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COLDSPARK DRIVEN ENERGY AND COST-EFFICIENT METHANE CRACKING FOR HYDROGEN PRODUCTION

D6.4 Techno-economic assessment

ColdSpark project partner	IREC-CERCA
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Nature of the deliverable

R	**Document, report (excluding the periodic and final reports)**	☒
DEM	Demonstrator, pilot, prototype, plan designs	☐
DEC	Websites, patents filing, press & media actions, videos, etc.	☐
DATA	Data sets, microdata, etc.	☐
DMP	Data management plan	☐
Ethics	Deliverables related to ethics issues.	☐
SECURITY	Deliverables related to security issues	☐
Other	Software, technical diagram, algorithms, models, etc.	☐

Dissemination level

PU	**Public — fully open (automatically posted online on the Project Results platforms)**	☒
SEN	Sensitive — limited under the conditions of the Grant Agreement	☐

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The ColdSpark® project will validate a novel non-thermal plasma technology to produce hydrogen at a large scale from methane, with overall process efficiency of 79%, achieving a conversion rate of 85% aiming at zero CO_2 emissions. This will be achieved by designing an industrial-relevant reactor that leverages the best features of the non-thermal plasma technologies, gliding arc and corona discharge, to ensure high efficiency and scalability. The innovation addresses for the first time the critical step of matching the reactor with a pulsed power supply. It enables a perfect fine-tuning of the cracking process parameters, to find the right electron density and energy distribution in the plasma reactor, to maximise energy efficiency. The up-and downstream gas management will be optimised to further contribute to the system's compatibility with the existing infrastructure. The project will develop and test a novel plasma reactor at a lab scale and validate it in conjunction with the power supply at a large scale, pursuing the industry's most power-efficient generation of hydrogen alongside high-value carbon. The technology will assess its application for both, natural gas and biomethane producers. A low energy cost (< 15 kWh/kg H_2 produced) without the need for catalysts and water, makes the proposed solution the most cost-competitive, environment-friendly, and less complex to implement. The reactor design and modularity bring lower CAPEX and OPEX and make it easily scalable and flexible. The project gathers the expertise of a mix of academic, research, and industrial partners from five countries, which bring both outstanding research and topic competence, as well as knowledge and access to the solution for end-user industries.

ColdSpark® is built on a strong consortium of 7 partners from Norway, Spain, Bulgaria, Germany, and the UK with SEID AS as Coordinator.

More information about the project can be found at: http://www.coldspark.eu/

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EXECUTIVE SUMMARY

The economic performance of the ColdSpark® NTP MS technology was analysed through an LCC and TEA analysis. The levelized cost of hydrogen (LCOH) was evaluated across different methane conversion efficiency scenarios (8.2, 20, 40, 60, 80 and 100%).

The 60% methane conversion efficiency achieves the lowest hydrogen price of 3.45 €/kgH_2, as a trade-off between lowering OpEx and CapEx and the reduced revenue from byproducts that occurs when methane conversion efficiency increases.

The obtained LCOH is then compared with the benchmarking hydrogen production processes. The ColdSpark® technology, with an LCOH of 3.45 €/kgH_2, is competitive with PEMEL (6.55 €/kgH_2) and reforming processes with CCS (SMR CCS 3.69 €/kgH_2 and ATR CCS 3.61 €/kgH_2), while still a slight increase is observed in comparison with SMR (2.93 €/kgH_2).

The LCOH identified changes according to the assumptions defined in the economic analysis; for this reason, a sensitivity analysis of the ColdSpark® LCOH is performed by varying the natural gas and electricity price, the CapEx, carbon selling revenues and the reactor power requirements.

The ColdSpark® process shows potential as low-cost hydrogen technology(LCOH ~2 €/kgH_2), when the geographical location is carefully selected according to the NG (~ 0.6 €/kg) and electricity prices (0.04 €/kWh), and when the carbon byproduct has high market value (1.50 €/kgC).
However, from the sensitivity analysis performed, it emerges that the ColdSpark® process can be competitive with the emerging low carbon hydrogen technologies only if the process parameters are optimised; specifically, methane conversion efficiency of at least 20% and reactor electricity consumption in alignment with the EU goal (15kWh/kgH_2) are required.

In future studies, experimental analysis should be carried out to validate the simulation results presented in this work. In particular, characterisation of the carbon byproduct is needed to determine its allotropic form and assess its potential applications. Additionally, the recirculation of acetylene within the splitting loop, rather than its separation, may influence the process economics, but this option could not be examined due to the current lack of experimental data. The reactor energy requirements should be analysed, and its alignment with the energy optimisation proposed in this study verified. Finally, conducting site-specific economic assessments will be crucial, given the pronounced variability in electricity and natural-gas prices across the EU.

ABBREVIATIONS

Abbreviation	Meaning

CapEx	Capital cost
CCS	Carbon capture technology
CO_2t&s	CO_2 transport and storage
CPCI	Chemical Plant Cost Index
ETS	Emission trading system
GHG	Greenhouse gases
HICPI	Harmonised Index of Consumer Price Index
LCC	Life cycle cost
LCI	Life cycle inventory
LCOH	Levelized cost of hydrogen
MS	Methane Splitting
NG	Natural gas
NTP	Nom-Thermal Plasma
NTP	Non-thermal plasma
OpEx	Operative cost
PSA	Pressure Swing Adsorption
Rev	Revenues
TEA	Technoeconomic analysis
VAT	Value-added tax

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1. INTRODUCTION

This report is part of Task 6.3 outcomes and focuses on conducting life cycle cost (LCC) and techno-economic assessment (TEA) of ColdSpark® Non Thermal Plasma (NTP) Methane Splitting (MS) technology. The analysis is conducted at an industrial scale with a reactor feed capacity of 2555 kg/h. The TEA is performed to evaluate ColdSpark® economic profitability and strategies for its industrial development. The TEA is based on ASPEN simulations developed by WP5 and based on SEID laboratory experimental data.

2. ECONOMIC PERFORMANCE: LCC AND TEA METHODOLOGY

This study evaluates the economic performance of the ColdSpark® technology adopting the Life Cycle Cost (LCC) and TEA (Techno-economic) methodologies. The economic analysis was performed on ColdSpark® at an industrial scale with a reactor feed capacity of 2555 kg/h, comparable to electrolyser hydrogen production capacity. The potential profitability of hydrogen production technologies was evaluated by estimating the levelized cost of hydrogen (LCOH), including the discounted lifetime costs. LCOH is defined in Equation (1). It computes the sum of expenditures/plant costs (CapEx), operating expenditures costs (OpEx), CO_2 transport and storage cost (CO_2t&s) and subtraction of the revenues from byproducts and allowances sales (Rev), emission trading system allowances cost (ETSa), divided by the total energy yield of the plant under consideration over its lifetime (n) and discounted to the reference year using a discount rate (r):

$$LCOH = \frac{\sum_{t=1}^{n} \frac{CapEx_t + OpEx_t + CO2t\&s_t + ETSa_t - Rev_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{H2t}{(1+r)^t}} \qquad (1)$$

Table 1 summarises the main economic assumptions adopted in the technoeconomic analysis. The real discounted rate identified is 6%, and it is intended as the most accurate value for the European context [1].

Table 1 Economic parameters

Parameter	Value	Ref
Operational plant lifetime (years)		[1,2]
Reforming processes	30	
ColdSpark®	20	
Capacity factor (%)	90	[2]
Annual operation time (h)	8760	[2]
Real discount rate	6%	[1]
Reference year	2024	
Number of operator shifts	5	[3]

Labour cost (€/person/h)	33.5	[4]
Natural gas price (€/kg)		[5]
Band I3	0.91	
Band I6	0.56	
Electricity prices excluding VAT and other recoverable taxes (€/kWh)		[6]
Band ID	0.14	
Band IE	0.14	
Band IF	0.12	
Band IG	0.11	
Water (€/m^3)	3.21	[7]
Carbon black (€/kg)	0.5	[8]
Acetylene (€/kg)	2.9	[9]
CO_2 transport and storage cost (€/tCO_2)	100	[10]
CO_2 price (€/tCO_2)	85	[10]

The price of natural gas and electricity was sourced from Eurostat, considering the European Union media [5,6]. The price excludes value-added tax (VAT) and other recoverable taxes and corresponds to the non-household 2024 band consumption in alignment with the process annual requirement. For water, the median EU value was adopted and calculated from the national values of the European Federation of National Associations of Water Services (EurEau) [7]. For other consumables (catalyst and other chemicals), the prices provided by Lewis et al [11] were converted to EUR and adjusted to the average 2024 European Harmonised Index of Consumer Price Index (HICP) [12]. For the labour cost, the European Union media value from Eurostat was applied [4]. Values refer to compensation of employees plus taxes minus subsidies for 2024. The revenues or costs from the ETS system was calculated considering a CO_2 price of 85 €/ton CO_2[10].

The ColdSpark® economic profitability was compared with the main hydrogen production process technologies: Steam Methane Reforming (SMR), SMR with carbon capture and storage (CCS), Autothermal Reforming with CCS (ATR CCS) and Polymer Exchange Membrane water electrolysis (PEMEL).

A sensitivity analysis of the ColdSpark® process on the natural gas and electricity price, carbon revenues, reactor energy consumption and CapEx was conducted.

TECHNICAL AND ECONOMIC ASSUMPTIONS

The process technical assumptions defined in this study are described in the following paragraphs and divided into Reforming Process, PEMEL and Non-Thermal Plasma ColdSpark® technology.

TECHNICAL ASSUMPTIONS

REFORMING PROCESSES

The technical parameters of the reforming processes (SMR, SMR CCS and ATR CCS) assumed in this study are summarised in Table 2 and sourced from the techno-economic performance study of the National Energy Technology Laboratory [11], in alignment with the H2A model [2].

Table 2 Technical parameters for reforming processes (SMR, ATR, ATR CCS) from Lewis et al. [11].

Parameter	SMR	SMR CCS	ATR CCS
Capacity (tH_2/h)	20.15	20.15	27.50
Electricity demand (kWh/kgH_2)	0.13	1.50	3.49
NG demand ($kg/kg\ H_2$)	3.53	3.75	3.52
Water demand ($kg/kg\ H_2$)	15.80	24.15	24.22
Direct CO_2 emission ($kg/kg\ H_2$)	9.30	0.38	0.51
CO_2 capture efficiency (%)		96.2	94.5

[a] with currency and overtime changes calculation

PEMEL

The PEMEL technical are defined in Table 3 and sourced from the European Hydrogen Observatory [1]. Together with hydrogen, the water splitting reaction produces oxygen. The oxygen market is already well established, with many uses in industry, such as blast furnaces and glass melting. However, electrolysers selling oxygen would face strong competition from air separation units that produce oxygen at a very low price [13]. Currently, no electrolysis project is selling the oxygen as a byproduct [13]. For this reason, the revenues from oxygen sales are excluded.

Table 3 Technical parameters for PEM sourced from European Hydrogen Observatory [1]

Parameter	PEM
Nominal load (kW)	20000
Electricity demand (kWh/kgH_2)	53.30
Stack durability (h)	60000
Full load hours (h)	4000
Annual degradation rate (% per 1000 hours)	0.19

COLDSPARK®

The technical assumptions for ColdSpark® industrial scale are reported in Table 4.

Table 4 ColdSpark© performance assumptions across the methane conversion efficiency scenarios.

		Methane conversion efficiency scenarios					
	Unit	8.2%	20%	40%	60%	80%	100%
Methane	(m^3/kgH$_2$)	4.57	4.52	4.44	4.29	4.29	4.22
Electricity	(kWh/kgH$_2$)	23.46	20.76	19.50	19.50	19.34	19.24
Carbon	(kg/kgH$_2$)	1.78	1.87E+00	2.01E+00	2.15E+00	2.29E+00	2.44E+00
Acetylene	(kg/kgH$_2$)	1.80	1.65E+00	1.43E+00	1.21E+00	9.99E-01	7.90E-01

For industrial upscale the reactor feed capacity of 2555 kg/h is selected to be comparable with electrolyser capacity. The study reports six scenarios in which the reactor efficiency is varied from 8.2 % to 20%, 40%, 60%, 80% and 100%. The data are sourced from the ASPEN simulation elaborated in the ColdSpark® project and are based on the experiments performed in the SEID laboratory. The SEID setup does not include the fuel gas recirculation, and the following assumptions are made for scaling:

- Experimental H_2 concentrations are based on test without recycling, while simulations include recirculation.
- Simulation includes the acetylene removal from the system.
- The plasma reactor energy requirements are optimised using the EU goal value defined in the last research call of 15 kWh/kgH$_2$ [14]
- Energy for the whole system is calculated as the sum of energy required in the splitting reactor and compression for PSA. The energy for the cooling and acetylene removal is out of the scope of this study.
- Energy consumption for H_2 compression from 3 bar to 25 bar is calculated by applying the formula proposed by the UK Low Carbon hydrogen guideline [15]. The energy consumption from 25 to 200 bar is sourced from Ecoinvent v3.11 [16].
- PSA recovery of H_2 is set at 60% ad H_2 purity is set at 96.23 % as recommended by WP2.

ECONOMIC ASSUMPTIONS

REFORMING PROCESSES CAPEX & OPEX

The CapEx of the reforming processes (SMR, SMR CCS, ATR CCS) was calculated in alignment with Shokrollahi et al. [3]. It includes the equipment cost, delivery cost, installation, engineering and supervision, construction overhead, start-up cost, and working capital. The calculation has been performed following the correlation summarized by Shokrollahi et al. [3] and in alignment with the Chemical Process and Design Integration book [17] and Plant Design and Economics for Chemical Engineers book [18].

The equipment costs are sourced from the National Energy Technology Laboratory TEA [11]. Firstly, monetary conversion is adopted [19], then to accommodate changes over time, a chemical plant cost index (CPCI) according to equation 1 has been applied:

$$C = C_{ref}\ x\ \left(\frac{CPCI}{CPCI_{ref}}\right) \quad (1)$$

where C is the cost needed for the total analysis. The German CPCI, provided by the German chemical industry association Verband der Chemischen Industrie (VCI), has been selected in this study [20]. This choice is adopted considering the absence of a unique European value.

OpEx includes raw materials, utilities, operating labour cost, maintenance cost, overhead costs, property insurance and taxes and general expenses. Raw material and utility consumption have been calculated based on technical assumptions.

The correlation used for maintenance cost, overhead costs, property insurance and taxes and general expenses calculation is sourced from Shokrollahi et al. [3], and in alignment with Perry's Chemical Engineer handbook [21] and Process design principles: synthesis, analysis, and evaluation [22]. The total number of operators was estimated using the equation provided in Perry's Chemical Engineers Handbook [21].

PEMEL CAPEX & OPEX

For PEM technology, technoeconomic data are sourced from the European Hydrogen Observatory [1] and summarised in Table 5.

CapEx cost is estimated by the European Hydrogen Observatory [1], where data from projects located in EU27, EFTA or the UK, interviews with developers and other industry sources are used [1]. It covers all the costs related to the production facility, including equipment and infrastructure costs, land acquisition (CapEx without stack replacement), and stack replacement costs (Equation 2):

$$CapEx = CapEx\ without\ stack\ replacement + stack\ replacement \quad (2)$$

OpEx is the sum of electricity cost, grid fees costs, electricity taxes costs, and other OpEx, including maintenance, water consumption et. (Equation 3):

$$OpEx = Electricity\ cost + grid\ fees\ + taxes\ + Other\ OpEx \tag{3}$$

Electricity prices were calculated differently from fossil fuel processes technologies, in alignment with the European Hydrogen Observatory. Prices for electricity considers only the 4,000 lowest price hours per country in 2022, summing then the grid fees and electricity taxes prices. European Union media data are reported in Table 5.

Table 5 Electricity, grid fees and electricity taxes EU median.

	Value	References
Electricity (€/MWh)	41.57	[1]
Grid fees (€/MWh)	17.85	
Electricity taxes (€/MWh)	8.55	

COLDSPARK® CAPEX & OPEX

The equipment cost of ColdSpark® technology includes primary feed system, plasma reactor, power supply, control system, carbon filter and collection PSA and compressor and assembling system. The price of the power supply and carbon filter and collection are sourced from the SEID laboratory scale data. The costs are then scaled up from the laboratory to the industrial capacity using the equation (4)

$$Cost_{ind} = Cost_{lab}\ x\ \left(\frac{Capacity_{ind}}{Capacity_{lab}}\right)^{n} \tag{4}$$

Where n is the scalability factor, equal to 0.6 for a generic chemical plant.

The remaining components cannot be scaled up from the laboratory scale, and following the expert's comments, costs are sourced from the reforming processes equipment cost of the H2A model for Current Distributed Hydrogen Production from Natural Gas [2]. The cost adapts for upscale and changes over time as described in Equations 1 and 4. CapEx and OpEx are then calculated following the methodology described for the reforming processes.

RESULT AND DISCUSSION

The results of the ColdSpark® NTP MS TEA and LCC analysis are presented in Figure 1. The LCOH is evaluated by varying the process methane conversion efficiency. Along with the scenario analysis, the CapEx and OpEx costs decrease as a result of the increased system capacity.

The CapEx contribution to the total LCOH varies from almost 32% to 8%. Simultaneously, the byproducts' revenues decrease as a consequence of the relative reduction in byproducts production.

The best scenario is represented by the 60% methane conversion efficiency scenario with LCOH of 3.45 €/kgH_2.

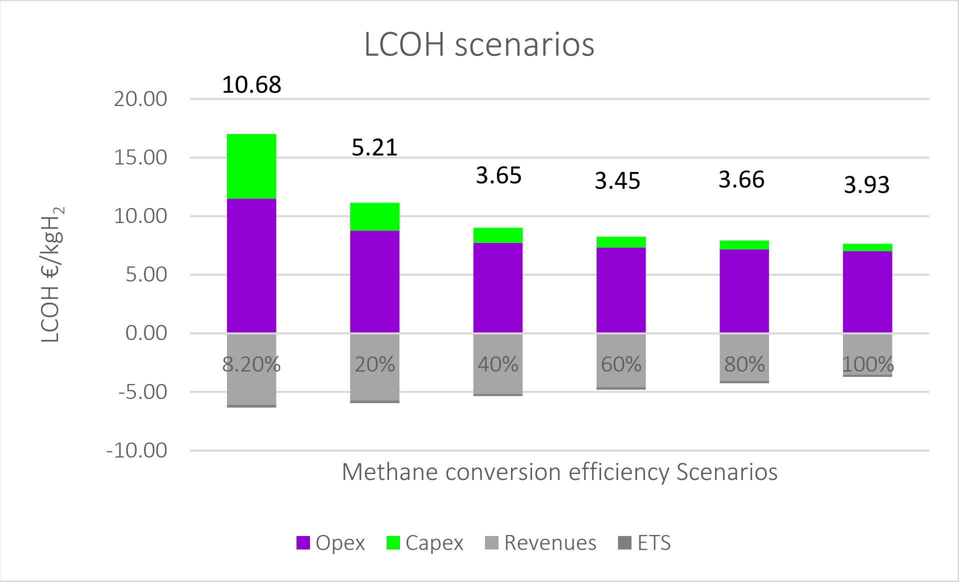

Figure 1 TEA results for ColdSpark® technology for methane conversion efficiency scenarios

This scenario is compared with the hydrogen benchmark production processes (**Error! Reference source not found.**). The ColdSpark® hydrogen price is competitive with PEMEL (6.55 €/kgH_2) and reforming CCS (3.76 €/kgH_2 and ATR CCS and 3.80 €/kgH_2 SMR CCS), which confirms that it is the most economically competitive low-carbon hydrogen production pathway.

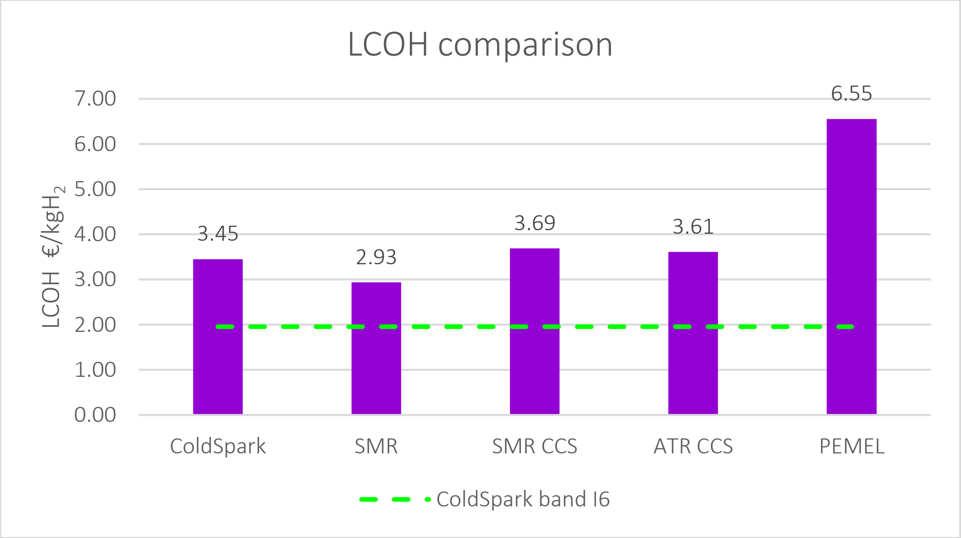

Figure 2 LCOH (€/kgH_2) of ColdSpark®, SMR, SMR CCS, ATR CCS and PEMEL.

Comparing ColdSpark® with the traditional hydrogen production process, even considering the CO_2 price of 85 €/ton, the SMR is confirmed to be the most economically advantageous (2.97 €/kgH_2). However, adopting a consumption scale comparable with reforming processes and considering an equal consumption band (I6), the ColdSpark® process can reach a lower LCOH than SMR, with an LCOH of 1.96 €/kgH_2.

The results obtained from the LCOH comparison are dependent on the technical and economic assumptions defined throughout the study. For this reason, the ColdSpark® economic sensitivity to natural gas and electricity price, carbon revenues, reactor energy consumption and CapEx, is analysed. The **Error! Reference source not found.** presents the results, illustrating the variation in LCOH baseline across the best and worst scenarios for all parameters evaluated.

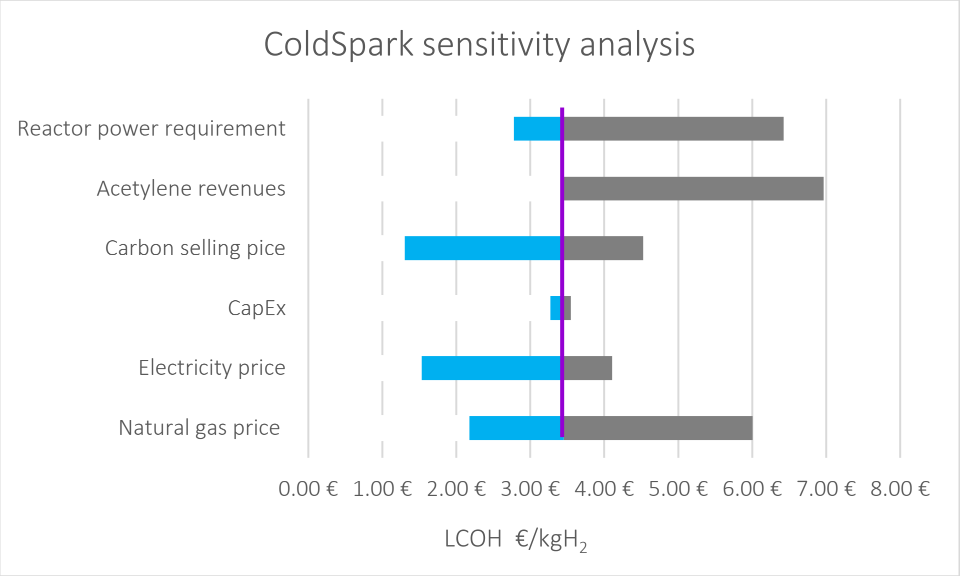

Figure 3 ColdSpark® LCOH (€/kgH_2) sensitivity analysis. The baseline LCOH (violet line) is shown alongside its variation under the best and worst scenarios for each parameter.

The technical assumption of this economic study is based on the industrial simulation modelled on the experimental data provided by the SEID laboratory throughout the project development. The reactor energy requirement was adjusted to reflect the system optimisation at an industrial scale and fixed at 15 kWh/kgH_2. The sensitivity of this assumption is verified by varying the reactor power input from 10.2 kWh/kg H_2, the value reported in the literature for NTP MS modelling [23], up to 34.5 kWh/kgH_2, which corresponds to the specific energy demand of the industrial-scale configuration from simulation (WP5). With increasing electricity consumption, the hydrogen reaches a cost of 6.43 €/kgH_2, exceeding the LCOH of reforming with CCS technologies.

In the sensitivity analysis, the NG and electricity prices are varied from the maximum to the minimum prices defined in the EU in 2024 in the corresponding consumption band of the ColdSpark® process.

The highest LCOH of 6.01 €/kg$H_2$is observed for the NG variation. In countries with high NG price fluctuation and elevated environmental tax on fossil fuel consumption, as Sweden and Finland, the ColdSpark® technology can reach LCOH comparable with electrolysis.

In the context where the NG prices are equivalent to 0.6 €/kg, which corresponds to the median value for high band consumption (I6), the LCOH reach 2.18 €/kgH_2. Further economic improvements, with a minimum LCOH of 1.53 €/kgH_2, occur with an electricity price of 0.04 €/kWh, corresponding to the Norwegian electricity market.

The most competitive price of 1.30 €/kgH_2 is observed, shifting the carbon selling price from 0.5 €/ton (carbon black price) to 1.5 €/ton graphite price range. This range could be further extended by 600€ per gram, if nanographene is produced [24] . The carbon allotropes obtained by the NTP MS reaction, therefore, have a determining role in the process of economic competitiveness. While considering no carbon revenues, the price increases to 4.53 €/kgH_2.

The CapEx is finally varied in a range of ±20%, observing an LCOH variation of 3.27-3.55 €/kgH_2. The CapEx sensitivity results evidence the marginal role of the CapEx for high methane conversion efficiency.

This sensitivity analysis reveals that in the EU market context, the NG and electricity prices, the process electricity consumption, and the carbon revenues have the greatest impact on cost fluctuations among the inputs analysed. The ColdSpark® economic competitiveness depended deeply on its geographical location, the carbon allotropic byproducts and the electricity consumption of the process.

CONCLUSION

This study assessed the economic performance of the ColdSpark® NTP MS technology through LCC and TEA. The process is analysed at an industrial scale using process simulation based on laboratory scale experiments, while the reactor energy requirements are independently fixed at 15 kWh/kgH_2, in alignment with the EU goals. The levelized cost of hydrogen (LCOH) is evaluated across methane conversion efficiencies ranging from 8.2% to 100%. A 60% conversion rate yielded the most competitive hydrogen cost at 3.45 €/kgH_2, balancing capital and operational expenditures with revenues from carbon and acetylene byproducts. When benchmarked against established hydrogen production routes, ColdSpark® is cost-competitive with PEM electrolysis (6.55 €/kgH_2), reforming processes with CSS (SMR CCS 3.69 €/kgH_2 and ATR CCS 3.61 €/kgH_2).

A sensitivity analysis revealed that ColdSpark® 's competitiveness depends strongly on natural gas and electricity prices, carbon revenues and process electricity consumption.

The LCOH can fall below 2.2 €/kgH_2, being comparable with SMR, under low-cost electricity conditions typical of Norway (0.04 €/kWh) or with a natural gas price of 0.6 €/kg, representative of

EU high-band industrial consumption. While a further price decrease to 1.30 €/kgH$_2$ can be achieved by selling carbon at 1.5 €/kg, corresponding to the graphite market price.

However, the sensitivity analysis reveals that the ColdSpark® economic competitiveness is deeply related to the process technical optimisation. The achievement of 20% methane conversion efficiency and a reactor electricity requirement of 15 kWh/kgH$_2$ is needed to be comparable with low-carbon hydrogen routes.

Future work should focus on experimental validation of the process assumptions, particularly the reactor energy requirement. In addition, the possible recirculation of the acetylene through the splitting loop, rather than its separation, could have a non-negligible effect on the process economic performance. However, it was not possible to evaluate this scenario due to the lack of experimental data. Site-specific economic analysis should be performed in the future, given the significant regional variability in electricity and natural-gas pricing across the EU, and carbon allotropic forms should be clearly defined to evaluate their revenue potential.

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