Monitor Deloitte.

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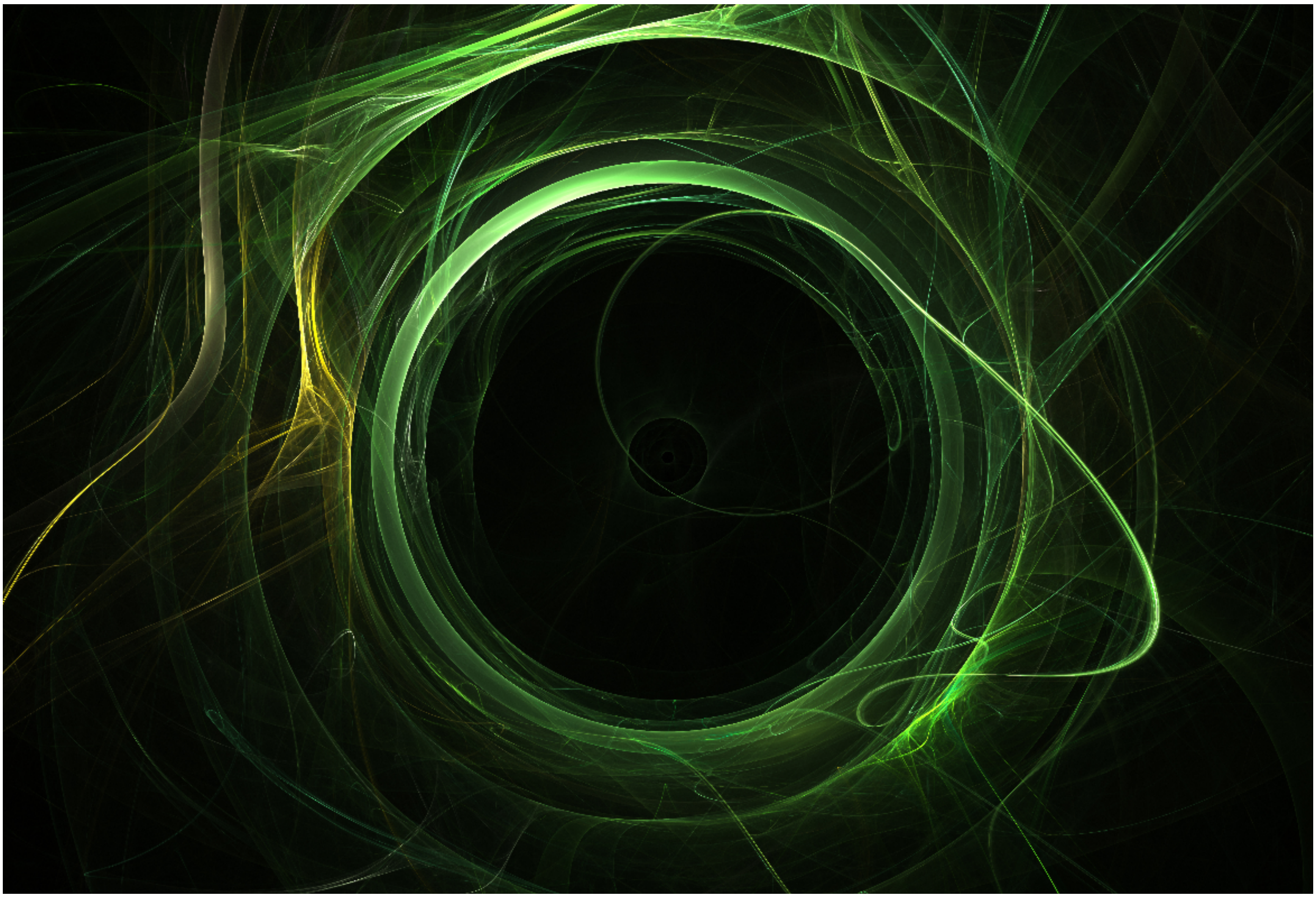


Fueling the future of mobility: hydrogen electrolyzers

Hydrogen Articles Collection

Under what conditions are electrolysis processes (AE, PEM, SOEC) likely to be both technically relevant and economically competitive against the SMR+CCS process by 2030?

Which renewable technology is the most suitable for electrolysis (PV, on-shore or off-shore wind)?

Which power supply mode (grid connection, access to renewables through various types of PPAs) should be favored to have the best operating point in terms of costs and GHG emissions?

Depending on the target hydrogen application, which operating model should be favored: a major hub with industrial-scale installations that benefit from economies of scale, or a distributed electrolysis model that is in proximity to consumption areas and that consequently does not require a distribution network?

Summary

Glossary

AE: Alkaline Electrolysis

CCS: Carbone Capture and Storage

CSP: Concentrated Solar Power

FCEV: Fuel Cell Electric Vehicle

GHG: Greenhouse Gas

O&M: Operations & Maintenance

PEM: Proton Electron Membrane

PPA: Power Purchase Agreement

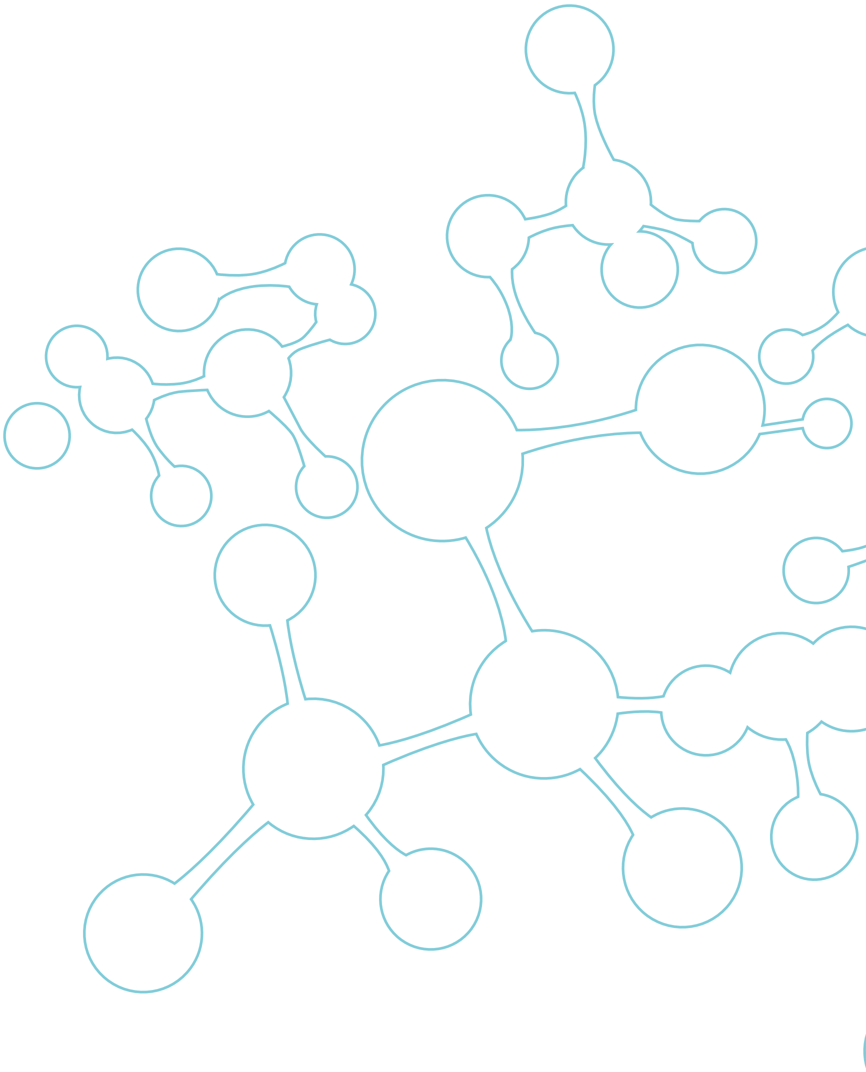
PSA: Pressure Swing Adsorption

PV: Photovoltaic

RES: Renewable energy sources

SOEC: Solid Oxide Electrolysis Cell

SMR: Steam Methane Reforming



Introduction

The EU has set ambitious Greenhouse Gas (GHG) emission reduction targets, aiming at carbon neutrality by 2050, with an ambitious milestone of -40% emissions by 2030. Hydrogen is a major pillar of this strategy, and its share in the European energy mix is expected to grow from less than 2% (including use as a feed stock) in 2018 to 13-14% in 2050.[46,49,50,51,52,53,54,67]

However, almost all hydrogen in EU-28 (94%) is produced from hydrocarbons, and therefore a strong source of GHG emissions. The addition of CO_2 capture (CCS) to conventional processes (e.g., SMR) will eventually reduce emissions by up to 90% ('blue' hydrogen) and will support the transition towards low-carbon hydrogen production. Thus, EU investments to support CCS retrofitting of existing plants is estimated to reach €11B. However, this pathway is essentially non-renewable, thus not a viable solution for the long term.[29,31,32,38,40,47,67]

Therefore, the key pillars of the 'green' hydrogen strategy will be the construction of 2 x 40 GW electrolyzer capacity by 2030 in the EU, and 40GW outside the EU in neighboring countries, with an additional 80 – 120GW capacity of Renewable Energy Sources (RES), split across the following 2 phases:[37,48]

- In the 1st phase, until 2024, 6 GW of electrolysers are expected to be installed, leading to the production of up to 1Mt of hydrogen, with target applications in chemical industry and heavy-duty transport.
- In the 2nd phase, until 2030, 40GW+ of electrolysers is expected to be deployed (incl. decentralized hubs), leading to the production of 10Mt of hydrogen that is intended for more sophisticated applications such as power generation and storage. In addition, a wider infrastructure of refueling station for mobility applications is also expected.

The GHG emissions level of electrolysis however is highly dependent on electricity supply, with the usage of only renewable ('green' hydrogen) or nuclear ('turquoise' hydrogen) energy for electrolysis being considered as decarbonated.

As of today, electrolysis processes are technologically advanced (TRL > 7 for AE and PEM), but not widely deployed at an industrial scale. Furthermore, their costs are prohibitive compared to traditional fossil fuel processes (x 2 to x4).

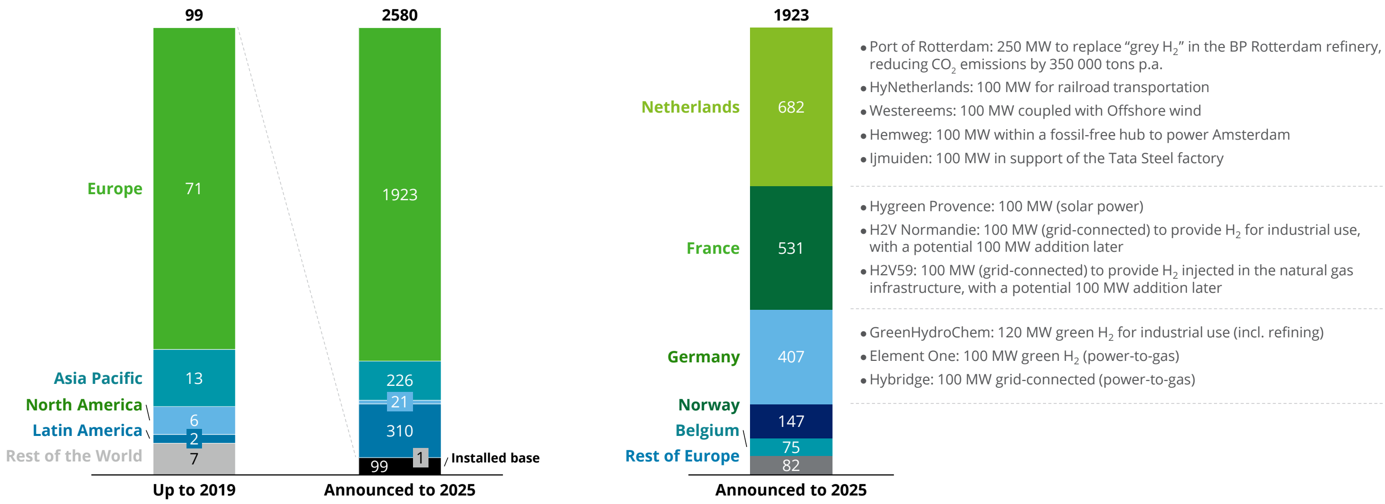
> Electrolysis mid-term adoption raises three major issues: economic competitiveness, power supply and suitability for eventual applications.

Figure 1.

A significant pipeline of new electrolysis projects is currently underway in Europe

Most of the electrolysis capacity currently installed and planned for installation is in Europe

Elecrtolyzer



Sources: IEA ; Monitor Deloitte Analysis

The deployment of electrolysis from a technical, economic and environmental point of view raises three major issues:

- Under what conditions are electrolysis processes (AE, PEM, SOEC) likely to be both technically relevant and economically competitive against SMR+CCS process by 2030?
- Which renewable technology is the most suitable for electrolysis (PV, on-shore or off-shore wind)? Which power supply (grid connection, access to renewables through various types of PPAs) should be favored to offer the best operating metrics in terms of costs and GHG emissions?
- Depending on the target hydrogen application, which operating model should be favored: a major hub with industrial-scale installations that benefit from economies of scale, or a distributed electrolysis model that is in proximity to consumption areas and that consequently does not require a distribution network?

The answer is complex and highly geographically dependent – depending on factors such as access to renewables, country grid parameters incl. availability of nuclear plants and renewables, proximity to consumption areas, types of target end-markets, etc.

NB: The role of nuclear generation in hydrogen production will be addressed in another article in this series.

Electrolysis 101: the basics of electrolysis competitiveness

In this paragraph, we will discuss the techno – economic aspects of electrolysis processes and provide guidelines on how they can be deployed in a competitive way by 2030, especially against the SMR+CCS pathway. [15,17,18,19]

As of today, the 3 major water electrolysis technologies are as follows:

- **AE (Alkaline Electrolysis)** is the oldest and most mature technology and has already been implemented in industrial scale projects (up to 150MW), especially in the chlorine industry (with brine water instead of fresh water). [21]
- **PEM (Proton Exchange Membrane)** is reaching maturity as it witnesses rapid development thanks to its above-par plant compactness and land footprint utilization. Furthermore, it presents favorable flexibility and H_2 purity parameters. [60]
- **SOEC (Solid Oxide Electrolysis Cell)** is a technology still at the demonstration stage but promising high energy efficiency potential as long as it is coupled with a fatal heat source (e.g., in theory a nuclear power plant or industrial heat) and a stable power supply. [22,60,62]

The choice of the best-suited electrolysis process should be done in relationship with both the preferred electricity source, and targeted H_2 utilization. In addition to maturity and current scale, major parameters for electrolysis processes are H_2 purity, process flexibility, and economics (power efficiency and OPEX / CAPEX levels):

- **Hydrogen purity[16]** determines the possible end-usage of an electrolyzer. While 99.95% purity is usually acceptable for general industrial applications (Quality Verification Level "B"), higher levels are necessary for advanced uses, such as specialty chemistry, propellants, or semiconductor applications (up to 99.999%, corresponding to "F", "L" or "A" Quality Verification Levels). The emergence of Fuel Cell Electric Vehicle (FCEV) led to the introduction of new purity norms to avoid catalyst poisoning that leads to performance degradation (especially for PEM fuel cells, as older technologies such as PAFC are less sensitive). Technical specifications included in the ISO 14687-2 standard set specific constraints especially for sulfur (4ppm) and carbon monoxide (200ppm), the sum of total impurities being less than 300ppm (i.e. H_2 purity of 99.97%).

The choice of an electrolysis process depends on the targeted H_2 utilization, and depends on technology maturity, scale, necessary H_2 purity, process flexibility and economics.

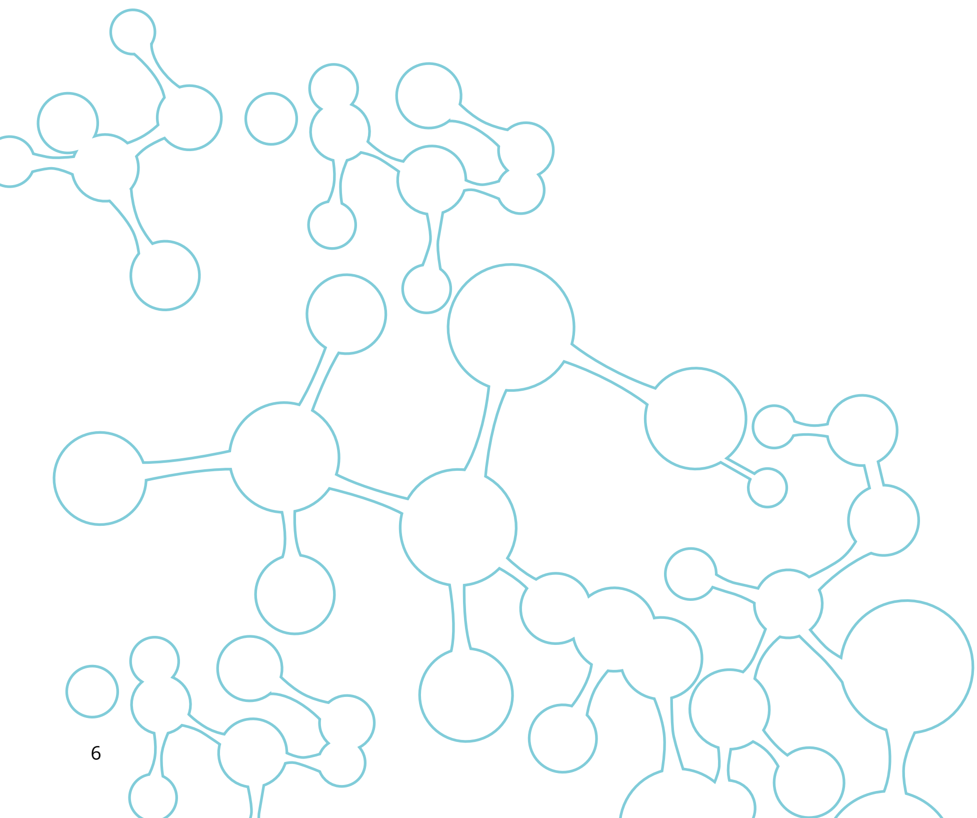


Figure 2.

Electrolysis processes vary across several key parameters
(Maturity, scale, purity, flexibility, power efficiency and CAPEX/OPEX)

Hydrogen electrolysis production processes properties (2020 – 2030)

			AE (Alkaline)		PEM (Proton Exchange Membrane)		SOEC (Solid Oxide Electrolysis Cell)	
			2020	2030	2020	2030	2020	2030
Overall	Technical Maturity	Maturity	Mature		Commercial		Demonstration	
	Typical Plant Scale	kg / day	Up to 70 000		Up to 50 000		Pilot Scale	
	Land footprint	m²/kWe	0.095		0.048		n.a.	
	Purity	%	99,7 – 99,9		99,9 – 99,9999		>99%	
Flexibility	Start Response	Minutes	Up to 10		5 seconds to 1 minute		High	
	Ramp-up / down	% / second	0,2 to 20		100		Slow	
	Shutdown Response	Minutes	Up to 10		Few seconds		High	
	Load Range	%	10 - 110		0 – 160		20 - 100	
	Operating Pressure	Bars	1 - 30		3 – 80		1	
	Operating Temperature	°C	60 - 80		50 – 80		650 - 1000	
	Reverse mode	Y/N	N		N		Possible	
Lifetime	Full System	Years	20		20		20	
	Stack	Hours	75 000	95 000	60 000	75 000	25 000	60 000
Power efficiency	Power consumption	kWh / kg H_2	48 - 53	47 - 51	56 – 60	49 - 53	40 – 45*	37 – 43*
	Degradation	% / 1000 h	0,1	0,1	0,2	0,1	1,9	0,5
CAPEX	Full System	€/kW	750 - 1400	400 - 900	800 – 1800	600 - 1400	800 - 2300	500 - 1400
	Stack	% of Full System	35	30	35	30	50	40
OPEX	Yearly % of Capex	%	2 to 4		2 to 4		5 to 7	

*If running with a source of fatal heat

Sources: IEA, IRENA, ICCT, Tampere University, DOE Hydrogen & Fuel Cell Program, Store & Go Program; Flex CHX Program, Offshore Wind Industry Council, FuelCell Energy, Imperial College of London, Hydrogen Council, NREL, Monitor Deloitte analysis

Different hydrogen production processes present uneven purity performance:

- **Recent SMR process designs**, coupled with PSA (Pressure Swing Adsorption) currently provide hydrogen at very high purity (as high as 99.999%), suitable for most applications.
- **Alkaline Electrolysis** provides purity in the 99.7 to 99.9% range, making additional purification process steps necessary (e.g., scrubbing, adsorption, permeation or cathodic cleaning) in FCEV or advanced applications.
- **PEM electrolysis** offers the highest purity levels, reaching up to 99.9999% levels, making it the most suitable for FCEV applications. [60]
- According to recent studies, H_2 output of **a SOEC installation** has a purity of 94%, which can be purified up to >99% if required (ECN 2018).

• **Flexibility** determines primarily the most suited electricity supply for an electrolyzer, thus its ability to be coupled with either grid or intermittent renewables (Solar PV, onshore or offshore wind): [61 68 69 71 72]

- **Alkaline Electrolysis** provides **average flexibility** performance, with response times for start-up or shutdown up to 10 minutes, ramp-up and ramp-down speeds in the range of 0.2 to 20% per second and a load range of 10 to 110% of nominal capacity. It is suited to be used primarily in an industrial environment because of the rather complex maintenance required, as the electrolyte (KOH) is corrosive as well as hard to recover and recycle.
- **PEM electrolysis is the most flexible process,** thus the most suited for a coupling with **proprietary renewable sources** as ramp-up and ramp-down sequences can be performed within seconds. Furthermore, it also has the capability to operate at 160% of its nominal power for a short period of time. Its limited land footprint of ~ 0.05m² / kWhe makes it more easily integrated in non-industrial environments, thus making it a preferable solution for distributed hydrogen production. [60]
- **SOEC electrolysis** operates at high temperature (up to 1000°C), and thus needs to be coupled with a large source of fatal heat - typically nuclear power plants or large industrials – and stable supply of power. Consequently, the use of SOEC will be limited to specific locations and end-uses. In some cases, SOEC can also be reversible, and operate as a fuel cell, thus being able to address a wider range of power generation applications.[22 60 62]

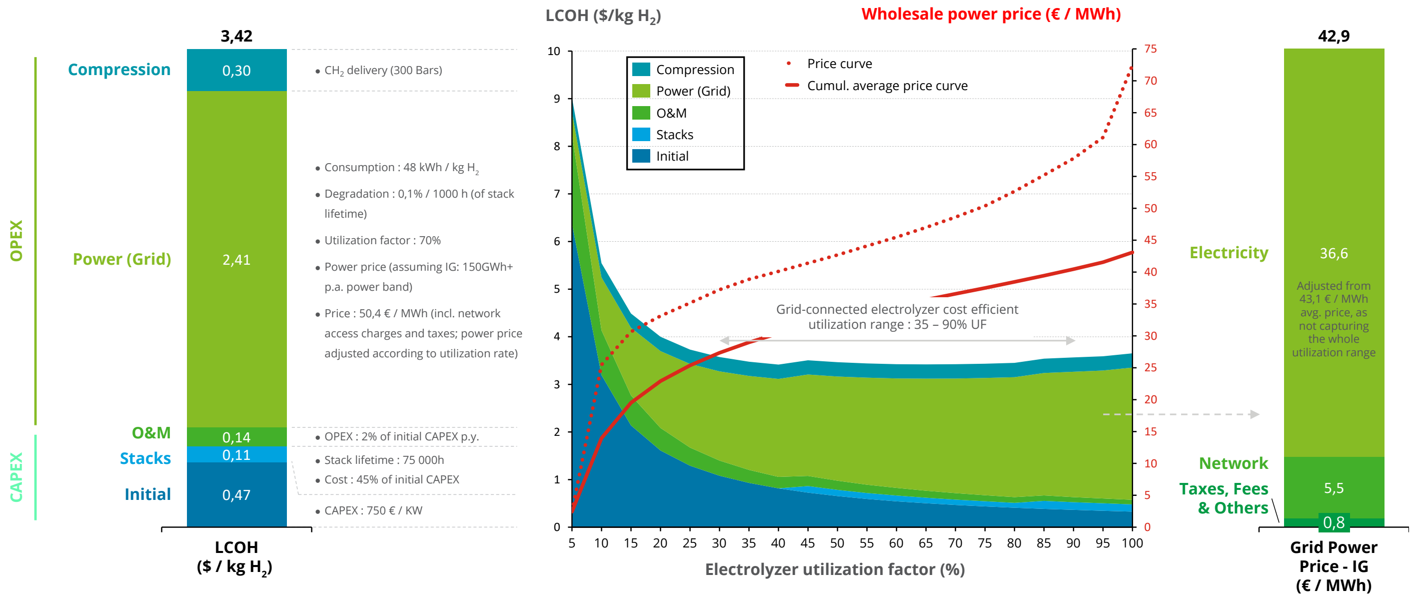
• **In terms of the economics of the process**, LCOH is driven by 3 key factors. [1] [14 15 20 23 24 25 26 27 28 30 34 36 39 41 42 63 64 70 73]

Figure 3 [14 73].

example of grid connected alkaline (AE) process

Electrolyzer costs (LCOH) are influenced by three major parameters: CAPEX, cost of power, and utilization factor

Hydrogen Cost from AE process – Illustrative Example (LCOH; \$ / kg H_2; 2020; France; Technical assumptions in the favorable range)



Sources: IEA, IRENA, ICCT, Tampere University, DOE Hydrogen & Fuel Cell Program, Store & Go Program; Flex CHX Program, Offshore Wind Industry Council, FuelCell Energy, Imperial College of London, Hydrogen Council, NREL, Monitor Deloitte analysis

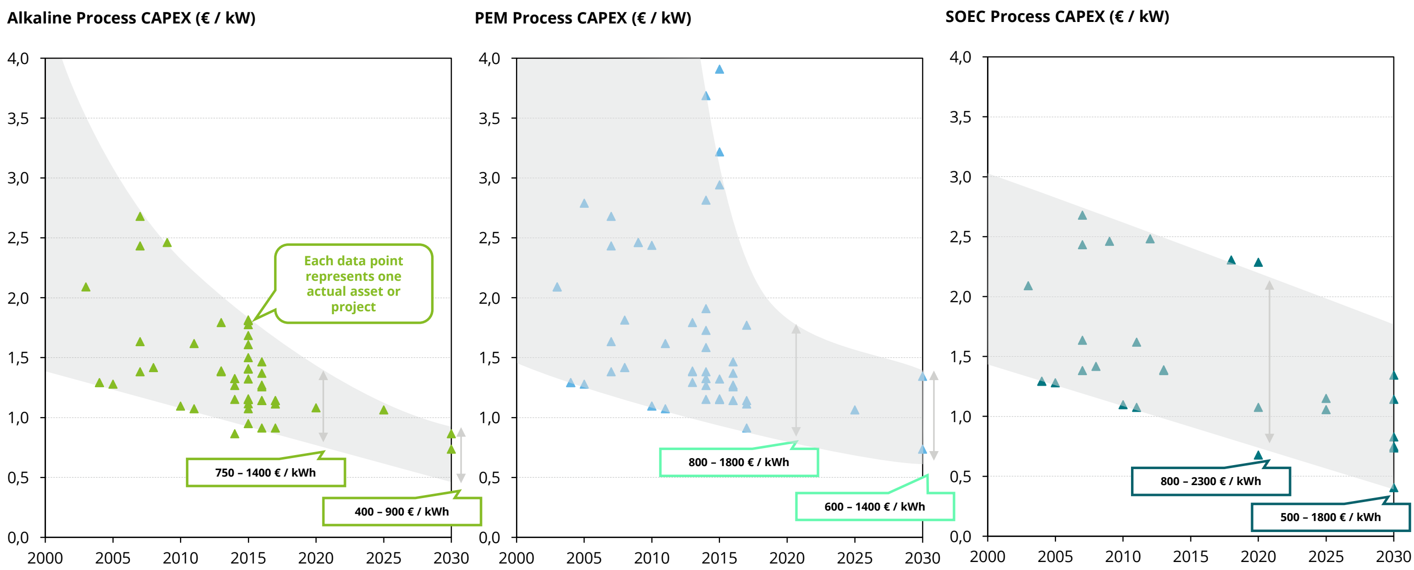
- Apart from the cost of electricity – which will be discussed in a further section – variable costs depend mainly on **power efficiency.** Thanks to the energy provided by heat, SOEC is expected to be significantly better (37 – 43 kWh / kg H_2 by 2030 – as feasible thermodynamic limit can already be achieved at the cell level according to experts, with improvements focusing on transitioning it to the system level) in terms of electric power consumption than AE and PEM (47 – 51, resp. 49 – 53 kWh / kg H_2 by 2030). Key drivers of power consumption improvement by 2030 will be thinner membranes (for PEM), slightly higher operating temperatures and more efficient ancillary systems (e.g., hydrogen purification efficiency).
- **Utilization factor** is also a key driver of the economics of electrolyzers. Indeed, below 30% of UF, the CAPEX and fixed costs absorption in insufficient. On the other hand, running at 90%+ UF levels could require high marginal cost power supply (i.e. merit order effect) hampering the electrolyzers' competitiveness.
- **CAPEX levels** are expected to fall significantly by 2030, down to 400 – 600 kWh / kg H_2 range, driven by on-going R&D initiatives and scale. [2 3 4 5 6 7 8 9 10 11 12 13 33 35 56 60]
  - **Process intensification:** increased process pressurization and current density (Up to 0.6A/cm^2 for AE and >3A/cm^2 for PEM), allow proportionally higher hydrogen production relative to stack size.
  - **Better process design:** zero-gap design (AE), thinner membrane (PEM), improved material microstructure integration for better oxygen conductivity (SOEC), alkaline polymer systems, better component integration, optimized system set-up and balance-of-plant component at system level, and low-cost stacks design.

- **Lower use of expensive materials:** reduction of precious metals (platinum) based catalysts through the introduction of new materials (telluride, nano-catalysts, mixed-metal-oxides), reduction of titanium in bi-polar plates, and lower operating temperature of SOEC systems, allowing the use of lower cost materials such as stainless steel.
- **Component standardization,** coupled with **production scale-up,** enabling the shift to high volume production methods (laser cutting, plastic injection molding) are expected to have a significant impact, especially for less mature technologies (PEM and SOEC). [60]
- **Stack** (whose replacement costs account for approx. 30 to 40% of overall system CAPEX) **lifetime** is also expected to increase significantly by 2030, reaching 95 000 hours for AE (resp. 75 000 for PEM and 60 000 for SOEC), driven by better catalysts durability, high tolerance to impurity, structural improvements of electrodes and stability of membrane (for PEM).

Figure 4 [73].
Electrolysis process CAPEX trends

The CAPEX of all processes should drop significantly by 2030, driven by technological improvements and economies of scale

Hydrogen electrolysis production processes CAPEX evolution (2000 – 2030)



Sources: IEA, IRENA, ICCT, Monitor Deloitte Analysis

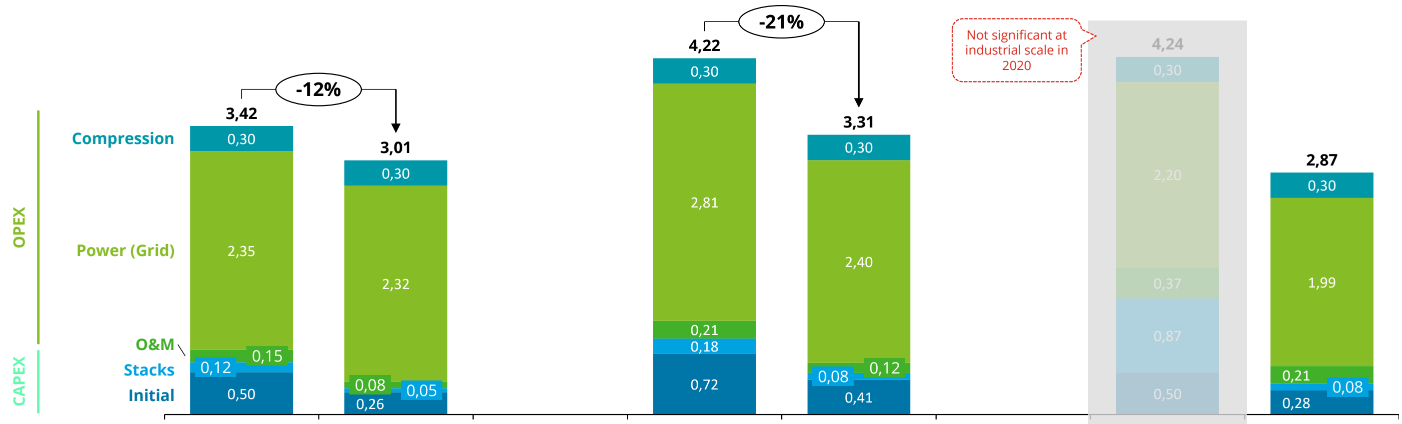
- Finally, **O&M costs** are assumed to be directly linked to CAPEX levels. By 2030, **O&M costs** are expected to range between 2 and 4% of CAPEX for AE and PEM processes, mainly depending on project scale, and more in the 5%+ range for SOEC. [2 3 4 5 6 7 8 9 10 11 12 13]
- Consequently, even assuming current best cost and technical parameters (i.e. large-scale systems) and reasoning at constant cost of power supply, **LCOH is expected to drop significantly by 2030 by approximately another 20%, thanks to merely internal factors.** In locations when SOEC is possible (i.e. nuclear plants, sources of industrial fatal heat), another 15% could be achieved.

Figure 5 [73].

Economics by process 2020 vs. 2030 (grid-connected)

By 2030, costs of electrolysis processes are expected to fall – driven by lower power consumption and CAPEX, as well as increased stack lifetime

Hydrogen Cost – Illustrative Example (LCOH; $ / kg H_2; 2020 - 30; France; Technical assumptions in the favorable range; constant grid price of power)



	AE (2020)	AE (2030)	PEM (2020)	PEM (2030)	SOEC (2020)	SOEC (2030)
Power cons. (kWh / kg H_2)	48	47	56	49	40	37
Perf. degrad (% / 1000 h)	0,1	0,1	0,2	0,1	1,9	0,5
O&M (% Init. CAPEX p.a.)	2	2	2	2	5	5
Initial Capex (€ / kW)	750	400	900	600	800	500
Stack CAPEX (% Init. CAPEX)	45	40	35	30	50	40
Stack life time (h)	75 000	95 000	60 000	75 000	25 000	60 000

Sources: IEA, IRENA, ICCT, Tampere University, DOE Hydrogen & Fuel Cell Program, Store & Go Program; Flex CHX Program, Offshore Wind Industry Council, FuelCell Energy, Imperial College of London, Hydrogen Council, NREL, Monitor Deloitte analysis

Ensuring power supply to the 'green' hydrogen production:

We explained in the first section how electrolysis economics and environmental performance are closely related to power supply. In this paragraph we will discuss the two major dimensions of powering hydrogen production and explain how they are dependent on both geography and target applications.

- Which power supply is the most suitable for electrolysers? Grid connection vs. proprietary renewables? Are there any relevant hybrid models?
- Which operating model should be adopted for renewable power sourcing – On-site or off-site power generation? And how can we ensure the traceability of Green Energy?

<u>**In terms of power supply,**</u> several options arise to allow the production of decarbonated hydrogen: grid connection, or dedicated power supply from renewables or nuclear power plants.

- **Grid connection:** grid suitability for hydrogen electrolysis depends mainly on location, as each country in Europe has a different power generation mix, but also on electrolyzer scale, as grid prices are highly dependent on annual consumption band.
  – **Costs:** price of electricity purchased on the grid results from 3 major factors: (1) the cost of electricity itself, as network access costs and taxes have a "fixed" component. Therefore, the larger the electrolyzer is, the more scale is brought to the cost of grid electricity. Hence, large scale industrial installations could potentially benefit from half prices vs. small scale ones. (2) Taxes can also be a key competitiveness factor, as countries such as Germany apply significant "renewable" taxes on non-household clients. (3) Running electrolyzers exclusively on curtailed electricity does not appear as a reliable option in EU in the near future, as utilization factors of approx. 5% are expected in such a scenario (e.g., Denmark, where electricity wholesale prices are at ~ 0 € / MWh in average 400 hours / year). [3]

Grid power supply can be suitable for mid to large scale electrolyzers in country with a decarbonated generation mix.

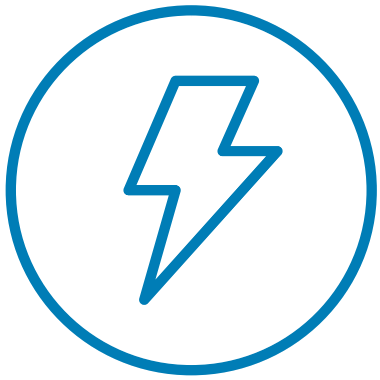
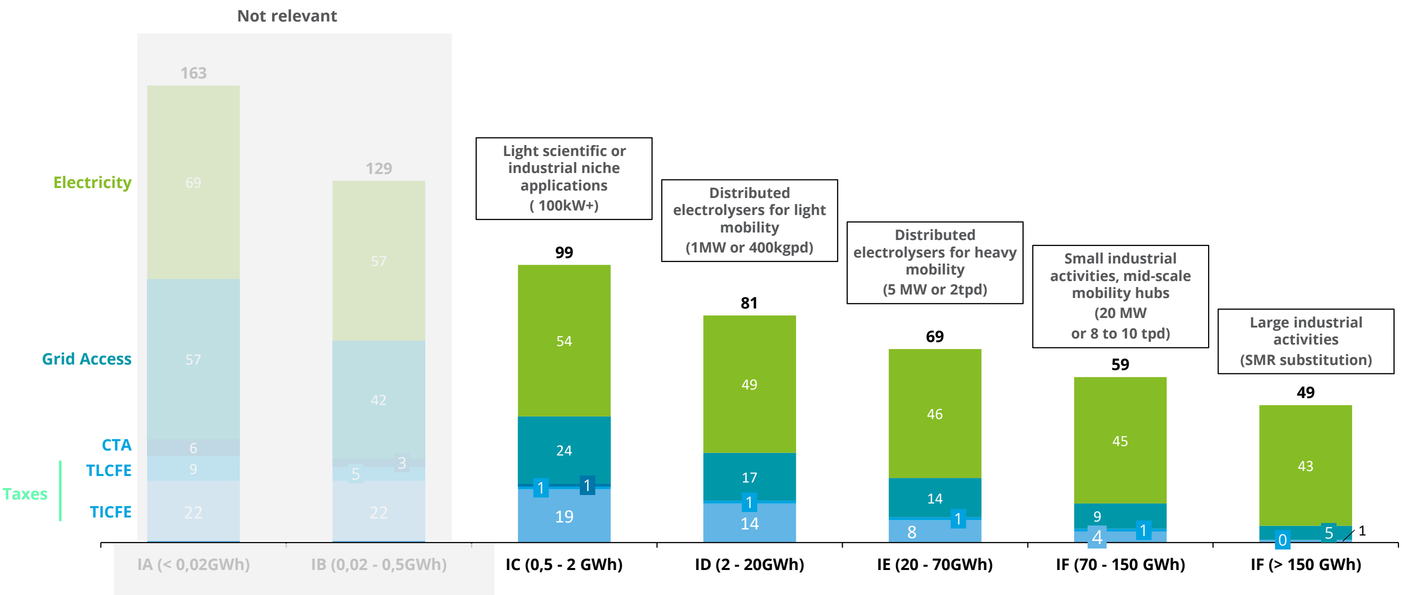


Figure 6.

Grid-connected electrolysis competitiveness

Depending on the target application and scale, power costs from the grid vary significantly (illustrative example of France)

Grid-connected electricity prices in France (2019; €/MWh)



Sources: Eurostat; SDES

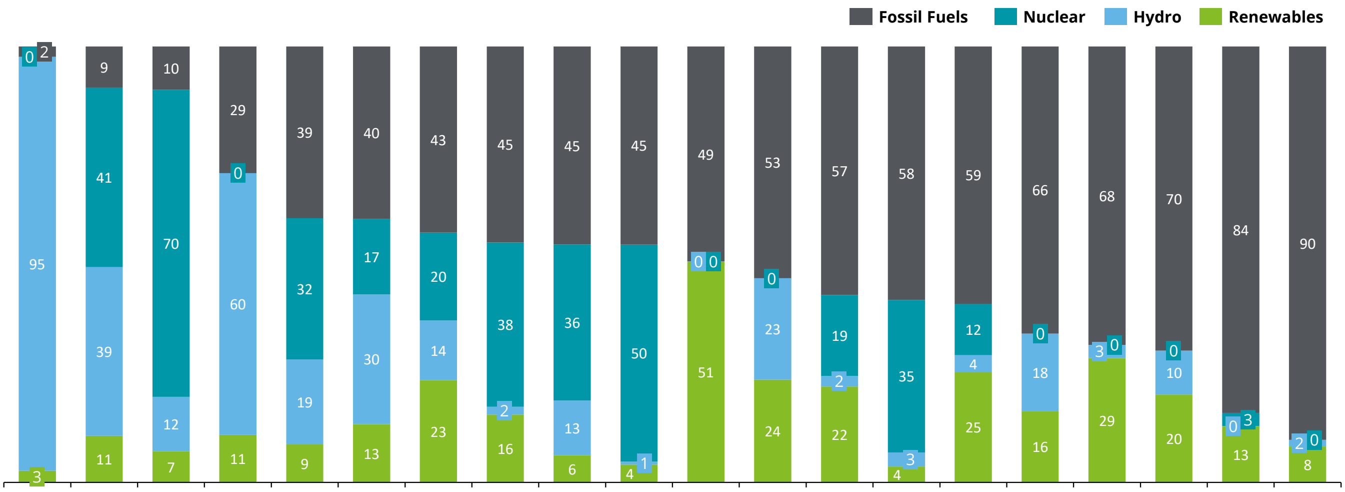
- **GHG emissions:** as of today, a precious few country benefit from a truly decarbonated grid, making it a relevant solution for 'green' hydrogen production. Norway (9 g CO_2 / kWh in 2018) benefits from an almost exclusively hydro power mix, while Sweden (16 g CO_2 / kWh) relies on a mix of hydro and nuclear. France is also a rather good candidate for grid-powered electrolysis (66 g CO_2 / kWh), as it runs 70% on nuclear power. All the other major European countries significantly rely on fossil fuels in their electricity mix (usually < 30%). By 2030, a few countries such as Hungary, Portugal, and to a lesser extent Austria and Bulgaria, could also became credible candidates.[50]

Figure 7 [6].

Grid-connected electrolysis competitiveness

Today, grid power supply is almost carbon-free in only a precious few countries (Norway, Sweden, and, to a lesser extent, France)

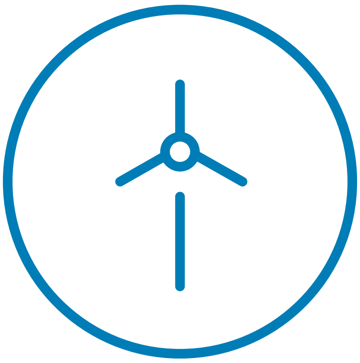
Grid-connected power generation mix for key European countries (%); and associated GHG emissions (g CO_2 / kWh) -2018)



	NO	S	FR	AT	FI	RO	SP	BE	BU	HU	DK	PO	UK	CZ	GER	IT	IR	GR	NL	P
2018 gCO2/kWh	9	16	66	133	171	356	248	188	507	310	316	295	256	518	485	358	459	655	479	770
2030 gCO2/kWh	11	6	6	58	202	96	127	236	62	9	176	5	120	397	323	233	220	302	337	422

Sources: Eurostat; IRENA REMAP Scenario (2030)

- **Renewables:** the most credible option to feed 'green' hydrogen electrolysis is renewable power generation. In this section, we focus on wind (both onshore and offshore) and PV technologies, as they represent most of the expected capacity additions in Europe by 2030 (Wind: +242 GW and PV: +237GW vs. +5GW for CSP, + 42GW for Biomass and +16GW for Hydro in the Irena REmap scenario). The performance of renewable energy sources is highly dependent on geography and the selected technology, as these factors drive costs and capacity factors – which are essential in ensuring decent utilization rates for electrolyzers, while not requiring much additional grid power supply: [6]



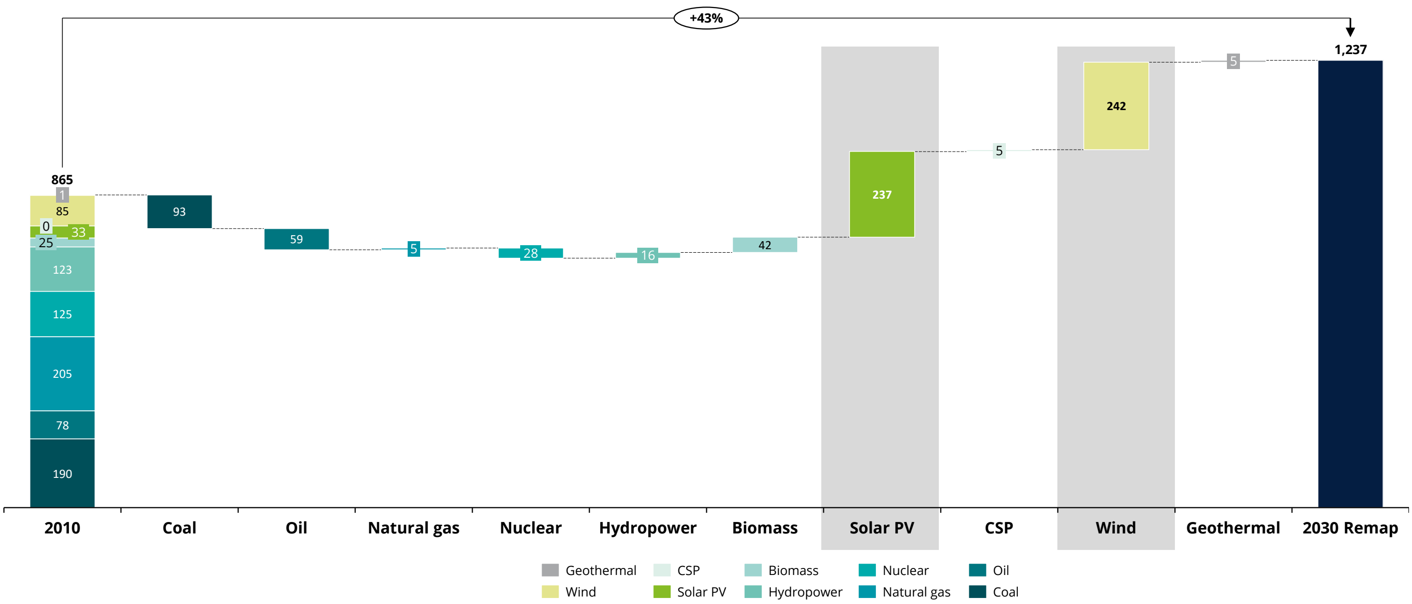
RES capacity factors and LCOE are highly dependent on technology and geography, with only a few premium areas in Europe.

Figure 8.

Renewable power generation economics in Europe : Installed Capacity build-up by 2030

The growth in installed power generation capacity in Europe up to 2030 is expected to be driven mainly by PV and Wind (onshore and offshore)

Installed power generation capacity by source in the EU-28 in 2010 versus 2030 REmap [GW]



Sources: IRENA 2018 Report - Renewable Energy Prospects for the European Union

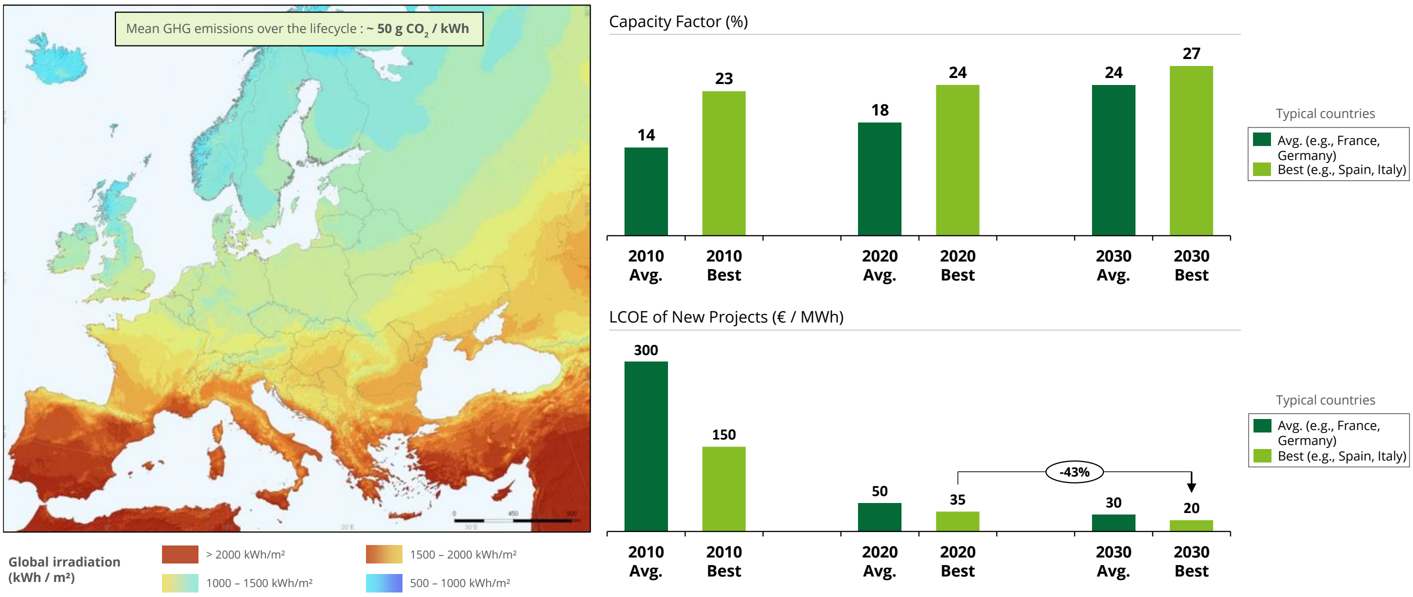
Figure 9 [74]**.**

Renewable power generation economics in Europe : Solar PV

Europe's solar PV potential is predominantly in the Mediterranean area, with sizeable improvement opportunity in both capacity factor and LCOE aspects

Solar PV potential in Europe
(Map Source : European Union PVGIS; 2012)

Solar PV economics in Europe (2010 – 2030)



Sources: IEA, IRENA, ICCT, Monitor Deloitte Analysis

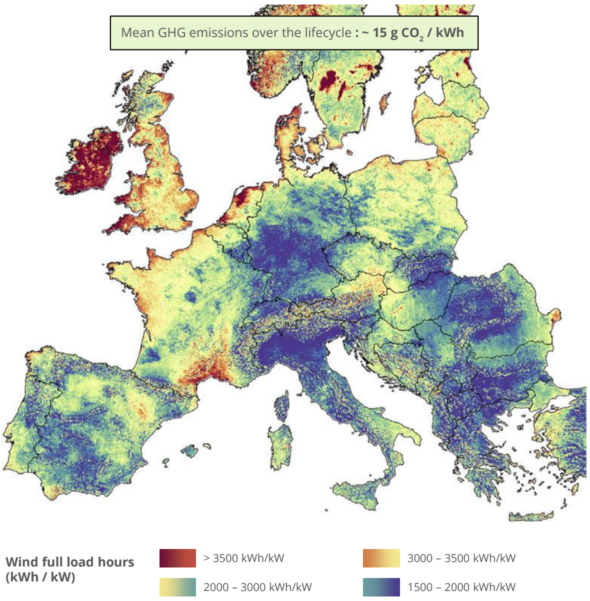
- **Solar PV** has a sizeable GHG footprint (~ 50 g CO_2 / kWh over assets lifecycle). Driven by irradiation, the best performances are achieved in Spain, Italy, and more generally along the Mediterranean coast (where irradiation is > 2000 kWh/m²), while average performance is found in areas of France and Central Europe (Germany). In terms of economics, LCOE has drastically dropped since 2010, as new capacities come to production at 35€ / MWh for best projects in 2020 (resp. 50€ / MWh for avg. projects), and are expected to reach even below 20€ / MWh by 2030 (resp. 30€ / MWh for avg. projects). Typical capacity factors will raise from 24% for best projects (resp. 18% for avg. ones) in 2020 to 27% in 2030 (resp. 24% for avg. ones). [26 28 64]

Figure 10 [71].

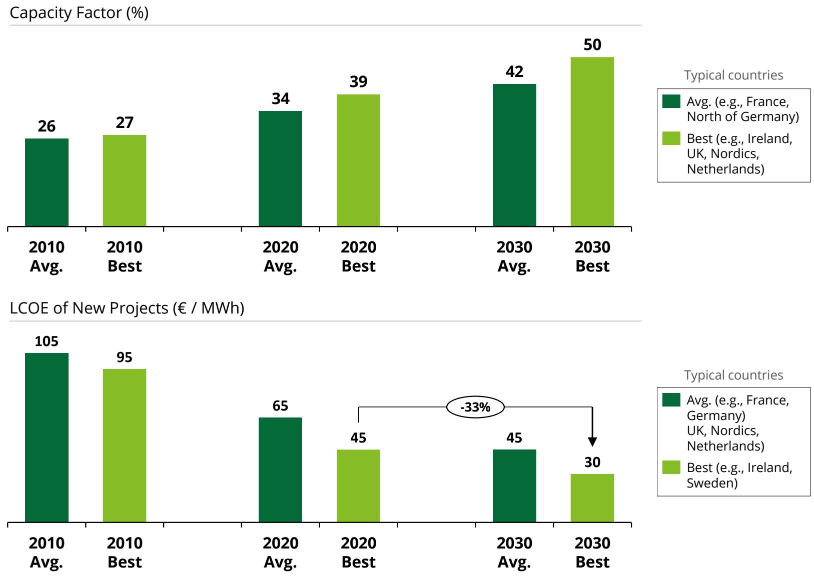
Renewable power generation economics in Europe : Onshore Wind

Europe's solar PV potential is predominantly in the Mediterranean area, with sizeable improvement opportunity in both capacity factor and LCOE aspects

Offshore wind potential in Europe
(Map Source : Carbonbrief; Ryberg et al., 2019)



Onshore wind economics in Europe (2010 – 2030)



Sources: IEA, IRENA, ICCT, Monitor Deloitte Analysis

- **Onshore wind** has a limited GHG footprint (~ 15 g CO_2 / kWh over assets lifecycle). Best performances are achieved in Ireland, West UK, West Norway and Northern Netherlands (> 3500 kWh / kW), while average performance is found in areas of France and North Germany. In terms of economics, LCOE has regularly declined since 2010, as new capacities come to production at 45€ / MWh for best projects in 2020 (resp. 65€ / MWh for avg. projects), and are expected to reach 30€ / MWh by 2030 (resp. 45€ / MWh for avg. projects). Typical capacity factors will raise from 39% for best projects (resp. 34% for avg. ones) in 2020 to ~50% in 2030 (resp. 42% for avg. ones). [75 71 72]

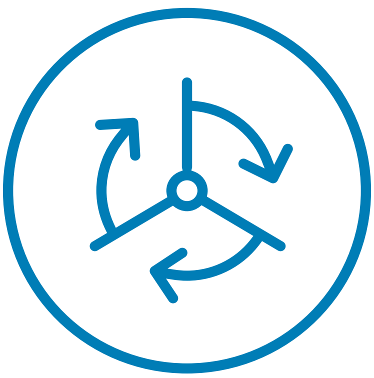


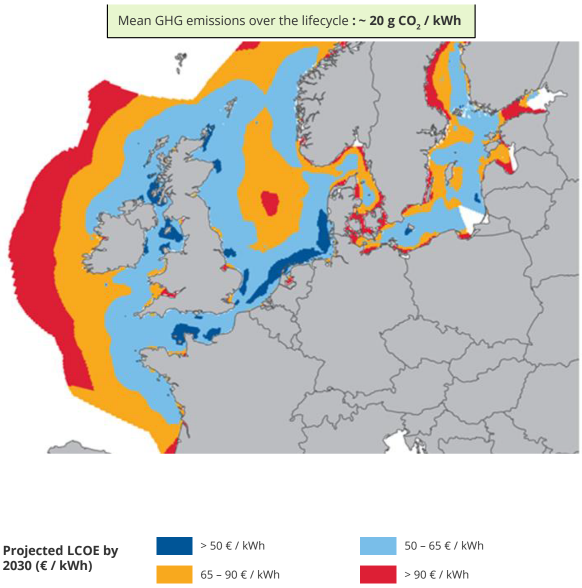
Figure 11 [71]**.**

Renewable power generation economics in Europe : Offshore Wind

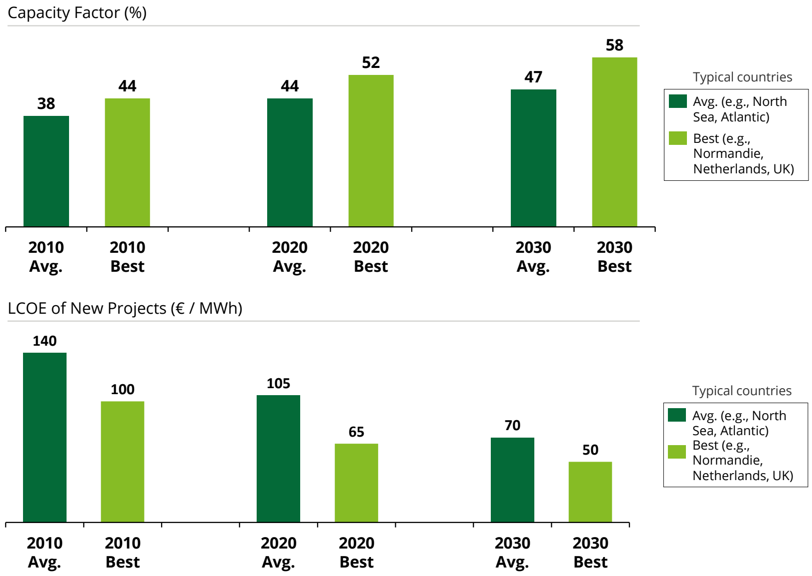
A few targeted areas in the North Sea will deliver below 50€ / kWh LCOE by 2030, with capacity factors above 50%

Offshore wind potential in Europe

(Map Source : Wind Europe)



Onshore wind economics in Europe (2010 – 2030)



Sources: IEA, IRENA, ICCT, Monitor Deloitte Analysis

– **Offshore wind** has a limited GHG footprint (~ 20 g CO_2 / kWh over assets lifecycle). Best performances are achieved in targeted coastal areas in North Sea, Irish Sea and Channel (expected LCOE of new projects by 2030 < 50 € / kWh), where complex conditions are satisfied simultaneously: wind conditions, distance to the coast, water depth, areas restricted because of shipping lanes, environmental protection or dumped munitions. In terms of economics, LCOE has regularly declined since 2010, as new capacities come to production at 65€ / MWh for best projects in 2020 (resp. 105€ / MWh for avg. projects), and are expected to reach 50€ / MWh by 2030 (resp. 70€ / MWh for avg. projects). Typical capacity factors will raise from 47% for best projects (resp. 44% for avg. ones) in 2020 to 58% in 2030 (resp. 47% for avg. ones). [61 69 71 72]

- **Nuclear power** can also be a credible alternative to produce low carbon hydrogen[77], with varied operating models (power only, heat only, mixed power & heat) being credible in combination with electrolysis and SMR processes. These options will be discussed in a separate article.

In terms of operating model, several power-supply options arise for electrolysis plants, leading to a full continuum of economic, technical and environmental performance levels, as well as potential business models. [57 58]

- **Direct On-site PPA:** the negotiated electricity is delivered from the renewable source to the electrolysis plant operator (i.e. the off taker) through a direct connection (the power generation facility being often located on the electrolysis operator's property). Usually, the renewable project developer makes the investment, as well as designs, installs, operates and maintains the plant. On the one hand, it is a competitive option in terms of electricity price, as the electrolysis operator can avoid certain costs such as the grid usage charges or taxes (as the power delivery process does not involve the usage of the public grid). Furthermore, when the on-site PPA comes to an end, generated electricity can become free if the electrolysis operator becomes the owner of the power plant. On the other hand, flexibility is limited, hampered by a single source of power. [43 44 55 65]

- **Direct Off-site PPA:** Electricity is supplied without direct connection between production sites and electrolysers. Operation is managed by an intermediary (supplier or aggregator) that transports electricity to the nominated sites. It offers additional flexibility, as the provider can supply power from several portfolio assets (e.g., coupling PV and wind), enabling operation at high utilization factor levels. Nevertheless, electrolyzers and generating facilities shall be located within the same grid region (and within a deregulated retail area for industrial clients – which is the case in the European Union), constraining the extent to which electrolysis operators can directly procure energy at scale. [65]

In both on-site and off-site direct PPAs, renewables intermittency can be managed with a complementary grid power supply, shortfalls being supplied either at pre-established prices (in "as-consumed" PPAs, where the supply usually comes from the supplier generation portfolio) or spot prices. This hybrid power supply has consequences on both price position, and potentially impaired GHG emissions level. [49, 50, 51, 55, 66]

- **Virtual Off-site PPA:** In such an agreement, the power supplier and the electrolyzer operator are only virtually connected, as no renewable power is physically delivered to the buyer. Indeed, instead of routing renewable power to the off taker, the generation facility sells renewable power to the grid, and receives the open market price. The electrolysis operator buys electricity from its usual retailer. The renewable project developer pays the difference to the off-taker when the agreed-upon PPA price (or strike price) is below the market price (and vice versa). This supply mode brings higher flexibility to the electrolysis operators, both in terms of utilization factors and geographical footprint, and is the most suitable for distributed small-scale electrolysis. [65]

In order to ensure the decarbonation of purchased power, each purchase agreement requires the transfer of **Guarantees of Origin** to the electrolysis operator. The Guarantee of Origin is a certification required to determine the amount of energy consumed produced from renewables. It is an electronic document whose issuance is linked to renewable energy production, but which can be disconnected from the electricity that is sold. It is a transferable certificate with a market value. It is thus possible for electrolyzers operators to "clean-up" their electricity by buying GOs afterwards.

Guarantees of origin are managed by a registrar (the European Power Exchange EEX now operates the French register) who is responsible for issuing, transferring and canceling guarantees of origin for a maximum period of 5 years. A guarantee of origin is equivalent to 1 MWh produced. Guarantees of origin are **currently trading at low levels** (< 1€ / MWh), because of an unbalanced market – as evidenced by the 594TWh supply vs. 326TWh demand in 2018, in Europe (incl. 53 TWh supply vs. 33 TWh demand in France), with the situation potentially having worsened in 2020 due to the Covid-19 crisis.

To ensure the decarbonation of purchased power, each purchase agreement should require the transfer of Guarantees of Origin to the electrolysis operator.

Operating models for hydrogen production: can one size fit all?

As of 2030, hydrogen demand is expected to increase significantly (+340 TWh between 2015 and 2030), with industry (+ 164 TWh) and mobility (+70 TWh) being the main growth contributors. Identifying the most suited hydrogen production operating models for these applications is therefore crucial.

In the previous sections, we discussed:

- Which electrolysis processes (AE, PEM, SOEC) are likely to be both technically relevant and economically competitive against traditional H_2 production (i.e. SMR+CCS), and why, depending on potential use cases.
- The most suited power supply options for electrolysis depending on geographies and use cases.

We will wrap-up our findings across the whole value chain through the analysis of 3 business cases, covering industry and mobility end-uses, based on 3 different operating models : large scale production (~100MW), small scale distributed production (~ 1MW) and mid-scale "semi centralized" production (10 – 40MW).

Large scale production (~100MW)

Industrial processes typically require ~ 50 tons per day (100MW+) of production. Electrolysis could act as a substitute for SMR+CCS process in areas where competitive direct off-site renewables PPA can be contracted (i.e. electrolysis assets laying in the same grid areas as renewable electricity sources), therefore making a decarbonated power supply credible.

- In such a situation, the electrolyzers could run at a 90%+ utilization factor, combining renewables at their nominal rate, and complementary grid supply backed by renewable Guarantees of Origin (assumed to be purchased at 2€/ MWh).

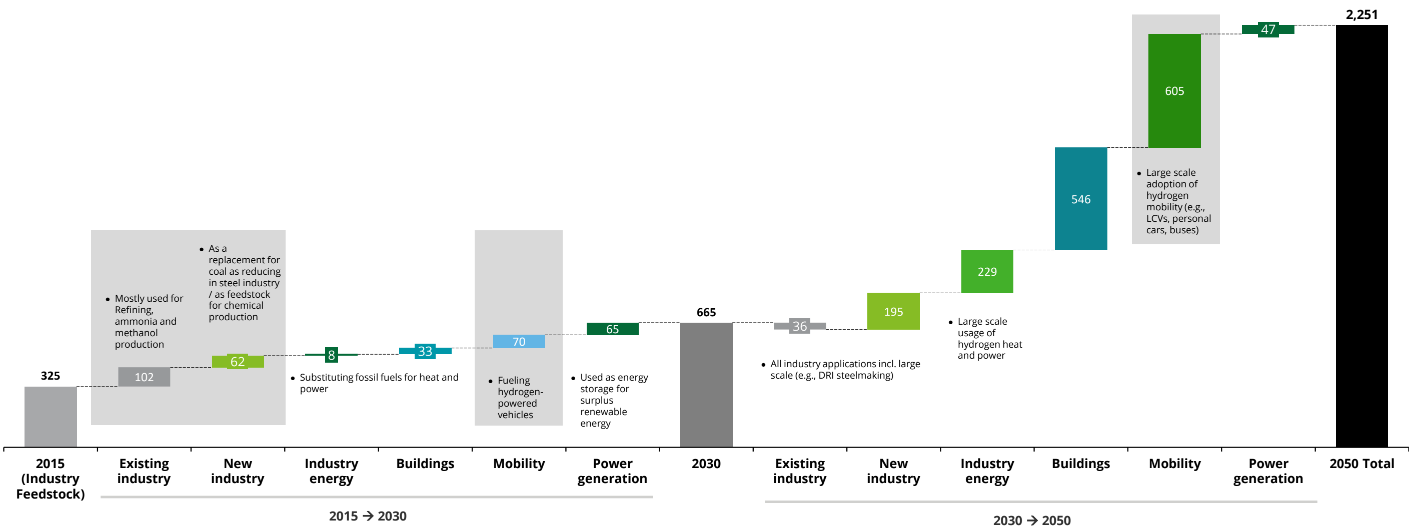
In the mid-term, SMR+CCS is expected to be a more competitive option than electrolysis for industrial applications.

Figure 12.

Hydrogen demand evolution

Industry and mobility are expected to be key contributors of incremental hydrogen demand by 2030

Potential Europe hydrogen demand evolution to 2030 by final use [TWh_{eq}]



Sources: Hydrogen Roadmap Europe, FCH (Public-Private partnership between European Commission, Industry and Research)

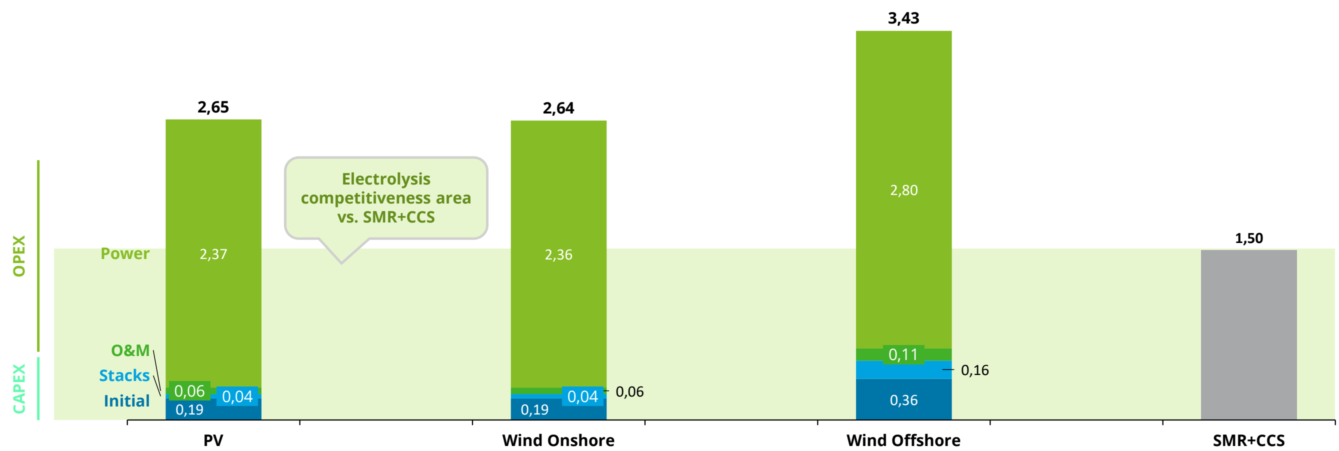
- Hydrogen purity levels required by such industrial processes are at traditional levels (99.95%, i.e. Quality Verification Level "B"), quite achievable by Alkaline electrolysis, a mature technology that has already been demonstrated at industrial scale (100MW+).
- Considering on-going scale and technical improvements that should occur by 2030, AE technical parameters are expected to improve to 47kWh / kg H_2 efficiency with a 0,1% / 1000 hours erosion and 95 000 hours stack duration lifetime. At such an asset scale, initial CAPEX should be as low as 400€ / kW, with yearly OPEX accounting for 2% of initial CAPEX.
- Assuming stable economic conditions by 2030 (no variations in gas and on-grid electricity prices, as well as no specific taxation or subsidies), even considering ambitious technical evolutions, all renewable power supply options (PV, Wind) would result in an **electrolysis LCOH significantly above expected levels for SMR+CCS** (> 2.5$/kWh vs. 1.5$/kWh for SMR+CCS). Therefore, **SMR+CCS** is expected to remain the most competitive production way for industrial applications.
- In terms of CO_2 emissions, CCS is expected to bring up to 89% capture rates for SMR plants, resulting in ~ 1kg CO_2 / kg H_2 emissions, comparable to those achievable with wind power supply (15 to 20 g CO_2 / kWh over assets lifecycle x 47 kWh / kg H_2), and below Solar PV solutions (~ 50g CO_2 / kWh).

Figure 13.

Business Cases: Industrial Applications

Most of the electrolysis capacity currently installed and planned for installation is in Europe

Hydrogen Cost – (LCOH for a very large AE electrolyzer; 100MW+; 90% capacity factor; $ / kg H_2; 2030)



	PV	Wind Onshore	Wind Offshore	SMR+CCS
Price of power (€ / MWh), mixed with IG band grid	20	30	65	NS
Capacity Factor of renewables, mixed with grid up to 90% (%)	27	50	58	NS

Sources: Monitor Deloitte Analysis

Small scale distributed production (~ 1MW)

"Distributed" H_2 production for light mobility requires typically ~400 - 500 kg per day (1MW) production, in order to feed a small-size captive fleet of trucks or buses (~15 trucks or buses). In France, such limited size assets are rather easy to develop, as only a prefectural declaration is needed of up to 1t of H_2 storage, a more formal authorization being required only above 1t (based on ICPE 4715 norm, which should be supplemented with mandatory authorization for production sites larger than 100 kg / day – "Directive IED, Rubrique 3420). [79]

- Such electrolyzers will be grid connected and running with a 90%+ utilization factor with power supply from the grid being backed by renewable Guarantees of Origin (assumed being purchased at 2€/ MWh). Some electrolysis stations could be opportunistically associated with Renewable Energy Sources, thus benefitting from more favorable power supply conditions. This will be documented further in the 3rd business case.
- Hydrogen purity required by FCEV must comply with ISO 14687-2 levels (99.97%), achievable **by PEM electrolyzers.** Furthermore, the limited land footprint of PEM technology makes this process more suitable for space constrained areas.
- Considering on-going scale and technical improvements that should occur by 2030, PEM technical parameters are expected to reach 49kWh / kg H_2 efficiency with a 0,1% / 1000 hours erosion and 75 000 hours stack duration lifetime. At such limited asset scale, initial CAPEX should be at 1400€ / kW level, with yearly OPEX accounting for 4% of initial CAPEX.
- Assuming stable economic conditions by 2030 (no variations in gas and on-grid electricity prices, as well as no specific taxation or subsidies), even considering mid-term technical evolutions, distributed hydrogen generation would result in an **electrolysis LCOH significantly above expected levels for SMR+CCS with delivered costs within a 200 – 300km max. range** (> 6.3$/kWh vs. 4$/kWh for SMR+CCS : 1.5$/kWh for production and 2.5$/kWh for logistics). The main parameter hampering small-scale hydrogen electrolysis is the cost of grid power supply, smeared with high network access and taxes costs (approx. 30€/ MWh+ for a 1MW electrolysis station in France, belonging to the "ID" consumption band: 2 to 20 GWh / year).
- However, several factors support the case for distributed electrolysis, potentially leading to the **public sector supporting this technology through subsidies:**
  - Setting-up distributed electrolysis is **a rather easy way** (requiring modest CAPEX) **to launch green mobility initiatives at the local level, promoting adoption of FCEV.** It does not require the setup of complex and CAPEX-heavy investments (CCS and/ or PSA retrofits of SMR facilities to ensure carbon capture resp. H_2 quality, compression/liquefaction capacity, supply chain, etc.)
  - **H_2 logistics complexity could become excessive** as FCEV vehicles scale-up and as remote deliveries are less relevant in areas far from H_2 SMR+CCS merchant capacities, which are mainly located in North-Western Europe.
  - Even if benefitting from limited GHG emissions, hydrogen produced through the SMR+CCS route is non-renewable, thus **not matching with the environmental ambition of many public authorities.**

Small scale distributed electrolysis is a practically straightforward way of launching green mobility initiatives at a local level, but it will require a significant support from the public sector.

Mid-scale "semi centralized" production (10 – 40MW)

A "Semi-Centralized" mobility hub would typically require ~4 tons per day of H_2, feeding simultaneously several fleets (e.g., logistic hub for FCEV trucks + municipal busses and garbage trucks + FCEV train operating on a non-electrified line, …). Typical setups should involve large size 10 MW to 40 MW electrolyzers, depending on target capacity factors.

- Several power supply models can potentially be leveraged for such a platform, from grid connection (with Guarantees of Origin) to proprietary RES of different types (PV, onshore / offshore wind) - allowing to save on network connection fees and taxes - depending on the most competitive technologies available in each geography.
- Hydrogen purity required by FCEV must comply with ISO 14687-2 levels (99.97%), achievable **by PEM electrolyzers.** Furthermore, the combination with RES requires high flexibility, which is a key distinctive feature of PEM technology, start-up and ramp-up / ramp-down being achievable within seconds.
- Considering on-going scale and technical improvements that should occur by 2030, PEM technical parameters are expected to reach 49kWh / kg H_2 efficiency with a 0,1% / 1000 hours erosion and 75 000 hours stack duration lifetime. At such limited asset scale, initial CAPEX should be at 600€ / kW level, with yearly OPEX accounting for 2% of initial CAPEX.
- Assuming stable economic conditions by 2030 (no variations in gas and on-grid electricity prices, as well as no specific taxation or subsidies), most of the contemplated power supply models (grid, proprietary RES) could be competitive against **SMR+CCS delivered costs within a 200 – 300km max. range by 2030** (LCOH at par or below 4$/kWh for SMR+CCS : 1.5$/kWh for production and 2.5$/kWh for logistics, for both average and top performing assets), assuming the access to an adapted electricity source.
- Therefore, given their scale, **"Semi-Centralized" hubs appear as a competitive operating model** for hydrogen production, on the condition of being able to structurally combine spots with attractive renewable energy sources (or low price and low GHG grid) and enough local H_2 consumption to bring the necessary scale (e.g., logistic hub on a critical freight corridor, strategic position on a non-electrified railway line). Careful **localization studies** will be required to position those "semi-centralized" mobility hubs well, and so will **public sector coordination** and financing be crucial to accelerate the emergence of these projects.

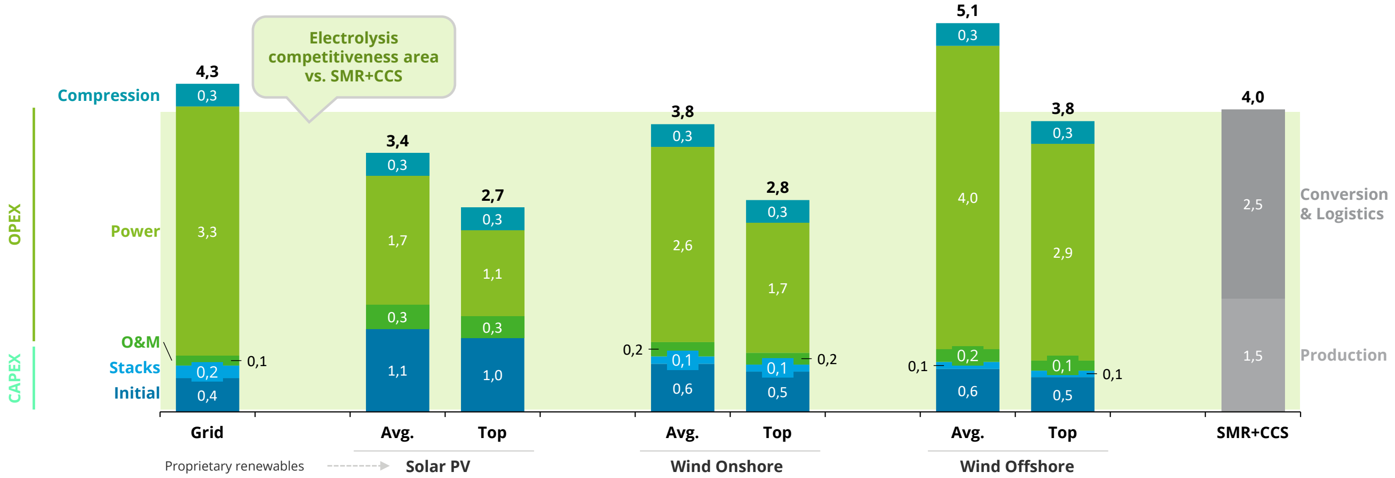
Strategically located hydrogen "Mobility Hubs" could be competitive in the mid-term, as they will combine a sizeable H_2 local demand potential with the access to an attractive power supply.

Figure 14.

Business Cases: Mobility Hub

By 2030, mobility hubs combining electrolysis with proprietary renewables are expected to be competitive vs. remote deliveries from an SMR+CCS plant

Hydrogen Cost – (LCOH for a large PEM electrolyzer; 10 – 40 MW; $ / kg H_2; 2030)



	Grid	Solar PV Avg.	Solar PV Top	Wind Onshore Avg.	Wind Onshore Top	Wind Offshore Avg.	Wind Offshore Top	SMR+CCS
Price of power (€ / MWh)	57 (ID Range)	30	20	45	30	105	65	NS
Capacity Factor (%)	90	24	27	42	50	47	58	NS

Sources: Monitor Deloitte Analysis

The way ahead

In this document, we discussed the technical considerations of existing electrolysis processes (AE, PEM, SOEC) and their competitiveness against the SMR+CCS process by 2030, highlighting key parameters such as hydrogen purity, process flexibility and costs. We also documented which power supply options are the most suited to feed hydrogen electrolysis, showing how both grid properties and renewables potential (translated into capacity factor and LCOE) are differentiated across geographies. By doing so, we developed a techno-economic model for electrolyzers, providing LCOH for the entire range of possible configurations.

Considering a few operating models in industrial and mobility applications:

- We demonstrated that hydrogen electrolysis can find areas of cost competitiveness in **'semi-centralized' models,** fueling **mid-to-large scale mobility hubs** in areas that are far from SMR merchant facilities.
- **In industrial applications,** as CCS reaches technical maturity, costs of 'blue' hydrogen are expected to match with current 'brown' processes, with high capture rates making it significantly more competitive than electrolysis.
- **Distributed hydrogen production,** which is fundamental for **light mobility applications** from a technical and operating point of view, is nonetheless structurally hampered by limited scale and grid power supply costs. Therefore, significant public support is fundamental to rapidly bring significant scale to this application.

The hydrogen value chain activation will require both public and private stakeholders to coordinate for funding and consistent business models.

Figure 15.

Summary : LCOH by process

Estimation of LCOH (in 2030; $/ kg H_2) based on technology, scale, power costs and capacity factor

LCOH ($ / kg H_2) in 2030, for 3 electrolysis processes, depending on LCOE (€ / MWh) and Capacity Factor (%)

	Capacity Factor (%) →	AE				PEM				SOEC			
	LCOE (€/MWh)	30	50	70	90	30	50	70	90	30	50	70	90
Large (100MW)	20	1,82	1,55	1,47	1,39	2,28	1,93	1,72	1,65	1,98	1,66	1,53	1,41
	30	2,37	2,10	2,02	1,95	2,85	2,50	2,29	2,22	2,44	2,13	2,01	1,88
	40	2,91	2,66	2,57	2,50	3,42	3,07	2,86	2,80	2,91	2,60	2,48	2,35
	50	3,46	3,21	3,12	3,06	3,99	3,65	3,44	3,37	3,38	3,	Nuclear Backed Production	2,83
	60	4,00	3,77	3,68	3,61	4,55	4,22	4,01	3,95	3,84	3,		3,30
	70	4,55	4,32	Industrial Applications	4,16	5,12	4,79	4,58	4,52	4,31	4,00	3,90	3,77
	80	5,09	4,87		4,72	5,69	5,36	5,15	5,10	4,77	4,47	4,38	4,24
Medium (10MW)	20	2,19	1,77	1,65	1,54	2,85	2,32	2,00	1,90	2,71	2,17	1,95	1,74
	30	2,73	2,33	2,20	2,09	3,42	2,89	2,58	2,47	3,18	2,64	2,42	2,21
	40	3,28	2,88	2,75	2,65	3,99	3,46	3,15	3,05	3,64	3,10	2,89	2,68
	50	3,82	3,43	3,31	3,20	4,56	4,04	3,72	3,62	4,11	3,57	3,37	3,15
	60	4,37	3,99	3,86	3,75	Semi Centralized Mobility Hubs		4,29	4,20	4,57	4,04	3,84	3,62
	70	4,91	4,54	4,41	4,31			4,87	4,77	5,04	4,51	4,31	4,10
	80	5,46	5,09	4,96	4,86	6,26	5,75	5,44	5,35	5,51	4,98	4,79	4,57
Small (1MW)	20	3,11	2,33	2,08	1,88	4,41	3,34	2,74	2,31	4,36	3,26	2,81	2,42
	30	3,65	2,89	2,63	2,43	4,98	3,91	3,31	2,88	4,82	3,73	3,28	2,89
	40	4,20	3,44	3,19	2,99	5,55	4,48	3,89	3,46	5,29	4,20	3,76	3,36
	50	4,74	3,99	3,74	3,54	6,11	5,05	4,46	4,03	5,75	4,67	4,23	3,83
	60	5,29	4,55	4,29	4,10	6,68	5,63	5,03	4,61	6,22	5,14	4,70	4,30
	70	5,84	5,10	4,84	4,65	7,25	6,2	Distributed Production	5,18	6,69	5,61	5,18	4,78
	80	6,38	5,66	5,40	5,20	7,82	6,		5,76	7,15	6,07	5,65	5,25

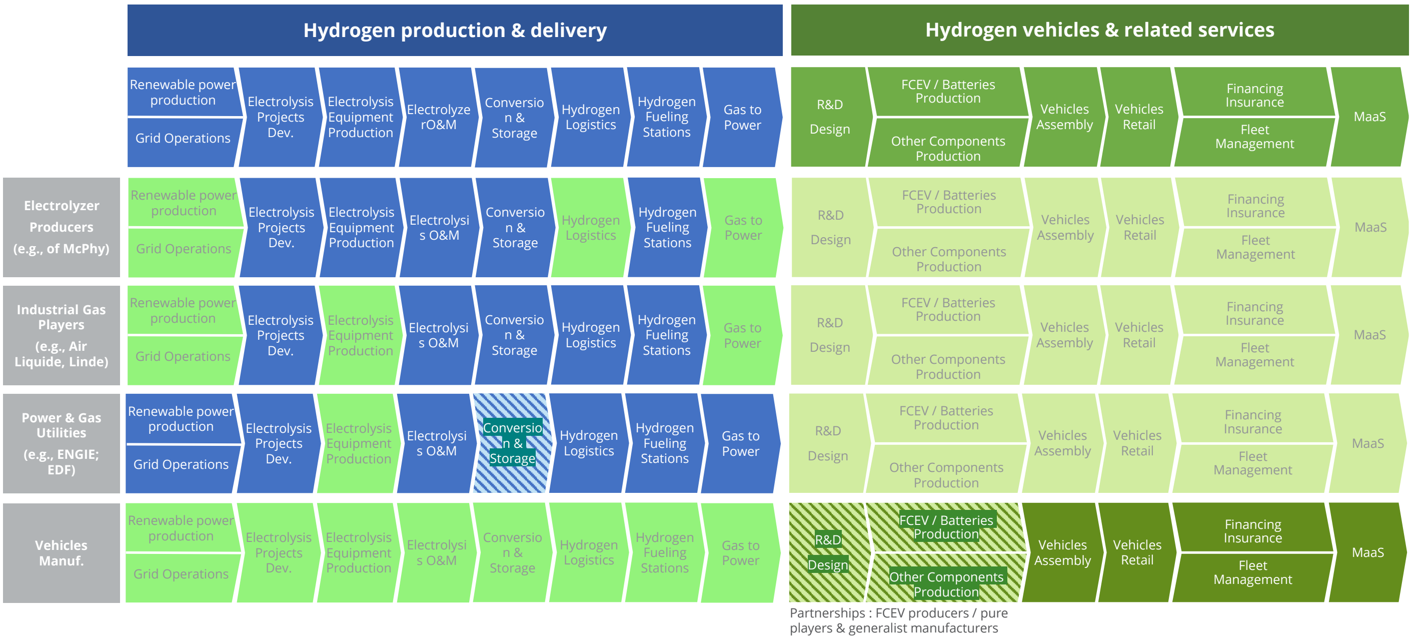
Source : Monitor Deloitte analysis

Figure 16.

Business Models

Varied types of players contemplate operating within the hydrogen-powered mobility value chain by leveraging diverse business models

Hydrogen for Mobility simplified value chain



Source : Monitor Deloitte analysis

Developing projects based on Value Chain activation strategies will require both public and private stakeholders to coordinate for funding and operating end-to-end value chains, emphasizing the need to build winning business models. As of today, a flurry of players is contemplating the hydrogen powered mobility sector, each with a specific value chain position:

- Certain player types have begun **to integrate several steps of the hydrogen value chain,** including electrolysis projects development: electrolysis equipment manufacturers (e.g. McPhy, Hydrogenics, Ergosup – acquired by Air Liquide, Areva H_2 GEN – acquired by GTT...), power & gas companies (ENGIE, EDF – through its Hynamics subsidiary, Total...), industrial gas producers (Air Liquide, Linde, ...), industrial players (Bouygues Energie & Services, ...)

- Other player types have a **more targeted approach,** addressing only one step of the value chain: FCEV / stack manufacturers (Ballard, SinoHytec, ...), hydrogen compression, storage and transport specialists.

- Finally, in terms of **FCEV production,** several models have emerged, as in heavy duty vehicles, where **alliances between traditional truck manufacturers and FVEC specialists** have been established (IVECO / Nikola, MAN / Esoro, Scania / Renova, ...)

The winning business models are as yet unknown, and as of today, none of them fully articulates the end-to-end "hydrogen for mobility" value chain.

Finally, even if mobility and industry are expected to be the two most significant hydrogen applications by 2020, **other should also emerge** (stationary energy generation and storage, domestic energy, etc.) with their own specific technical and economic needs.

Future of Mobility

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