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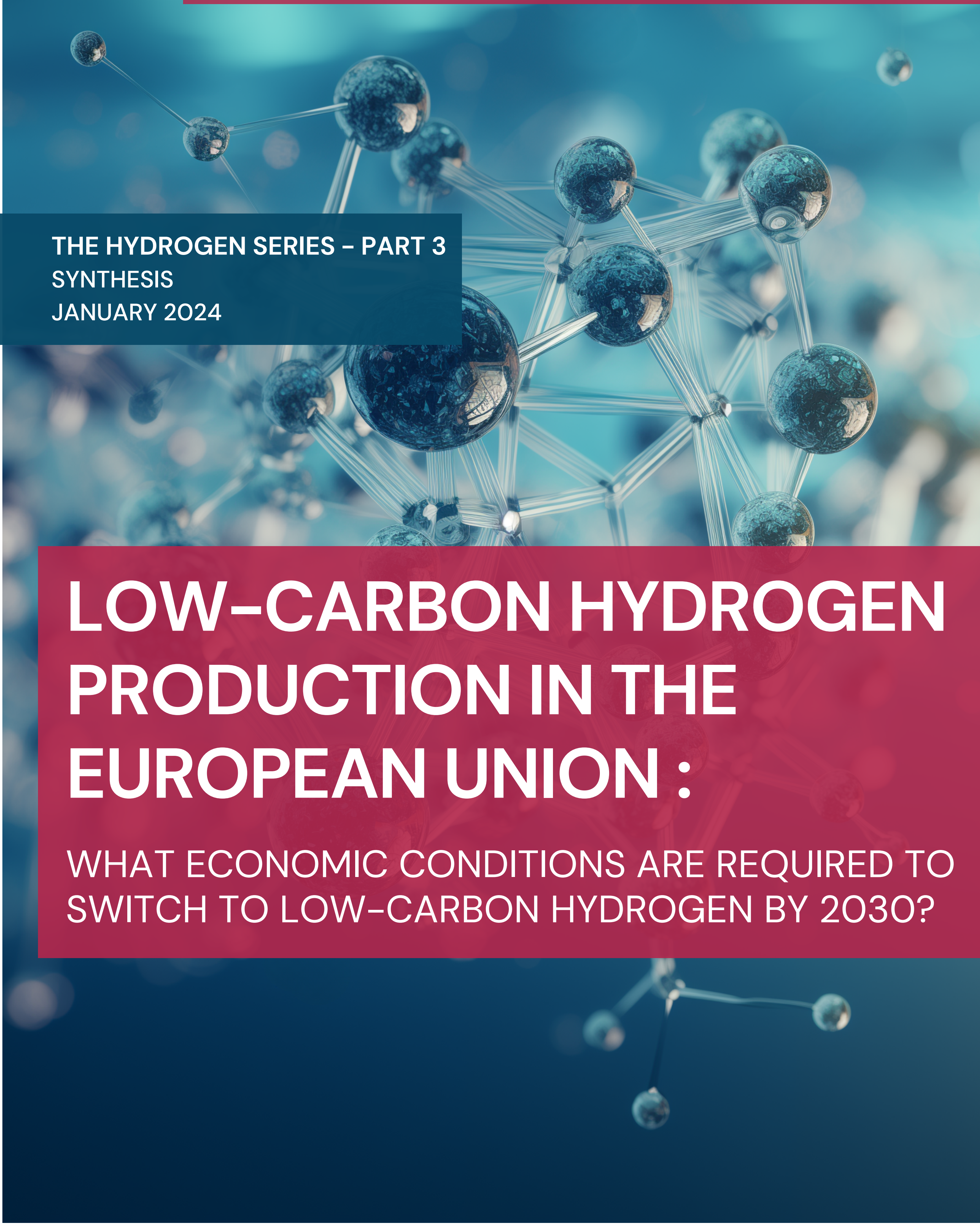


THE HYDROGEN SERIES – PART 3

SYNTHESIS

JANUARY 2024

LOW-CARBON HYDROGEN PRODUCTION IN THE EUROPEAN UNION :

WHAT ECONOMIC CONDITIONS ARE REQUIRED TO SWITCH TO LOW-CARBON HYDROGEN BY 2030?

1. Producing low-carbon hydrogen from the current hydrogen users' standpoint

In 2020, 82%[1] of the 8.7 million tons of hydrogen (H_2) demand in Europe were used not as an energy vector but as a chemical input by two main industries: refining (4,4 Mt) and ammonia production (2,5 Mt). The remaining 18% of hydrogen is currently consumed by the chemical industry for methanol production and for others industrial processes such as steel production, electronic components manufacturing, glass manufacturing, etc.

At the same time, 91% of the European hydrogen production capacity relied on fossil fuels as feedstocks, mainly through Steam Methane Reforming (SMR) technologies, which causes more than 80 million tons of CO2 per year, ie. 2.5% of total EU-27 emissions[A].

Decarbonizing hydrogen production in Europe by 2030 implies for the two main current users to switch to low-carbon hydrogen production technologies. While multiple low-carbon hydrogen production routes exist, Europe focuses on electrolysis-based technologies, which require significant renewable electricity capacities[B]. Hydrogen production based on carbon capture system could also be considered as a complementary way to achieve EU decarbonization goal[A].

Beyond the technological and industrial challenges of low-carbon hydrogen production, competitiveness of levelized cost of hydrogen (LCOH) is also a major key enabler of transition dynamics. Indeed, from the standpoint of a current consumer, the main barrier to switch over to low-carbon hydrogen still lies with its cost of production. The objective of this report is thus to analyse under which economic conditions low-carbon hydrogen would be cost-competitive compared to SMR production-based hydrogen in Europe by 2030, or more generally how much more a consumer would have to pay to lower its CO_2 emissions by switching to low-carbon hydrogen.

Even though a large variety of set-ups could be considered to produce hydrogen, the three following scenarios have been selected as they will most likely be the only available technologies by 2030 to produce H_2 at industrial scale:

- **A** Steam Methane Reforming plant
- **B** Steam Methane Reforming with a Carbon Capture and Storage (CCS) system
- **C** Alkaline electrolysis with dedicated renewable electricity production (offshore wind power plant)

[A] Cf. Part 2 of our Hydrogen Series, analysing EU's ambitions for hydrogen production by 2030[2].
[B] Cf. Part 1 of our Hydrogen Series, comparing the different hydrogen production technologies[3].

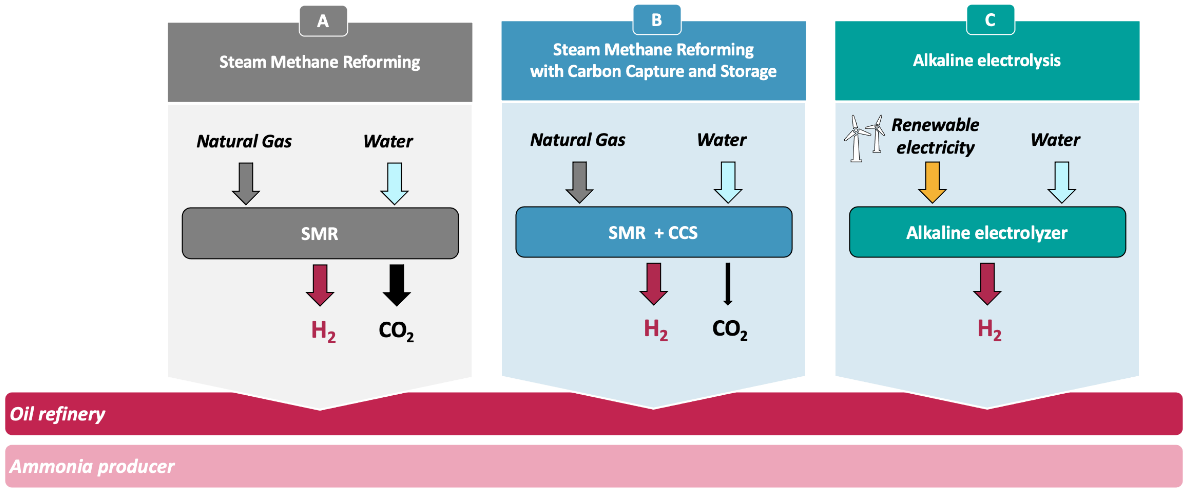


Figure 1 – Hydrogen production scenarios considered

For each scenario, the levelized cost of hydrogen (LCOH) for a typical H_2 users, either a large refinery or an ammonia plant requiring both 80 ktons of H_2 annually, has been calculated - considering an investment date in 2025 under European conditions. A first simulation (base case) has been conducted in an economic configuration where:

- Electrolyzers CAPEX = 800€/kW (C1) or 1050€/kW (C2)
- European natural gas price = 40 €/MWh
- European renewable electricity price (LCOE) = 45€/MWh (offshore wind)
- European CO_2 allowance price (ETS market) = 100€/ton of CO_2
- Electrolyzers capacity factor = 51%
- Discount rate (WACC) = 8%

The sensitivity of LCOH to the above-mentioned parameters is then assessed and discussed. Assumptions can be found at the end of this document (see detailed methodology and discussion on key assumptions in the full version of this study).

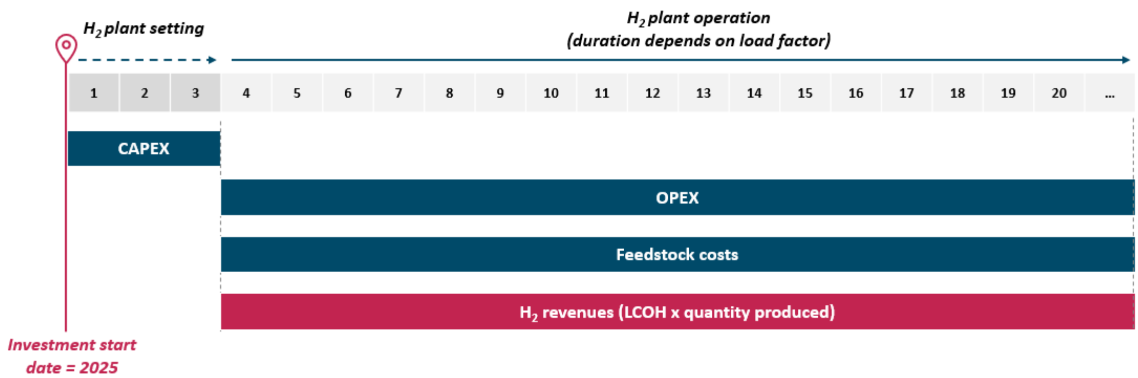


Figure 2 – Costs and revenues over the hydrogen plant lifetime for LCOH calculation

2. LCOH comparison in base case

In the base case, H_2 production cost by SMR + CCS technology (Scenario B) is close to the production cost of SMR without carbon capture system (Scenario A). They are both significantly dependent from natural gas prices (~60% of total LCOH at 40€/ MWh) but ETS system at 100€/ton of CO_2 seems to compensate for the additional CCS CAPEX and OPEX.

However, H_2 production cost from alkaline electrolysis is evaluated to be 15 to 25 % higher than SMR (Scenario A) and 10% to 20% higher than SMR+CCS (Scenario B).

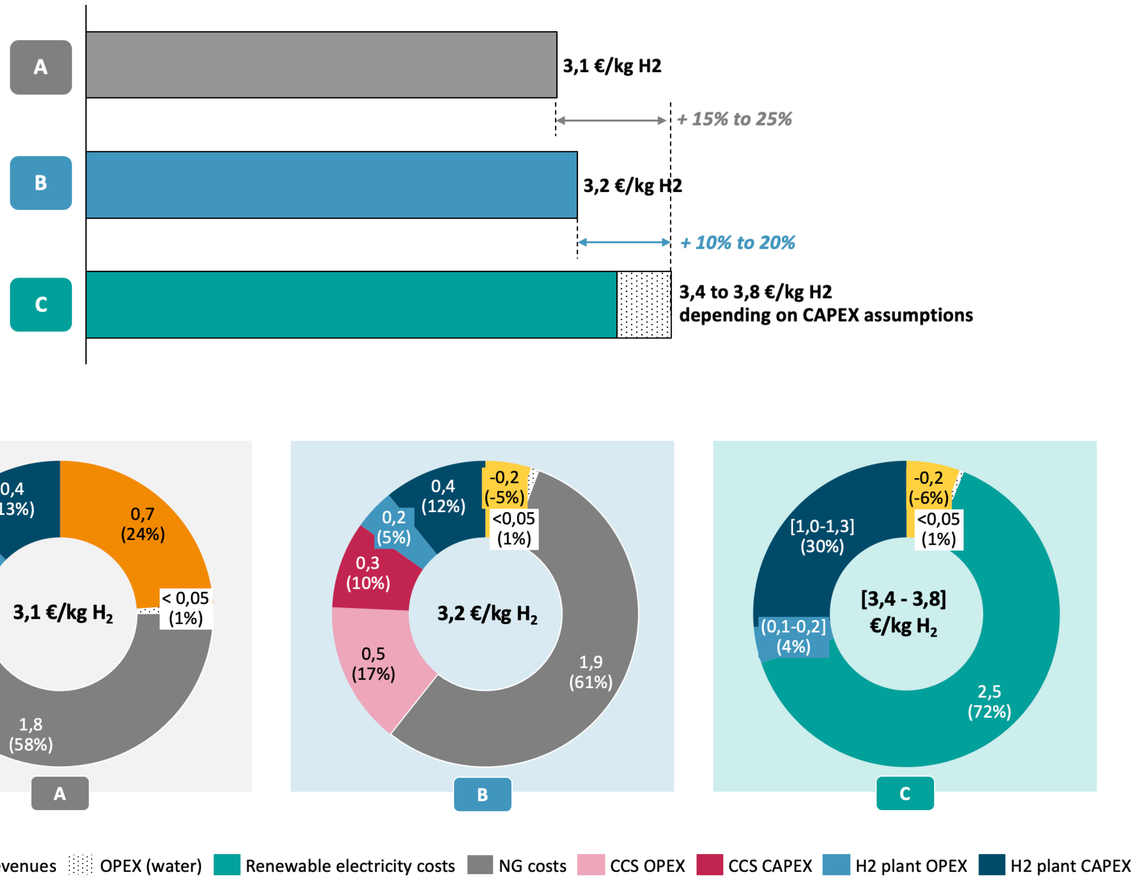


Figure 3 – Base case LCOH in scenario A, B and C

In the scenario C, renewable electricity cost is the main contributor to the LCOH (72%) before electrolyzer CAPEX (~30%). Nevertheless, R&D and industrial efforts to support electrolysis technology improvement and large-scale deployment are a major driver of green hydrogen competitiveness.

3. Switching conditions

LCOH sensitivity to electrolyzer CAPEX demonstrates that the alkaline electrolyzer CAPEX should reach 500 to 600 k€/KW by 2025 to incite current H_2 users to switch – other parameters unchanged (cf. Fig. 3). However, the latest IEA Global Hydrogen review[4] shows that current CAPEX required to install electrolysers are still higher than expected in the Net Zero Emissions by 2050 scenario (1700 for ALK to 2000 $/kW for PEM in 2023 compared to 900 to 1000 $/kW forecasted in 2025) mainly due to an increase in materials and labour costs with significant discrepancies between manufacturing countries (basically cheaper in China than in Europe or North America). Electrolyzers CAPEX decrease is still expected thanks to economies of scale (e.g., PEM electrolyzer gigafactory announced by Siemens and Air Liquide in 2023) but several technological and industrial challenges should be tackled in the very coming years to fulfill this ambition:

- **Reduce the dependency to scarce materials especially platinum and cobalt for alkaline technology and Teflon and iridium for PEM,**
- **Increase the size of facilities to reduce the cost of balance of plant,**
- **Improve automatization and standardization of electrolyzer manufacturing,**
- **Secure ramp-up of the whole supply chain.**

In this context and given the current uncertainty about electrolysis CAPEX forecast by 2025, we consider a range from 800 to 1050 €/kW as base case assumption in all the following sensitivity analyses.

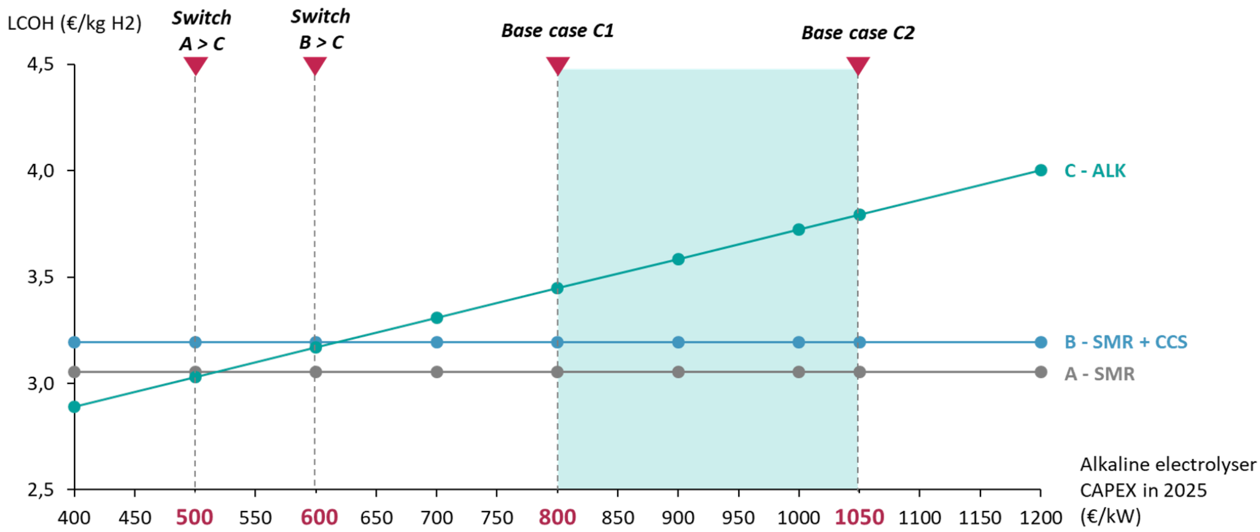


Figure 3 – Base case LCOH in scenario A, B and C

The LCOH sensitivity analysis to electricity supply price (all other parameters are unchanged compared to base case) shows that LCOE should drop down to 30-40€/MWh to reach the switching point to Alkaline scenario (cf. Fig. 4).

Dropping to that level with offshore wind seems to be more a target for 2035 – 2050. Currently, the average LCOE of newly commissioned offshore fixed bottom wind farms in Europe in 2021 was around 60€/MWh, with a 2030 target of 35 to 65€/MWh. Though, it is possible to target a LCOE of 30€/MWh with an ad hoc combination of photovoltaic and onshore wind power. However in this case, without adding storage capacity, the capacity factor of the electrolyzer would also decrease in average and be more volatile. It would have two impacts:

- a direct one, as H_2 plant CAPEX per kg H_2 would increase (even though total CAPEX cost would stay significantly inferior to renewable electricity cost),
- an indirect one, as capacity factor volatility may lead to a higher cost over the ALK electrolyzer lifecycle (shorter lifetime, higher maintenance costs).

Another way to reduce the impact of LCOE on competitiveness is to improve process energy efficiency through electrolyzer technological development. In the Scenario C, 55 kWh/kg H_2 have been considered in 2025 while the 2050 target is close to 45 kWh/kg H_2 (see assumptions tables p.11). This strategy would drive both technological and product roadmap orientations of the industrial players.

Setting renewable power plants to directly power electrolyzers near existing refineries or ammonia production plants implies obvious operational challenges. Physical Power Purchase Agreement (PPA) is an alternative compliant with European definition of "renewable hydrogen" (even off site PPA under temporal and geographical conditions). From an economic perspective, this mechanism enables the hydrogen producer to build its investment plan with less exposure to electricity price volatility and thus reduces the financial risks of the project. From an industrial perspective, PPAs (especially off site) widen the range of possibilities of renewable electricity plant locations and allow the structuration of the value chain around two specialist players: hydrogen producers and renewable electricity producers.

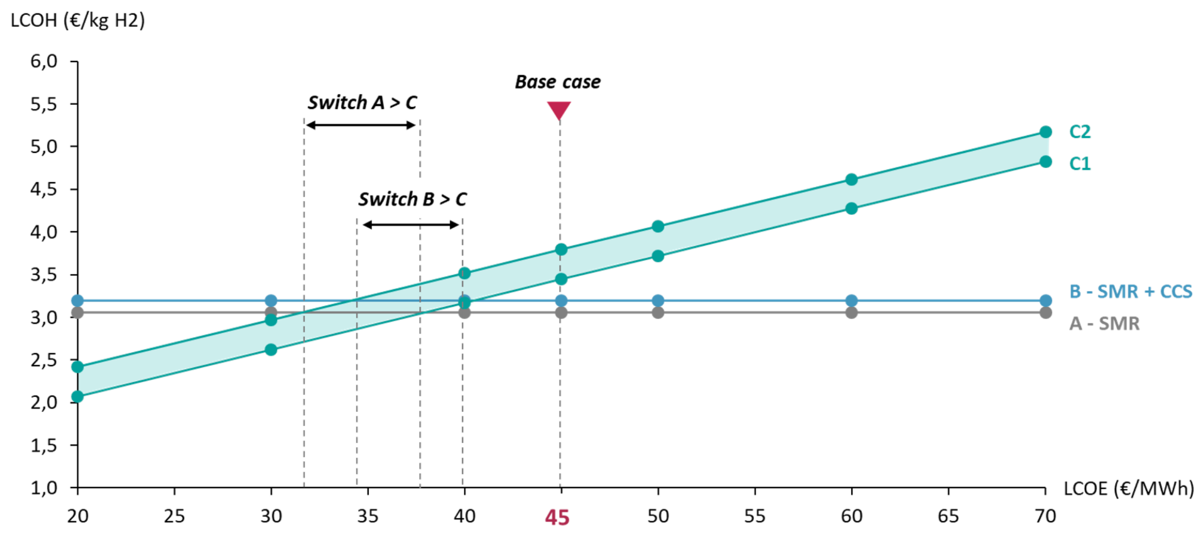
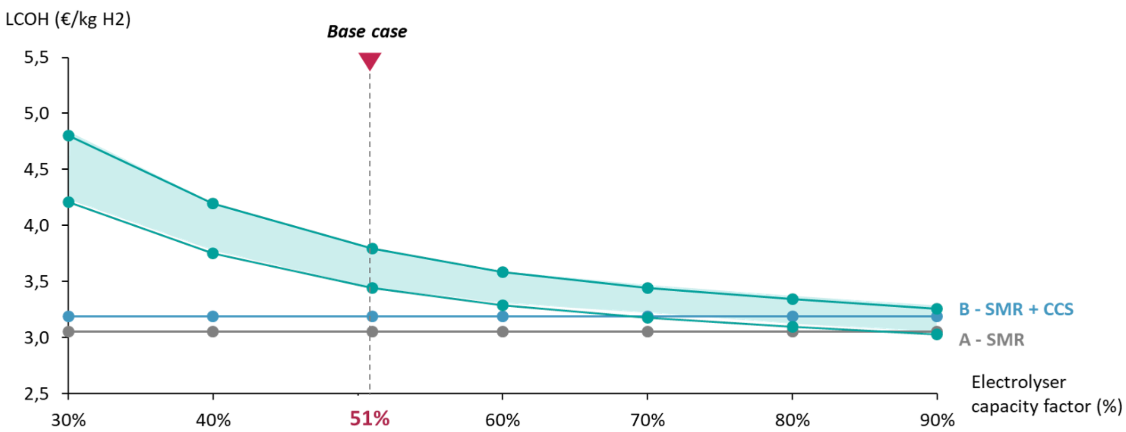


Figure 4 – LCOH sensivity to electricity supply price

The decrease of CAPEX due to a higher electrolyzer capacity factor is not sufficient to reach the LCOH of the SMR-based hydrogen production scenarios (Fig. 5). Besides, some of the electricity supply models that enable higher electrolyzer capacity factors **might require additional CAPEX** (e.g. electricity storage).

An alternative to complementary storage is to supply all or part of the electricity from the grid. However, not all grid supply configurations are compliant with the current European renewable hydrogen definition (cf. EU Delegated Acts I and II adopted in February 2023[5]). Indeed, **appropriate renewable energy capacities** (solar, wind or hydro) **must be added to the grid** (possibility off site and through physical Power Purchase Agreement) **and fulfill temporal and geographical correlation criteria.** Even if the hydrogen production plant is connected to a grid where the CO_2 emissions intensity is below 18 gCO_2e/MJ (in France for example), renewable PPA with temporal and geographical correlation must be set by the hydrogen producer[6].



Electrolyser capacity	1710 MWe	1300	1000	850	720	630	560
Electrolyser lifetime	57 years	43	35	30	26	23	21

Figure 5 – LCOH sensivity to electrolyzer capactity factor

High natural gas prices (45 to 58 €/MWh) would be required over the investment period to reach the cost of electrolysis-based hydrogen production (Scenario C) and then incite current users to switch from a strict economic standpoint.

Indeed, Natural gas (NG) supply in Europe was significantly affected by the Russia-Ukraine war in the past 2 years leading to **an unprecedent increase in supply costs** (133€/MWh in average in 2022 compared to 12 €/MWh in 2020).

Then, natural gas prices dropped down to 42 €/MWh on average over the first semester of 2023. Even though dynamics is difficult to forecast, **tensions should remain on this market over the next years leading to high price level expectations.**

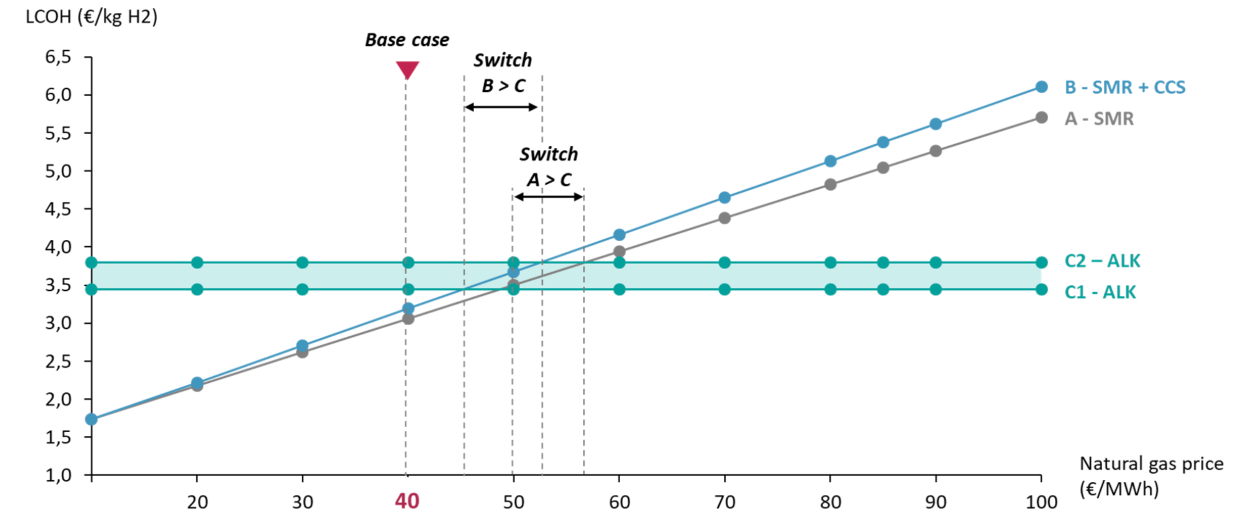


Figure 6 – LCOH sensivity to natural gas price

The LCOH sensitivity analysis to ETS market demonstrates that the CO_2 allowance price should reach 150-180 €/kg CO_2 (x2 compared to S1 2023) to make electrolysis-based hydrogen production (Scenario C) LCOH competitive with SMR-based hydrogen (Scenario A). Even though the CO_2 price has strongly increased since 2020 (from 20 €/ton of CO_2 to 100 €/ton of CO_2 in February 2023) and that the European Commission intends to stronger leverage carbon regulation to support its decarbonation policy for the next decade[7], current H_2 users don't have enough visibility on CO_2 prices evolution to secure financially viable investment plan.

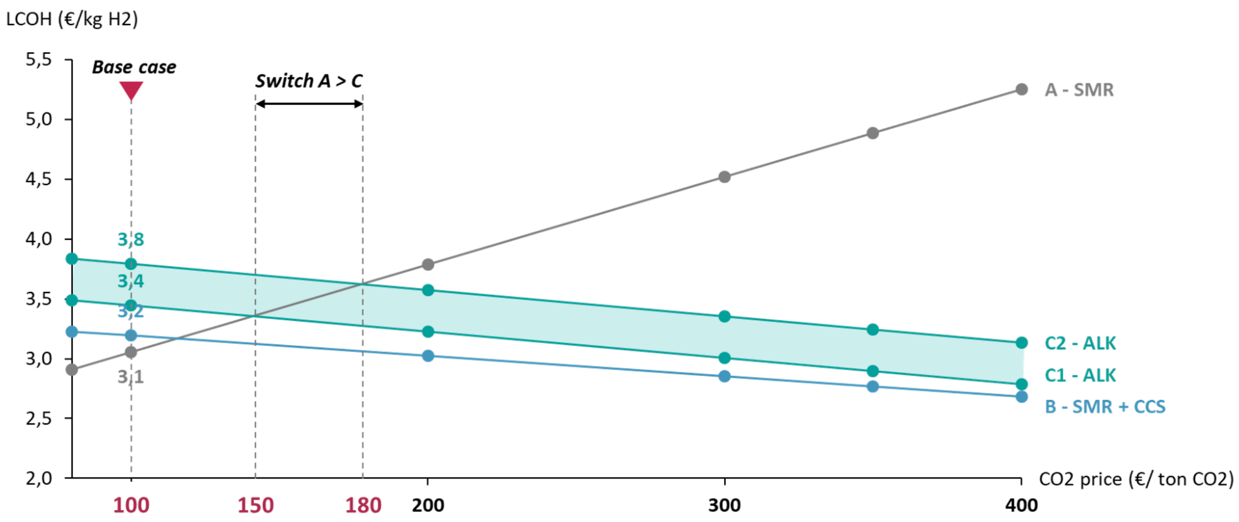


Figure 7 – LCOH sensivity to CO_2 price

The LCOH sensitivity analysis to discount rate (WACC) demonstrates that the risk discrepancy between the SMR-based and the electrolysis-based scenarios should be out of standard to be the only switching driver. **While similar discount rates have been considered in the scenarios A, B and C (8% in base case), different reasons could justify a varying WACC between these scenarios. The lower technology readiness level of alkaline electrolysis compared to steam methane reforming could have been considered as an additional risk factor. On the contrary, current attractiveness for "green" investments on financial markets could argue for lower WACC in Scenario C. Others factor could also influence the WACC such as the financial strength of the enterprise, the plant location, or the level of state guarantees on loans.**

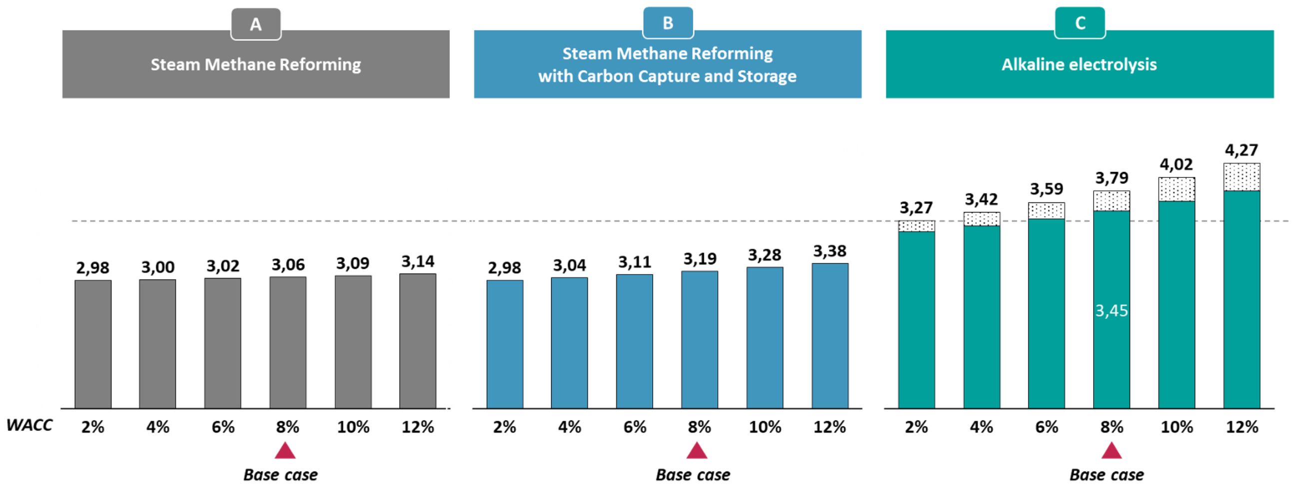


Figure 8– LCOH sensivity to discount rate (WACC)

CONCLUSION

1 The industrial switch to “green” hydrogen production technologies by the end of 2030 compared to Steam Methane Reforming technology will not be triggered only by the economic rationale.

2 Innovative business models to create additional revenue streams from hydrogen production are yet to be identified (e.g. compensation for available electricity capacity, electricity sale during peak hours…). The over-cost of “green” hydrogen could be addressed through the design of appropriate risk sharing model (in volume and price) between hydrogen producers, hydrogen consumers and governments to foster the “green hydrogen” projects ramp-up.

3 The main lever for renewable hydrogen LCOH reduction relies on Europe’s ability to produce sufficient and competitive renewable electricity by the end of 2030. To meet the volume objective, the industrial challenge of renewable energy production capacity ramp-up (wind and solar) would have to be addressed as well as the political proritization of renewable energy uses between hydrogen production and European electricity mix decarbonization (cf. Part 2 of our Hydrogen series). Evolutions of the European carbon allowance policy (ETS and CBAM) could facilitate the switch if it results in a significant increase of carbon market price over the next decade (at least 200 €/ ton CO_2).

4 In this context, low-carbon H_2 industrial producers would face strategic issues in terms of value chain positioning to secure a viable business model: should they vertically integrate renewable electricity production capabilities? Would H_2 industrial production specialists emerge from electricity pure-players, gas pure-players or from ad-hoc joint-ventures?

SCENARIOS ASSUMPTIONS

Key parameters for scenario A	Assumptions [8]
Technology	Steam Methane Reforming (SMR)
Carbone Capture and Storage system	No
Plant capacity factor	90%
Plant lifetime	20 years
Plant setting lead time	3 years
Process energy efficiency (LHV)	76% [8]
Unit CAPEX for SMR plant (full system)	760 €/ kW H_2 [9]
SMR plant OPEX	4,7% of CAPEX per year [8]
Water consumption	7 L/kg H_2
Water cost	4 € / m^3
H_2 transport and distribution cost	0 € (use of existing pipes < 15 km)

Key parameters for scenario B	Assumptions [10]	vs. scenario A
Technology	Steam Methane Reforming (SMR)	=
Carbone Capture and Storage (CCS) system	Yes	=
Plant capacity factor	90%	=
Plant lifetime	20 years	=
Plant setting lead time	3 years	=
Process energy efficiency (LVH)	69% [8]	←
Unit CAPEX for SMR plant (full system)	760 €/ kW H_2 [9]	=
OPEX	4,7% of CAPEX per year [8]	=
Water consumption	7 L/kg H_2	=
Water cost	4 € / m^3	=
H_2 transport and distribution cost	0 € (existing pipes < 10 km)	=
CCS CAPEX	642 €/kW H_2 [9]	←
CCS OPEX	3% of CAPEX per year [9]	←
CO_2 transport, storage and treatment	50 €/t CO_2	←
CO_2 capture rate	90% [8]	←

Key parameters for scenario C	Assumptions [8]
Technology	Alkaline electrolyser
Plant capacity factor (with overbuilding)	51% [11]
Electrolyser lifetime	35 years (140 000 hours) [12]
Plant setting lead time	3 years
Stack lifetime	19 years
Process energy efficiency – 2025	55 kWh/kg H_2 [12]
Unit CAPEX for electrolysers (full system) - 2025	800 €/ kW (C1) or 1050 €/kW (C2) [13]
Stack replacement CAPEX – 2040	200 €/ kW
OPEX	1,5 % of the CAPEX per year [4]
Water consumption	10 L/kg H_2
Water cost	4 € / m^3
Transport and distribution cost	0 € (existing pipes < 10 km)
Capacity factor of wind offshore dedicated farm	46%
LCOE from wind offshore plant	45 €/MWh

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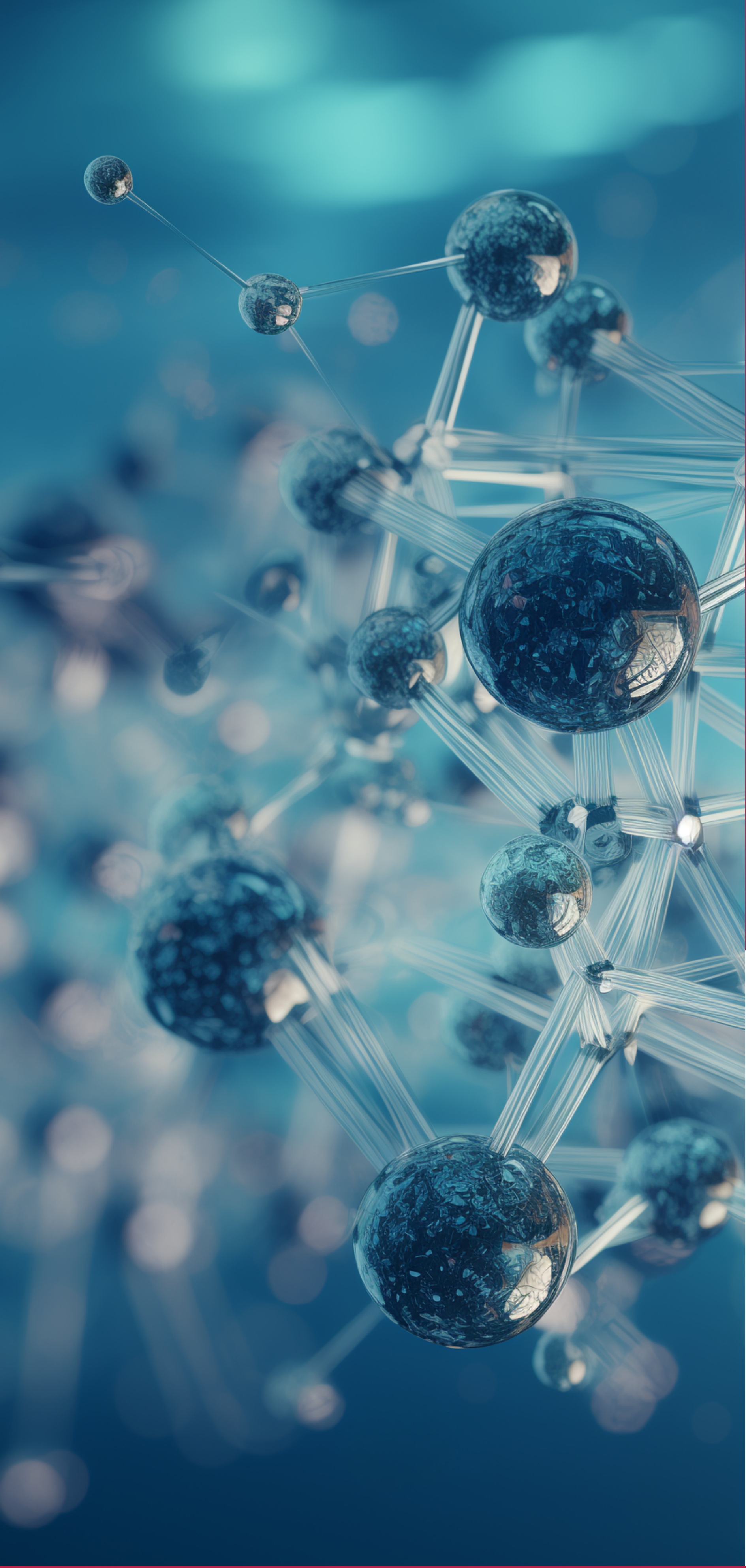

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