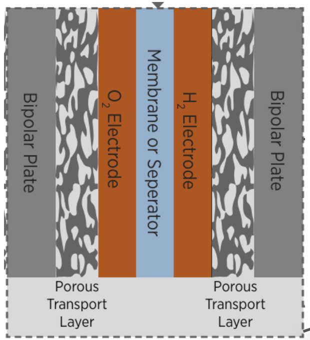
	AEL	PEM	AEM
Operating temperature	70-90 °C	70-80 °C	40-60 °C
Operating pressure	1-30 bar	< 40 bar	< 35 bar
Electrolyte	KOH 25-30%	-	KOH 5%
Water quality	Demineralized	Ultrapure	Demineralized
Separator	ZrO_2 (500 micron)	Proton exchange membrane (100 micron)	Anion exchange membrane (100 micron)
Electrode / catalyst (oxygen side)	Nickel coated perforated stainless steel	Iridium Oxide	High Surface Area Nickel or NiFeCo alloys
Electrode / catalyst (hydrogen side)	Nickel mesh	Platinum nanoparticles on carbon	Platinum nanoparticles on carbon

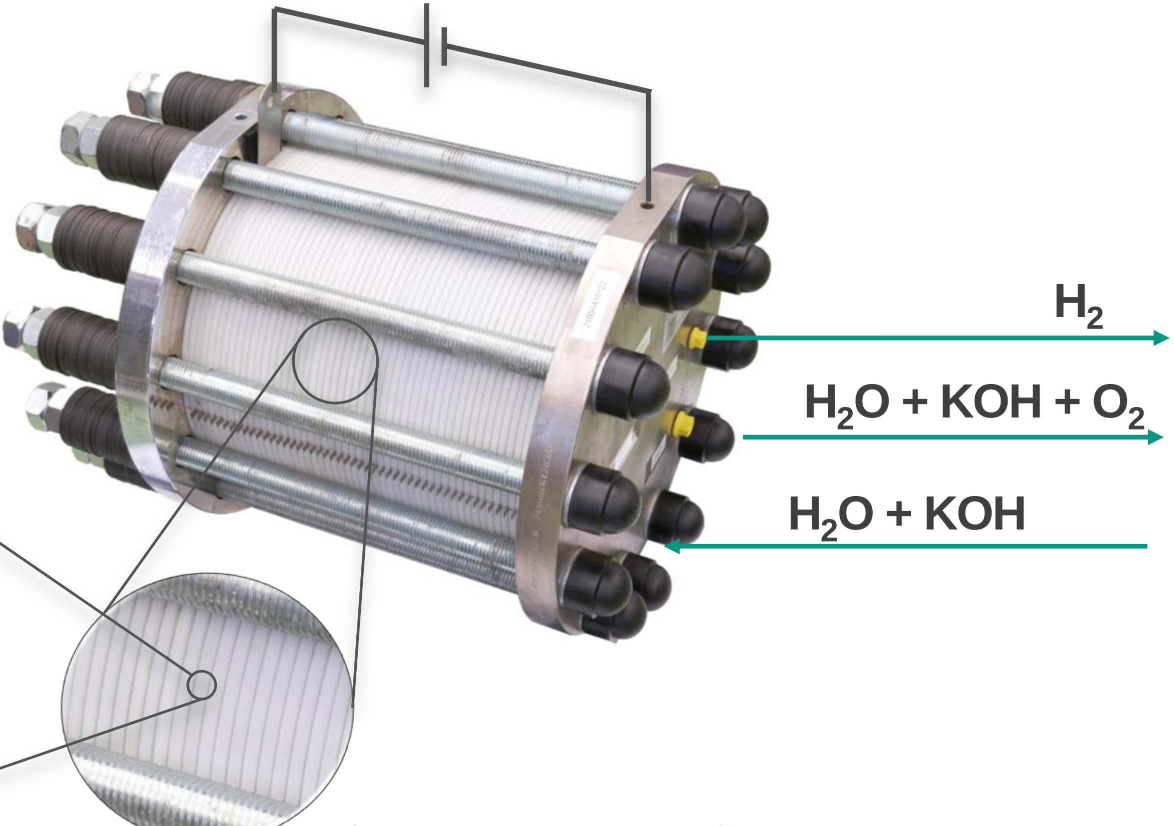
Electrolyser comparison: technology

	Alkaline	PEM	AEM
Efficiency	Up to 65-70%	Up to 70-75%	Up to 75-80%
Specific total consumption (kWh/kg)	53	51	51
Functioning range	20-100%	10-100%	10-100%
Current density (A/cm2)	0.2-0.4	2.5-3	0.6
CapEx	Very low	Very high	High
OpEx	Very high	High	Low
Gas purity (%vol)	99.5%	99.99%	99.99%
Stack lifetime (h)	60k-100k	20k-30k	20k
System response	Seconds	Milliseconds	Milliseconds

AEM Technology







Hyter solutions

	Rigel			Sirius	
STACK SIZE	10kW – 2Nm³/h			125kW – 25Nm³/h	
GENERATOR SIZE	M 10kW – 2Nm³/h […] 40kW – 8Nm³/h	L 50kW – 10Nm³/h 60kW – 12Nm³/h	V 80kW – 16Nm³/h […] 120kW – 24Nm³/h	V 250kW - 50Nm³/h 500kW – 100Nm³/h	Q 750kW - 150Nm³/h **1MW - 200Nm³/h**
DIMENSIONS	Tailor-Made		Standard 20' Container	Standard 20' Container	Standard 40' Container
	L: 3.071mm W: 1.265mm H: 2.521mm	L: 3.632mm W: 1.265mm H: 2.521mm	L: 6.060mm W: 2.440mm H: 2.521mm	L: 6.060mm W: 2.440mm H: 2.521mm	L: 12.200mm W: 2.440mm H: 2.521mm

Our solutions for hydrogen production

Hyter offers **a wide range of solutions for hydrogen production** with **AEMWE and PEM technologies**.

	AEMWE Rigel	AEMWE Sirius	PEM Solutions
STACK SIZE	10kW – 2Nm³/h	150kW – 33,8Nm³/h	1.250kW – 255Nm³/h
GENERATOR SIZE	2Nm³/h […] 24Nm³/h	33Nm³/h […] 200Nm³/h	200Nm³/h […] 2.000Nm³/h

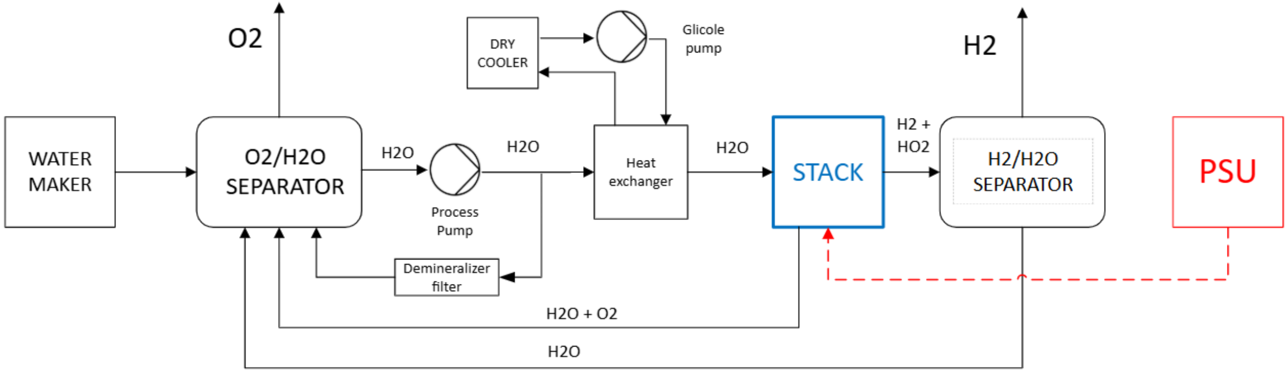
4

Balance of plant and consumptions

Balance of Plant - Functions

The Balance of Plant (BOP) provides core services for the electrolytic cell:

- Water for electrolysis
- Fluid management (H_2/O_2/H_2O separation and Water Maker)
- DC power, rectified from AC (PSU)
- Stack cooling (Dry cooler and Heat exchanger)



BOP – Operation Parameters (PEM)

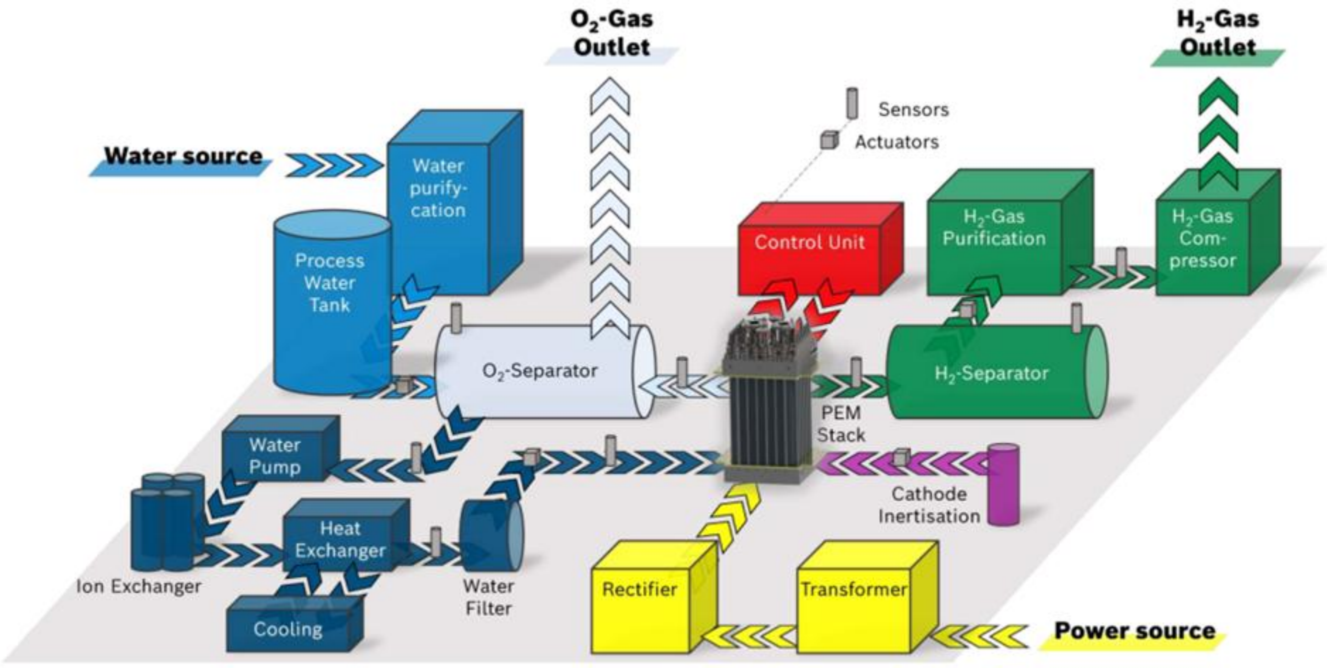
Anode Side

Parameter	Value
Operating temperature range	20 °C to 70 °C
Anode inlet water temperature	Min. 20 °C | max. 70 °C
Anode outlet water temperature	Min. 20 °C | max. 70 °C
Temperature difference outlet/inlet	ΔT_{anode} ± 5 °C
Max. temperature ramp rate	2 °C/min
Water flow	Min. 50 m^3/h | max. 104 m^3/h
Anode inlet water pressure	Min. 0 barg | max. 4.5 barg
Anode outlet water/O_2 pressure	Min. 0 barg | max. 4.5 barg
Max. pressure ramp rate	1 bar/s

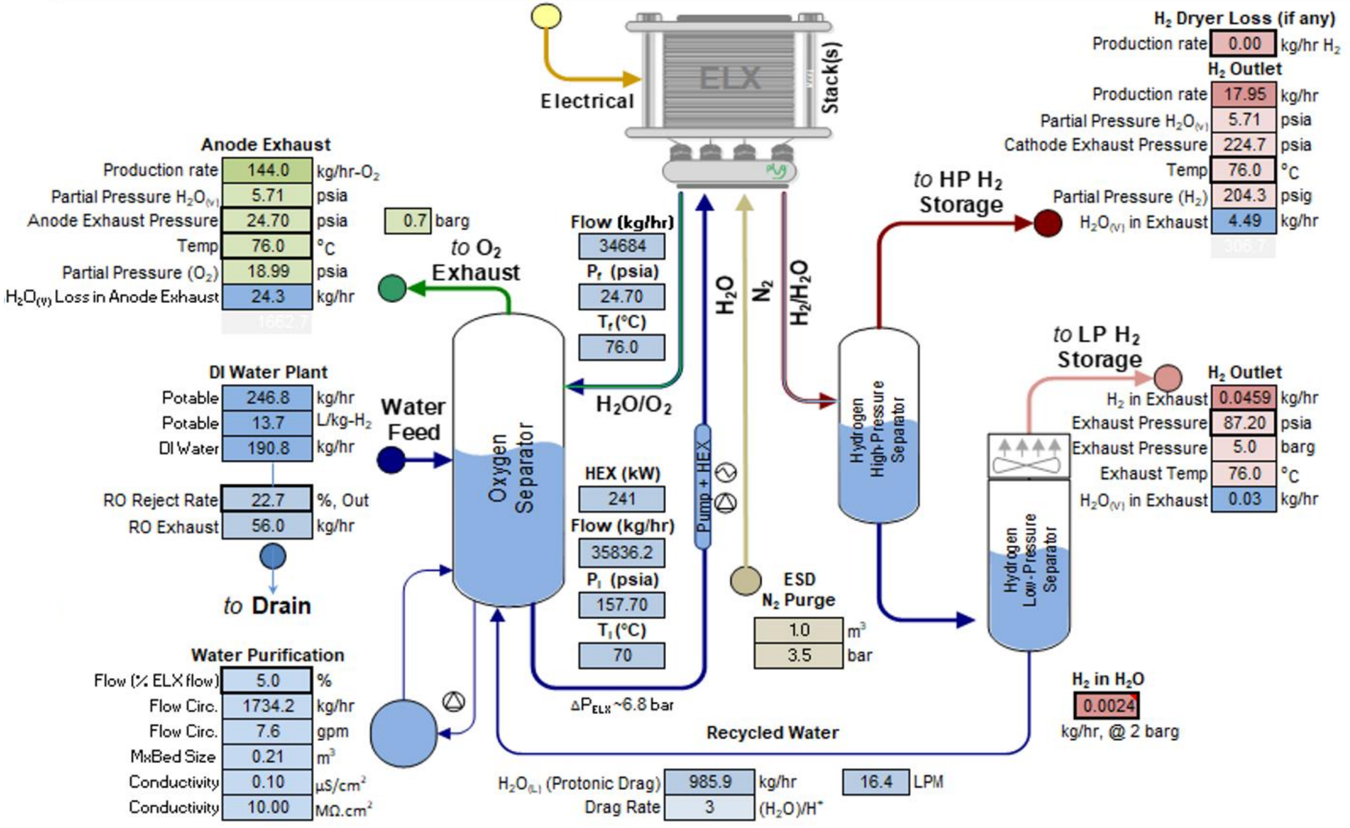
Cathode Side

Parameter	Value
Operating temperature range	20 °C to 70 °C
Cathode outlet hydrogen pressure	Min. 1 bar higher than anode inlet water pressure | max. 34 barg
Expected drag water flow	Max. 1.7 m^3/h
Purge pressure of water or gas	Max. 34 barg
Purge temperature water	$T_{water\ purge} = T_{anode\ inlet\ water\ temperature}$ ± 5 °C
Max. pressure ramp rate	1 bar/s

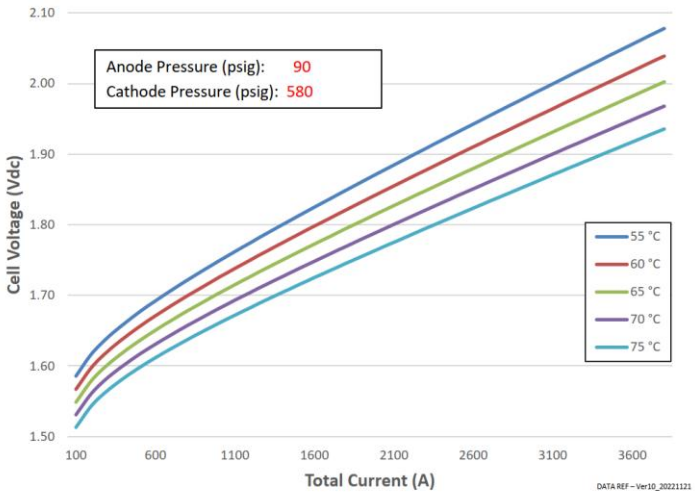
Balance of Plant – Main components

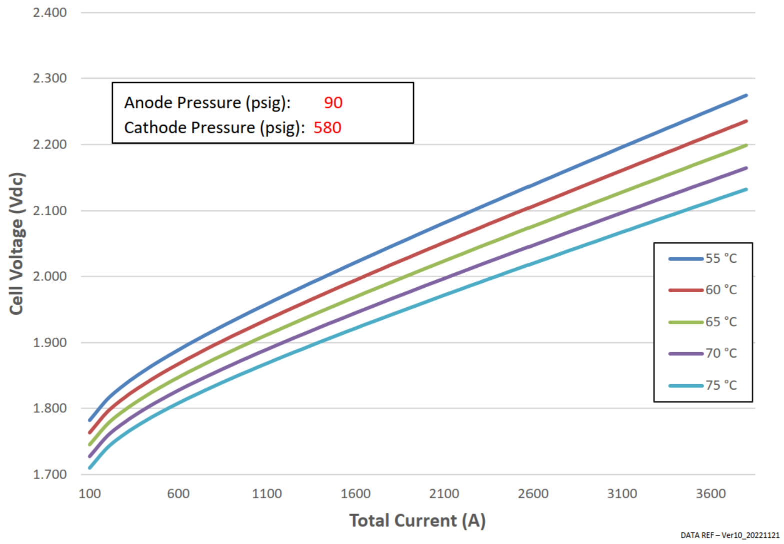


Balance of Plant – Process Flow Diagram



Stack performance – Polarization curve



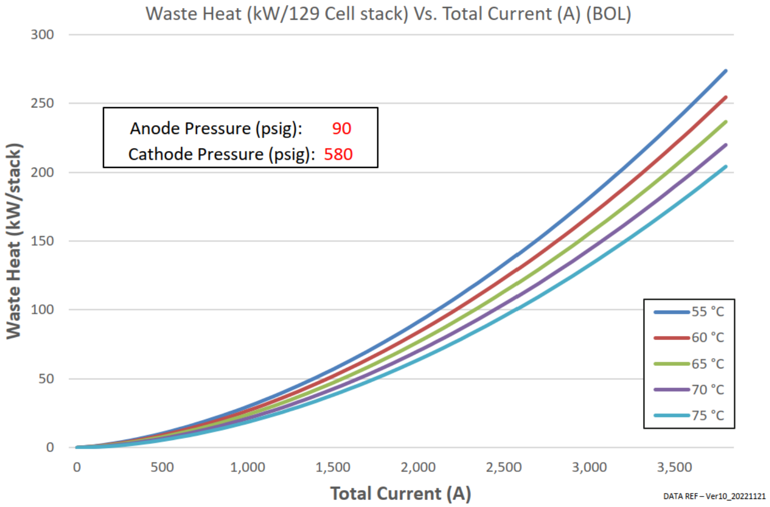


Stack performance – Waste Heat

@ 40 bar and 70°C;

$$V_n = 1.48 + \frac{8.314(343)}{2(96485)} \ln\left(\frac{(40)\sqrt{6.9}}{6.9}\right) = 1.48 + 0.04 = 1.52\ V$$

$$= \frac{\text{Ideal Stack Potential}}{\text{Actual Stack Potential}} = \frac{1.52}{1.788}(100) = 85\%$$



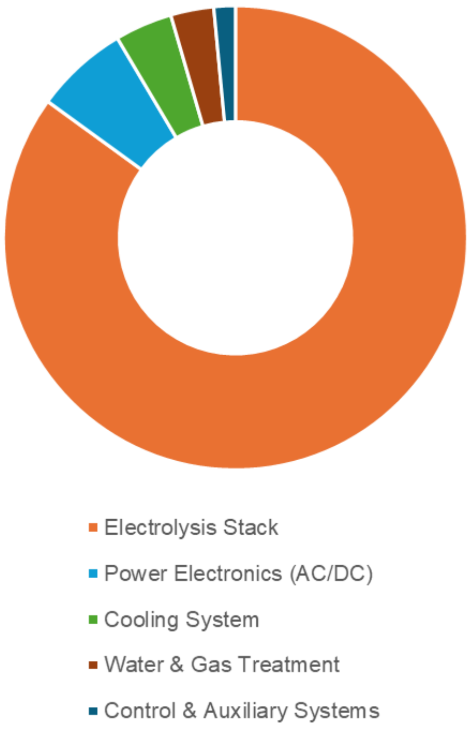
Stack performance – BOL vs EOL

	Power		BOL									
Set point	Current Density A/cm²	Current A	Voltage V	Cell Voltage U_cell V	Power DC_in kW	Thermal Losses kW	Water flowrate m3/h	H2 production Nm3/h	H2 production kg/h	Power Consumption kWh/Nm³_H2	Power Consumption kWh/kg	Voltage Efficiency %
25	0,6	810	265	1,656	215	23	50,0	52,3	4,7	4,10	45,7	89,4%
50	1,2	1620	275	1,719	446	62	50,0	104,6	9,4	4,26	47,4	86,1%
75	1,8	2430	285	1,781	693	117	50,0	156,9	14,1	4,41	49,1	83,1%
100	2,4	3240	295	1,844	956	189	50,0	209,2	18,8	4,57	50,8	80,3%

	Power		EOL									
Set point	Current Density A/cm²	Current A	Voltage V	Cell Voltage U_cell V	Power DC_in kW	Thermal Losses kW	Water flowrate m3/h	H2 production Nm3/h	H2 production kg/h	Power Consumption kWh/Nm³_H2	Power Consumption kWh/kg	Voltage Efficiency %
25	0,6	810	275	1,719	223	31	5,4	52,3	4,7	4,26	47,4	86,1%
50	1,2	1620	299	1,867	484	100	17,6	104,6	9,4	4,63	51,5	79,3%
75	1,8	2430	323	2,016	784	208	36,5	156,9	14,1	4,99	55,6	73,4%
100	2,4	3240	346	2,164	1122	355	62,2	209,2	18,8	5,36	59,7	68,4%

Consumption breakdown

Component	Description	Estimated (%)
Electrolysis Stack	Core electrochemical reaction	80–85
Power Electronics (AC/DC)	AC to DC conversion	5–7
Cooling System	Heat management	3–5
Water & Gas Treatment	Purification & deionization	2–4
Control & Auxiliary Systems	Monitoring & safety	1–2



5

Real field installations

Test bench

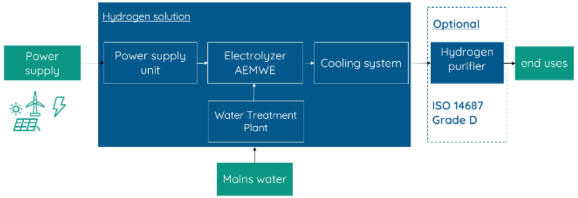
Sirius project (Bologna)

PROJECT GOAL

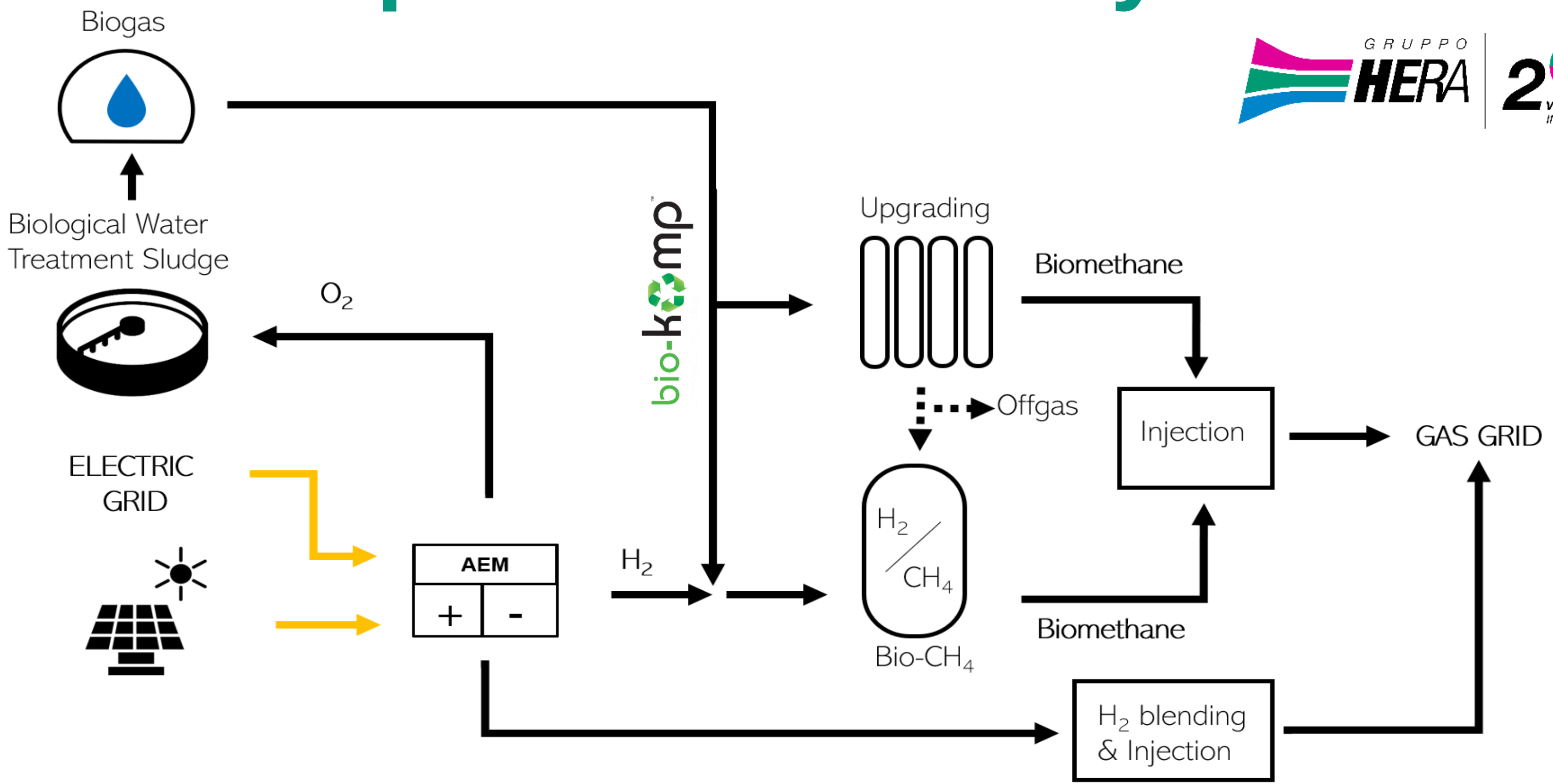
The project involves the installation at the FEA waste-to-energy plant located in Bologna of an electrolyser that uses the electricity coming from the waste-to-energy plant itself. The project belongs to the PNRR program.

DESCRIPTION

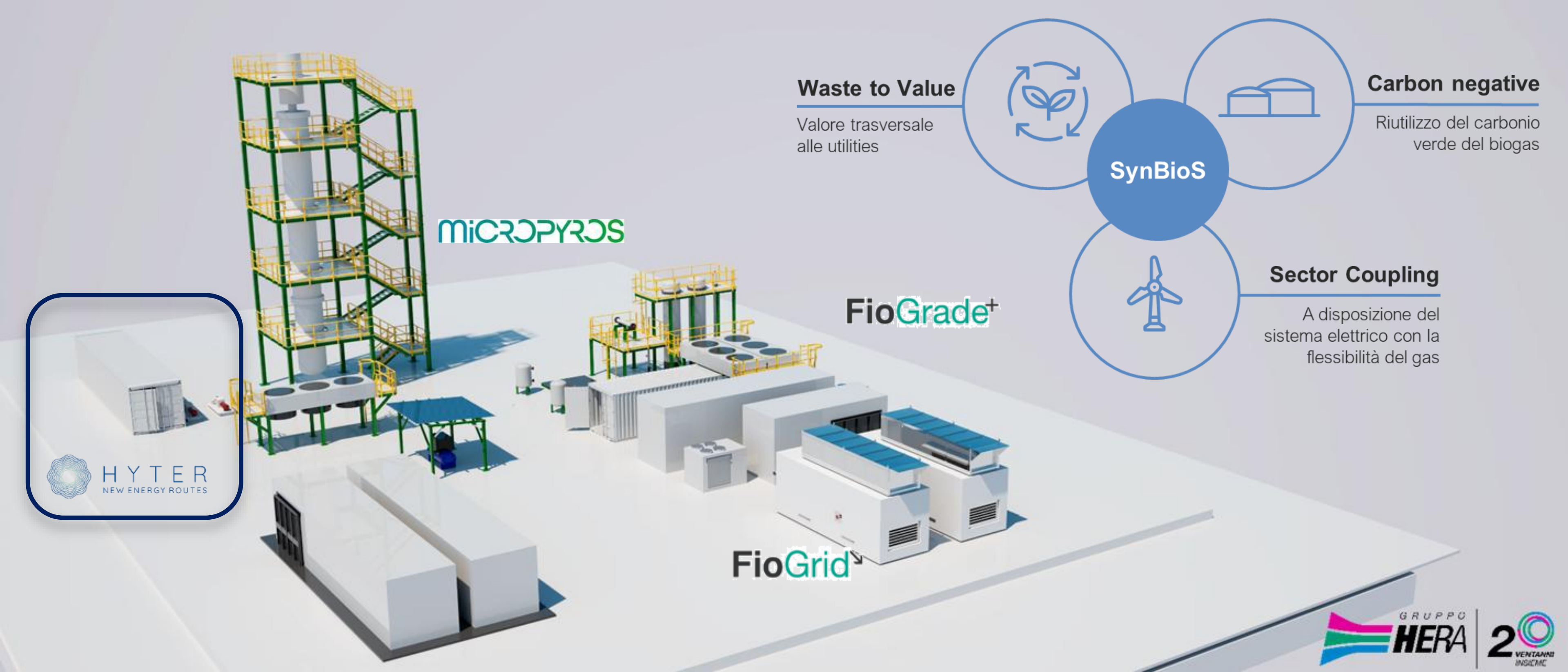
Installation of a **1 MW electrolyser** using innovative **AEMWE technology** with high potential for cost, scalability, and sustainability.



SynBioS: the first commercial plant for e-methane production in Italy



SynBioS: the first commercial plant for e-methane production in Italy



Electrolyser

Our role in the Italian Hydrogen Valley development

Dolomiti energia

PROJECT GOAL

Part of the “**PNRR M2C2-I3.1 ROVERETO**”. The aim of the Rovereto Hydrogen Valley is to produce hydrogen with our electrolyzer in order to use it in co-generation

DESCRIPTION

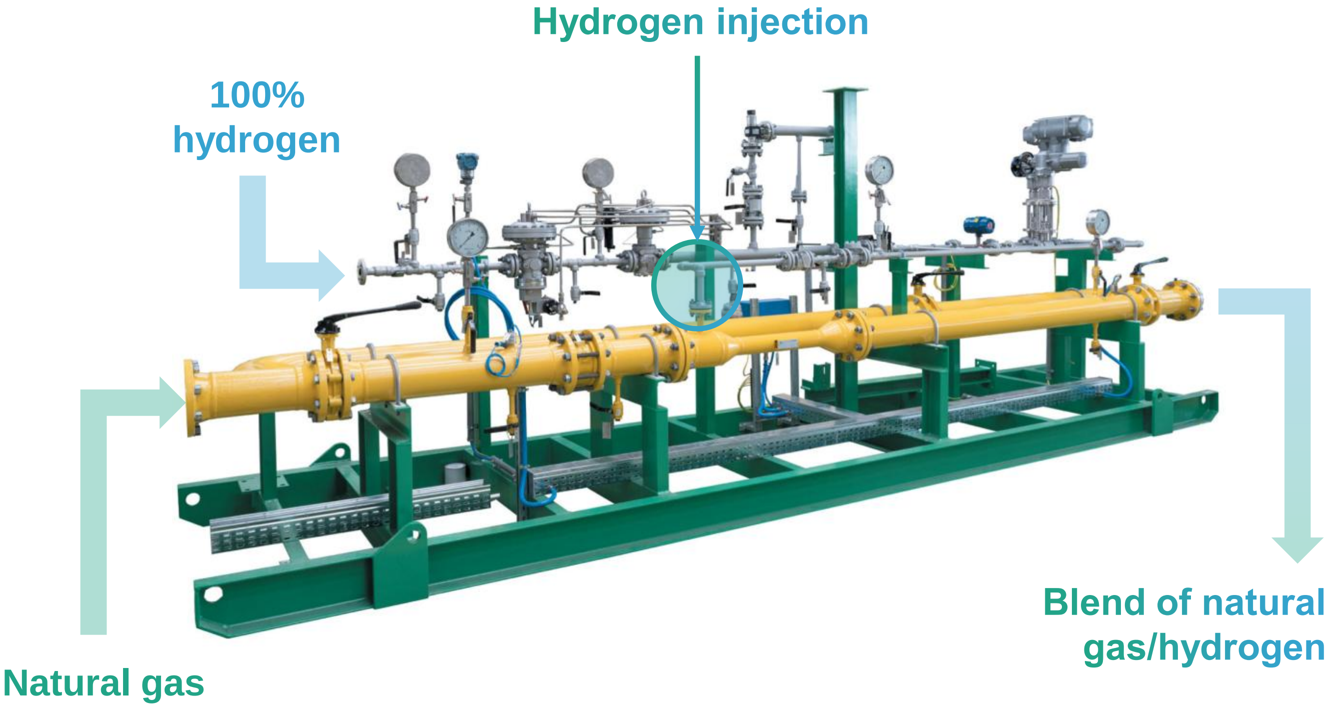
1 MW electrolyzer with PEM technology

Blending Station

Our solution: system to mix, control and analyze the flow of natural gas and hydrogen into the network

Operating conditions: systems capable of **mixing up to 100% H_2**

Potential applications: design easily adaptable to **low-pressure distribution** up to **high pressure transmission** networks and **industrial applications**



6

Market of Hydrogen

The European Hydrogen Market

Policies and incentives

- The European Union identifies renewable hydrogen as a strategic pillar for decarbonising hard-to-abate sectors.
- Countries with the most robust national support schemes: Germany, France, Netherlands, Portugal.
- EU funding concentration: ~50% of hydrogen-related funds allocated to four countries: Germany, Spain, Sweden, Netherlands.

European Funding and Directive

- IPCEI (Hy2Tech, Hy2Infra): electrolyser manufacturing, hydrogen infrastructure and storage.
- Directive RED III (UE 2023/2413): binding targets for RFNBOs, min 42% of H2 used in industry from renewable sources by 2030 → strong demand-side pull.

Global competition

China as the global industrial benchmark, as it is the world's largest producer and consumer of hydrogen and electrolysers:

- Electrolyser CAPEX: 500–550 €/kW vs 1500–2000 €/kW in EU/USA.
- Strategic control over critical raw materials (CRMs).

The Italian Hydrogen Market

Structural barriers

- **High electricity prices** → main driver of hydrogen **LCOH** in Italian business cases.
- Unsustainable production economics due to the lack of structural OPEX support, ineffective PNRR funding for hard-to-abate sectors (≈0% target achievement), and immature infrastructure with weak demand signals.

OPEX Decree update (February 2026)

- The OPEX (tariff) decree has completed EU pre-notification and is awaiting final EU approval, Court of Auditors clearance and GSE auctions, with incentive activation targeted for 2026 to bridge the cost gap between green hydrogen and fossil fuels.

Italy's roadmap to 2030

- Implementation of the **OPEX Decree** → production-side support.
- RED III transposition → **demand-side incentives** via decarbonisation contracts for hard-to-abate sectors.
- Definition of **acceleration areas** (dedicated areas with simplified authorization process)

Take home messages

Among low temperature electrolysers, Anion Exchange Membrane Water Electrolysis has advantages in terms of critical raw materials requirements and sustainability.

Anion Exchange Membrane technology still requires fundings for the development of the technology, especially for durability; large scale plants require more reliable technologies such as proton exchange membrane electrolysers.

To increase the number of projects to boost the use of hydrogen, fundings are required, as well as the development of renewable energy sources, which are intermittent. Projects are still linked to national and European fundings.

Thank you

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Pietro Fiorentini

4

Hydrogen purity

Purity of hydrogen

Standard ISO 14687

Table 1 — Hydrogen and hydrogen-based fuel classification by application

Type	Grade	Category	Applications	Clause
I Gas	A	—	Gaseous hydrogen; internal combustion engines for transportation; residential/commercial combustion appliances (e.g. boilers, cookers and similar applications)	7
	B	—	Gaseous hydrogen; industrial fuel for power generation and heat generation except PEM fuel cell applications	7
	C	—	Gaseous hydrogen; aircraft and space-vehicle ground support systems except PEM fuel cell applications	7
	D[a,b]	—	Gaseous hydrogen; PEM fuel cells for road vehicles	5
	E	PEM fuel cells for stationary appliances		6
		1	Hydrogen-based fuel; high efficiency/low power applications	
		2	Hydrogen-based fuel; high power applications	
		3	Gaseous hydrogen; high power/high efficiency applications	

Purity of hydrogen

Standard ISO 14687

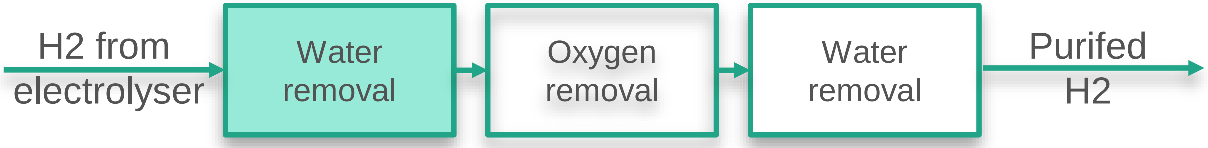
Table 2 — Fuel quality specification for PEM fuel cell road vehicle application

Constituents[a] (assay)	Type I, Type II grade D
Hydrogen fuel index (minimum mole fraction)[b]	99,97 %
Total non-hydrogen gases (maximum)	300 µmol/mol
Maximum concentration of individual contaminants	
Water (H_2O)	5 µmol/mol
Total hydrocarbons except methane[c] (C1 equivalent)	2 µmol/mol
Methane (CH_4)	100 µmol/mol
Oxygen (O_2)	5 µmol/mol
Helium (He)	300 µmol/mol
Nitrogen (N_2)	300 µmol/mol
Argon (Ar)	300 µmol/mol
Carbon dioxide (CO_2)	2 µmol/mol
Carbon monoxide (CO)[d]	0,2 µmol/mol
Total sulphur compounds[e] (S1 equivalent)	0,004 µmol/mol
Formaldehyde (HCHO)[d]	0,2 µmol/mol
Formic acid (HCOOH)[d]	0,2 µmol/mol
Ammonia (NH_3)	0,1 µmol/mol
Halogenated compounds[f] (Halogen ion equivalent)	0,05 µmol/mol
Maximum particulate concentration[g]	1 mg/kg

Table 4 — Fuel quality specification for applications other than PEM fuel cell road vehicle and stationary applications

Constituents (assay)	Type I			Type II	Type III
	Grade A	Grade B	Grade C	Grade C	
Hydrogen fuel index[a] (minimum mole fraction, %)	98,0 %	99,90 %	99,995 %	99,995 %	99,995 %
Para-hydrogen (minimum mole fraction, %)	NS	NS	NS	95,0 %	95,0 %
Impurities (maximum content)					
Total gases	20 000 µmol/mol	1 000 µmol/mol	50 µmol/mol	50 µmol/mol	
Water (H_2O) (mole fraction, %)	Non-condensing at all ambient conditions[b]	Non-condensing at all ambient conditions	c	c	
Total hydrocarbon	100 µmol/mol	Non-condensing at all ambient conditions	c	c	
Oxygen (O_2)	b	100 µmol/mol	d	d	
Argon (Ar)	b		d	d	
Nitrogen (N_2),	b	400 µmol/mol	c	c	
Helium (He)			39 µmol/mol	39 µmol/mol	
Carbon dioxide (CO_2)			e	e	
Carbon monoxide (CO)	1 µmol/mol		e	e	
Mercury (Hg)		0,004 µmol/mol			

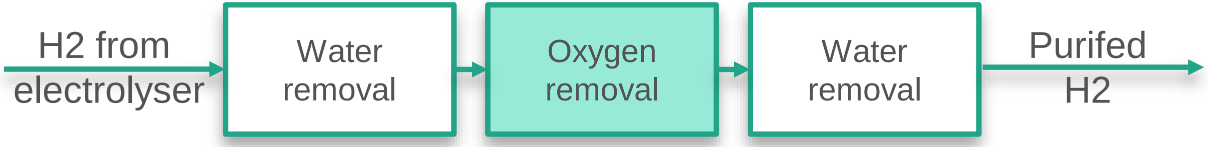
Purification technology: Water removal



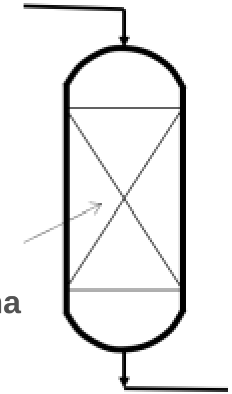
- Coalescence filters

- Heat exchangers

Purification technology: DeOxo



H2 stream with O2



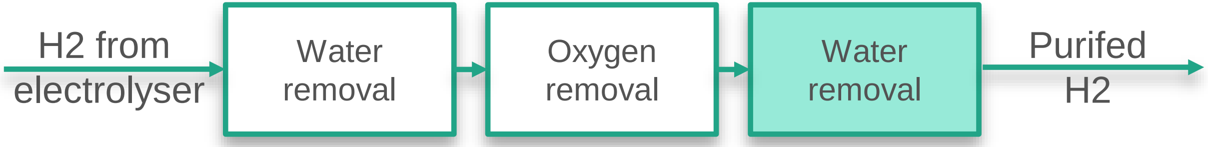
Catalyst:
Platinum or Palladium deposited on High Surface Area Allumina

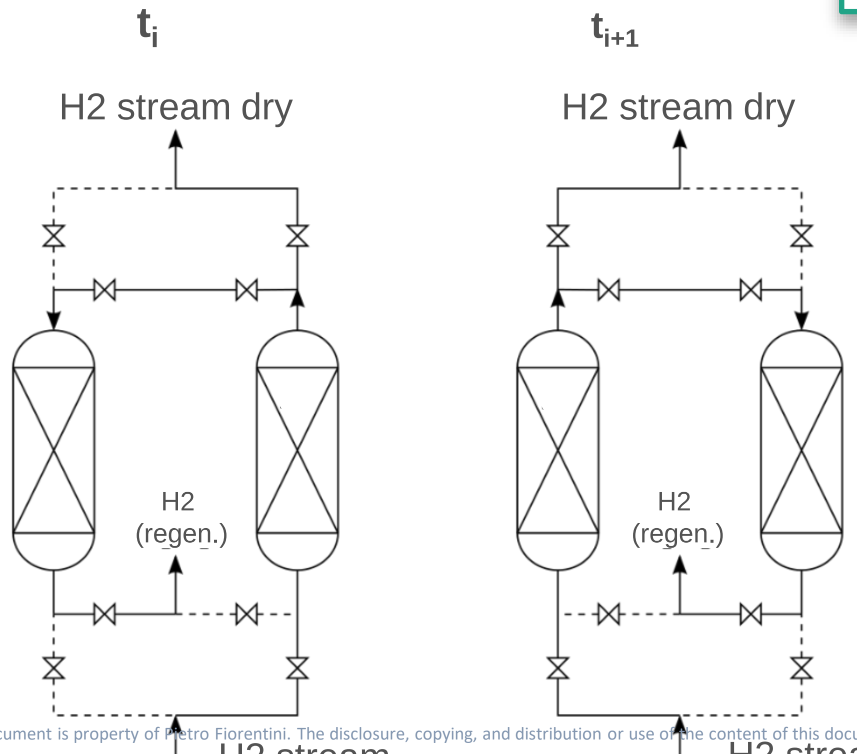
H2 stream with reduced O2 (less than 5 ppm)

Chemical Reaction:
$H_2 + \frac{1}{2} O_2 \rightarrow H_2O$

- **Reduce Hydrogen quantity**
- **Produce Water**

Purification technology: Purifier





- Reduce Hydrogen quantity (4-10%)

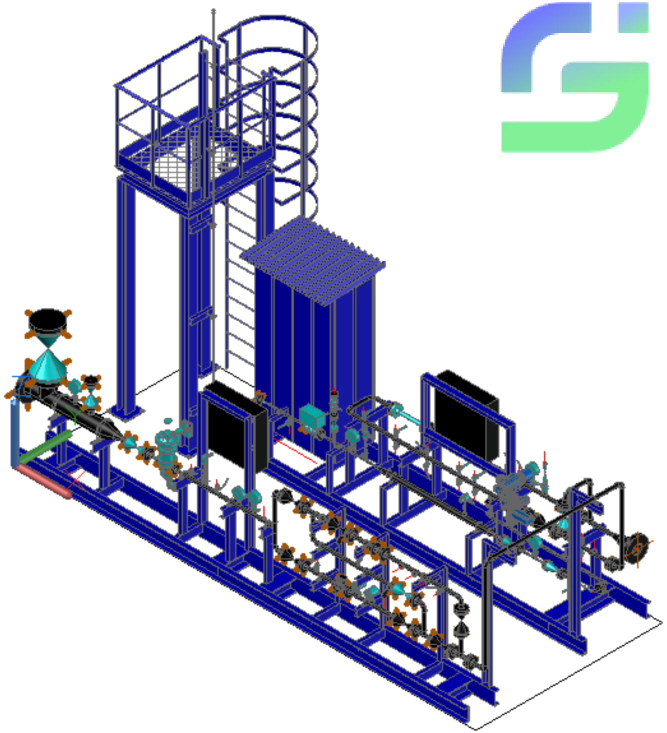
Blending Station

PROJECT GOAL

PNRR Hydrogen Valley/Delibera ARERA 404/22: decarbonisation project of the **industrial agglomeration of Frosinone** through the transition from methane to **methane/hydrogen blending**.

DESCRIPTION

Blending station to mix CH_4/H_2 up to 25% v/v with experimental plant for gas **stratification analysis**



Società Gasdotti Italia

Electrolyser Business Model

What are the cash flows of a hydrogen production plant?

Revenues

- Hydrogen as a product;

Peculiar Revenues

- Natural Gas saving reduced costs;
- Incentive;
- ETS saving;
- Oxygen as a by-product;

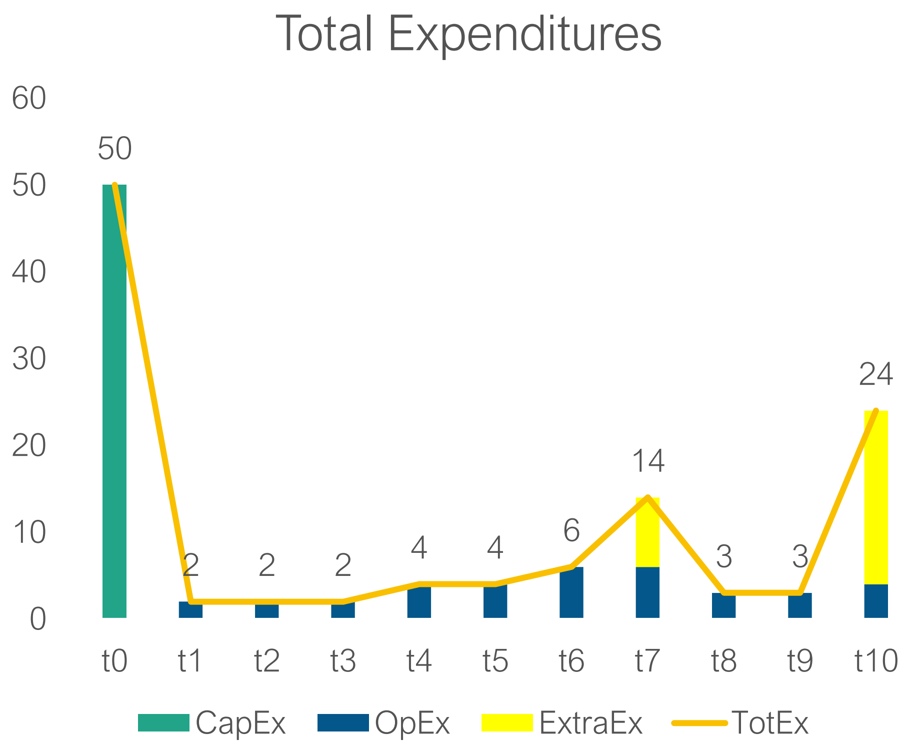
Costs

- Electricity;
- Stack revamping;
- Water;
- Nitrogen;
- Maintenance interventions;

Levelized Cost Of… Hydrogen

$$LCOH = \frac{\sum_{t_0}^{t_F} Costs_n\ [€]\ x\ k_n}{\sum_{t_0}^{t_F} Production_n\ [kg] x\ k_n}$$

- Investment costs (CapEx)
- Operation costs (OpEx)
- Extraordinary intervention costs (ExtraEx)
- Total costs (TotEx)
- Discount index (k_n)



Electrolyser structure

- Electrolysers are divided into two parts:

1) Electrolysis stack: where hydrogen is produced
2) Balance of Plant: equipment to run the electrolyser, i.e. pumps, power supply

Electrolyser Plant

Stack

Group of electrolytic cells, which are electrically in series; they produce hydrogen

Cell

Single electrolytic cell where electrolysis takes place

Balance of Plant

The system level includes equipment used to run the electrolyser:
- power supply
- water pump and water treatment
- cooling
- hydrogen purification, compression and treatment
- sensors and control system