NPHyCo Final conference

The Business Case

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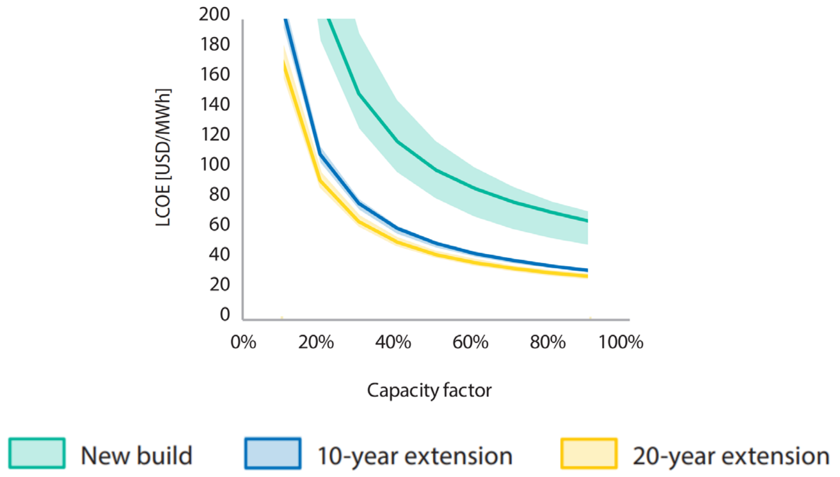
Nuclear Powered Hydrogen Cogeneration

THE NPPs CHALLENGES

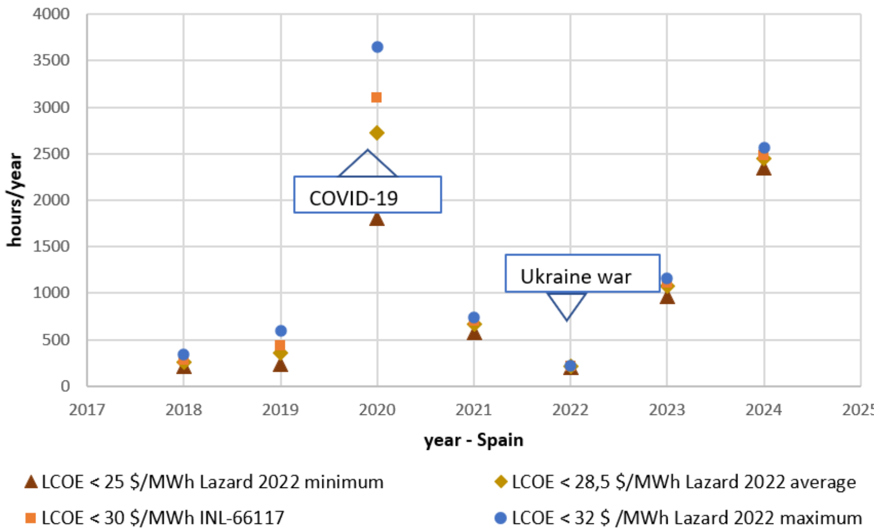
NPPs generate and provide **carbon-free electricity** in a continuous, stable and reliable basis. NPPs guarantee the electrical supply and at the same time, support the climate objectives.

The transition to climate neutrality is bringing about profound changes in an energy system with an increasingly higher penetration of variable renewables. In this new context, NPPs are expected to face **NEW CHALLENGES**:

- Increasing demand for flexible operation
- Greater number of hours with market prices close to zero, and thus below the NPPs production costs.



International Energy Agency (IEA), Nuclear Energy Agency (NEA), *"Projected Costs of Generating Electricity"*, 2020.



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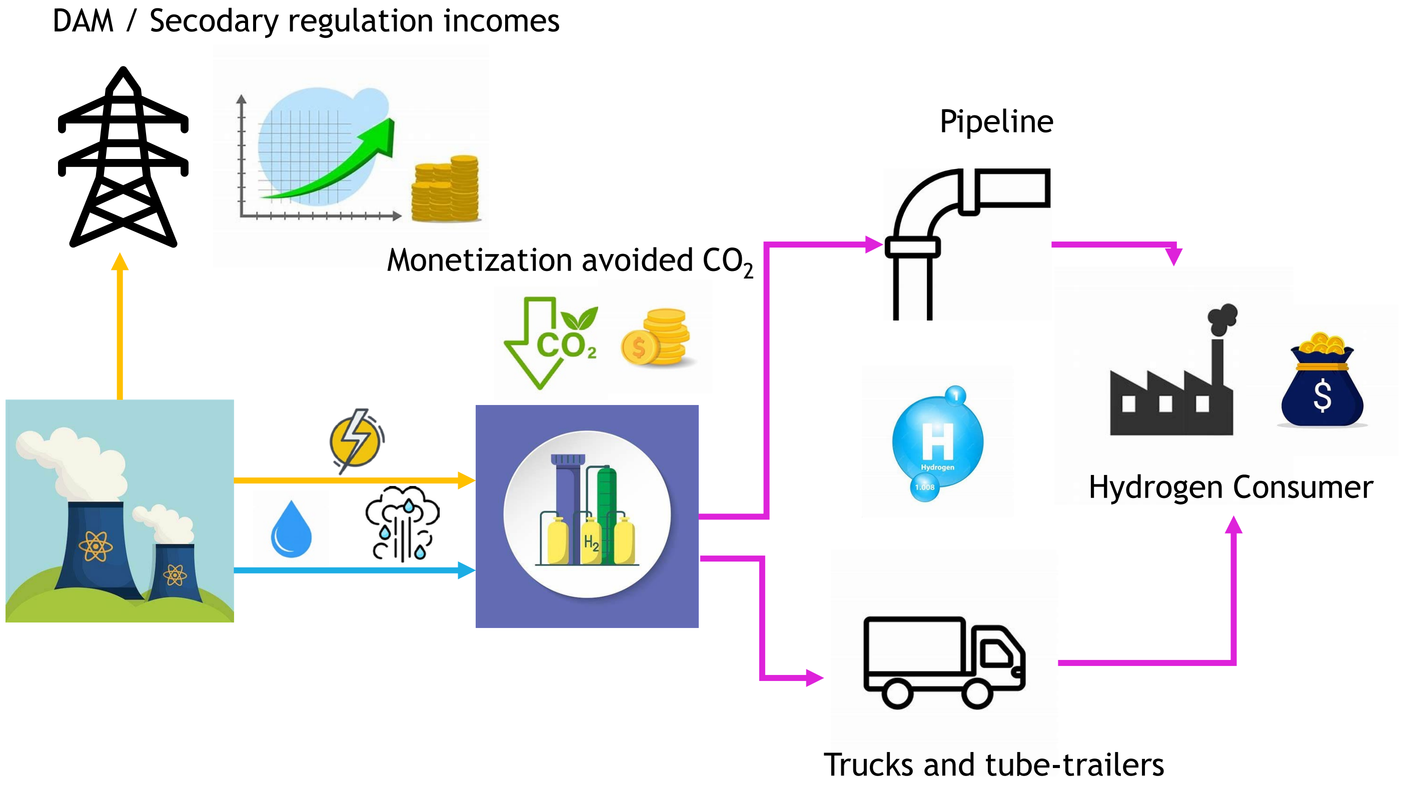
OUR CUSTOMER VALUE PROPOSITION

Generate and offer **large-scale, carbon-free electricity and hydrogen in a reliable basis** by means of the **already existing NPPs in Europe**. The low carbon hydrogen generated supports the decarbonization of “hard-to-abate” sectors. The coupling of a HPP to NPP ensure high load factors keeping its competitiveness in the new energy system paradigm.



Incomes stream	Marketplace
Electricity dispatching	Day ahead market (DAM)
	Secondary regulation market
	Power-to-X-to-Power scheme (seasonal storage, capacity market, ancillary services and energy arbitrage)
Hydrogen selling	Hydrogen consumers
Oxygen selling	Oxygen consumers
CO_2 monetization	Internal saving due to CO_2 non emission

Costs
Hydrogen production plant (3 technologies: PEM, AEL and SOEC)
NPP design modification costs
H_2 storage, transport and distribution (2 scenarios have been modelled. The selection of the transport scenario and distance will determine final cost)
NPP production costs
Costs associated to feedstocks consumption

Earnings Before Interest and Taxes (EBIT) = HPP incomes – HPP OPEX

TIMING AND MOMENT

- The total consumption was Europe was 8,2Mt in 2022. However, **only a 0,24% of the total consumption was clean hydrogen.** Emerging applications are the driver of clean hydrogen demand with 41% of the total clean hydrogen consumption (8,09kt) [1] .
- Traditional hydrogen production by SMR represents 91% of production capacity and only 0,3% is produce by means of electrolysis. **Clean hydrogen capacity amounts for only 0,42% of hydrogen production capacity in Europe** [1] **.**

LOW CARBON HYDROGEN CONSUMPTION AND PRODUCTION STILL HAS A LONG WAY TO GO

- There is a consensus that low-emissions hydrogen is a key opportunity for decarbonizing “hard-to-abate” sectors
- The energy crisis arising from Russia’s invasion of Ukraine highlighted the role of low emissions hydrogen which can enhance energy security of supply.

POLITICAL MOMENTUM BEHIND LOW EMISSIONS HYDROGEN REMAINS STRONG, HOWEVER, DEPLOYMENT IS NOT TAKING OFF

[1] European Hydrogen Observatory https://observatory.clean-hydrogen.europa.eu/tools-reports/datasets.

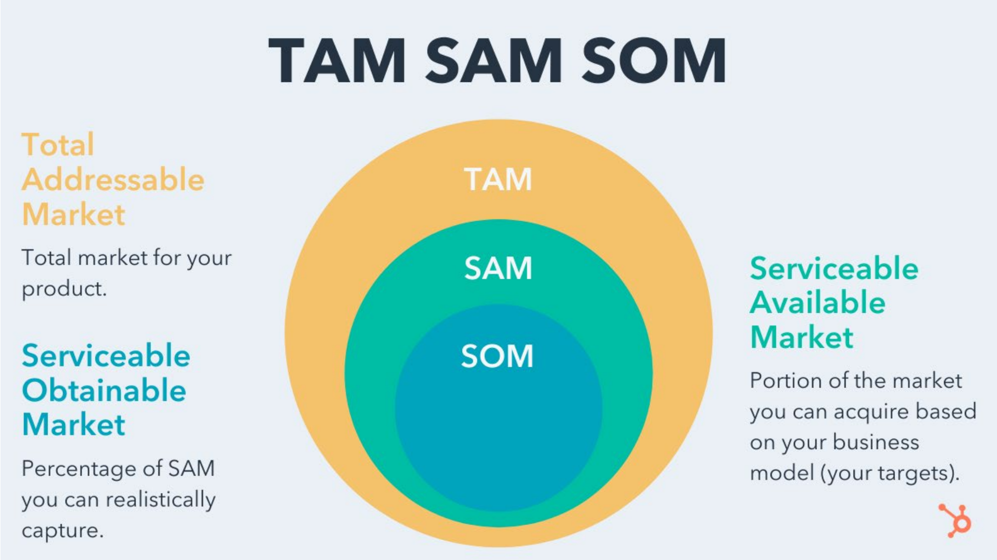
TIMING AND MOMENT- CHALLENGES

- The European regulatory framework for “low carbon” hydrogen, in which is expected nuclear hydrogen is tagged, is not still defined and is crucial signal for investor environments.
- Nuclear hydrogen needs to be considered in EU initiatives or programs related to renewable strategy (subventions, auctions, targets,..)
- Demand side must be adapted to consume low carbon hydrogen. Emerging applications are those in which the replacement of grey hydrogen is easier to perform but up to date it still represents a minor percentage.
- Regulatory barriers for licensing and permitting. No standard regulation between Members States is agreed or developed in case a NPP-HPP coupling is deployed.
- Creation of a competitive hydrogen market. Create and secure off takers for the long run, the implementation of certification schemes and the deployment of the necessary infrastructure are some of the needs to create the expected European hydrogen market.

THE MOMENT FOR R&D IS NOW. PUBLIC AND PRIVATE INVESTMENT FOR DEMONSTRATION PROJECTS **IS ESSENTIAL** TO MEET CLIMATE AMBITIONS BUT THERE ARE STILL MANY CHALLENGES TO OVERCOME.

EU AND STATE MEMBERS NEED TO MAKE ADDITIONAL EFFORTS TO STIMULATE AND EXPEDITE THE CONDITIONS THAT COULD MAKE NUCLEAR HYDROGEN PRODUCTION A REALITY.

MARKET ANALYSIS



NPHyCo TAM: estimated as all the existing European NPPs in operation.

NPHyCo SAM: Market segmentation criteria.

- Geographic
- Firmographic (Reactor type, remaining NPP lifetime)
- Psychographic (Interest in nuclear-hydrogen production)
- Behavioural (NPP life extension intention/ request).

NPHyCo SOM: Definition of several indicators (K) to support customers prioritization and selection.

- **K1:** NPPs operating lifetime moment.
- **K2:** Expression of clear interest on coupling hydrogen investment
- **K3:** Distance to large consumers or to an infrastructure to transport hydrogen
- **K4:** Electricity market prices and renewables impact

MARKET ANALYSIS

Country	NPP	K1: Lifetime moment	K2: Interest	K3: Consumers	K4: Electricity markets	Total
Belgium	Doel 4	0	1	3	1	5
	Tihange 3	0	1	3	1	5
Bulgaria	Kozloduy 5-6	3	1	2	1	7
Czech Republic	Dukovany 1-4	3	3	2	1	9
	Temelin 1-2	2	3	3	1	9
Finland	Loviisa 1-2	3	2	2	3	10
	Olkiluoto 1-2	3	2	2	3	10
	Olkiluoto 3	1	2	2	3	8
Hungary	Paks 1-4	3	1	3	1	8
Netherlands	Borselle	0	1	3	1	5
Romania	Cernavoda 1-2	1	1	2	1	5
Slovakia	Bohunice 3-4	3	1	3	1	8
	Mochovce 1-2	2	1	3	1	7
	Mochovce 3	1	1	3	1	6
Slovenia	Krško	3	1	2	1	7
Spain	Trillo	0	3	1	2	6
	Vandellós 2	0	1	3	2	6
Sweden	Ringhals 3-4	3	2	3	3	11
	Forsmark 1-2	3	2	2	3	10
	Forskmark 3	3	2	2	3	10
Switzerland	Gösgen	3	3	3	1	10
	Leibstadt	3	2	2	1	8
	Beznau 1-2	3	2	2	1	8
Ukraine	Rivne 1-4	3	3	3	1	10
	Khmelnytsky 1+2	3	3	3	1	10

COMPETITORS AND ALTERNATIVES

- **Direct competitors:** Companies with already existing nuclear power assets, companies with renewable assets, companies that were grey hydrogen producers and they are implementing carbon capture units in their processes.

- **Indirect competitors:** Already existent grey hydrogen producers

- **Potential competitors:** Companies with Small Modular Reactors

It has been considered that grey hydrogen should not be a direct competitors of clean hydrogen if the main goal is to reach a Net Zero economy. Clean hydrogen must be prioritized.

	SMR	Coal gasification	SMR+ CCUS	Photovoltaic + electrolysis	Wind + electrolysis	Nuclear + LTE	Nuclear + HTSE
TRL	9	9	9	9 (AEL) /7-8 (PEM)		9 (AEL)/ 7-8 (PEM)	5-7 (SOEC)
LCOH	0,95- 6,41 €/kgH_2 (period 2019- 2023)		2,18- 8,31 €/kgH_2	4,28- 7,67 €/kgH_2 (PV load factor from 33% to 12%)	3,26- 4,77 €/kgH_2 (Load factor from 38% to 20%)	New build (2,77- 5,63 €/kgH_2) LTO 20 years (2,10-2,22 €/kgH_2)	Not available data[4]
CO_2 intensity	10-13 kgCO_2eq/ kgH_2	22-26 kgCO_2eq/ kgH_2	1,5- 6,2 kgCO_2eq/ kgH_2 (reduction by 93%)	$<$ 3,38 kgCO_2eq/ kgH_2			
LCOH + CO_2 costs	1,25- 7,37 €/kgH_2 (period 2019- 2023)		0,0875- 0,22 €/kgH_2 (CO_2 emissions cost almost negligible)	CO_2 emissions cost negligible			
Production capacity	As long as natural gas and coal is available, the hydrogen production is guaranteed			10 % Finland 17% Spain	Onshore 23,9% Offshore 41,3% Average values for capacity factors in Europe [19]	Approximately 80% (period 2000-2025) [20]. NPPs capacity factor worldwide.	

Nuclear hydrogen is the only option that meets security of supply, CO_2 non-emission, no price fluctuation, possibility of relevant hydrogen rates and promising production costs.

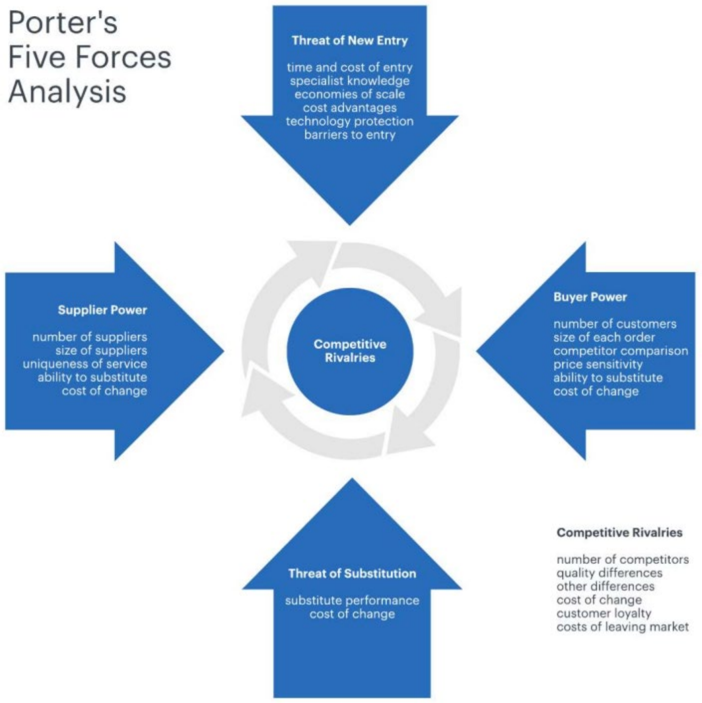
COMPETITORS AND ALTERNATIVES

- **Market attraction matrix:** prioritize investment across products and Strategic Business Units

ATTRACTIVENESS OF THE MARKET			
High (3,66-5)	Protect position	Invest to grow	Grow selectively
Medium (2,33-3,66)	Invest selectively	Seek profitability ★	Limit expansion
Low (1-2,33)	Redefine business model	Manage according to results	Cash Flow maximization
	High (3,66- 5)	Medium (2,33-3,66)	Low (1-2,33)

COMPETITIVENESS STRENGH

- **Porter's Five Forces Analysis:** determine the competitive landscape of nuclear hydrogen production from already existent NPPs, identify opportunities and solidify their position in the market.



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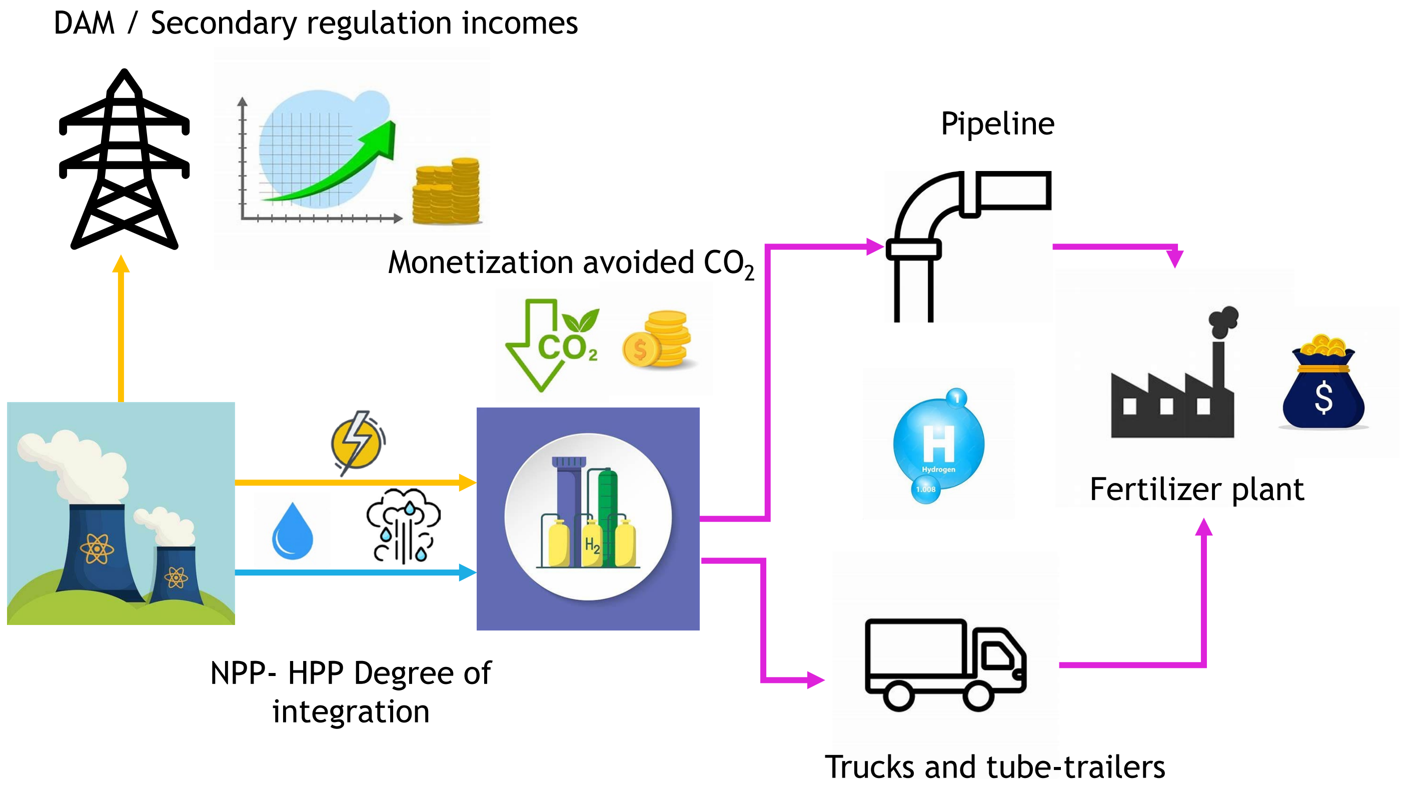
Economic Roadmap. Tasks overview



1. Techno-economic costs models
2. Techno- economic income models
3. Financial tool modelling
4. Sensitivity analysis for optimal configuration
5. Advanced operational strategies
6. KPIs comparison with other production methods
7. Business Plan (financial analysis)

HEEP — IAEA International Atomic Energy Agency

PERSEE — cea

H2A — NREL Transforming ENERGY

OptimHyzer — tecnatom

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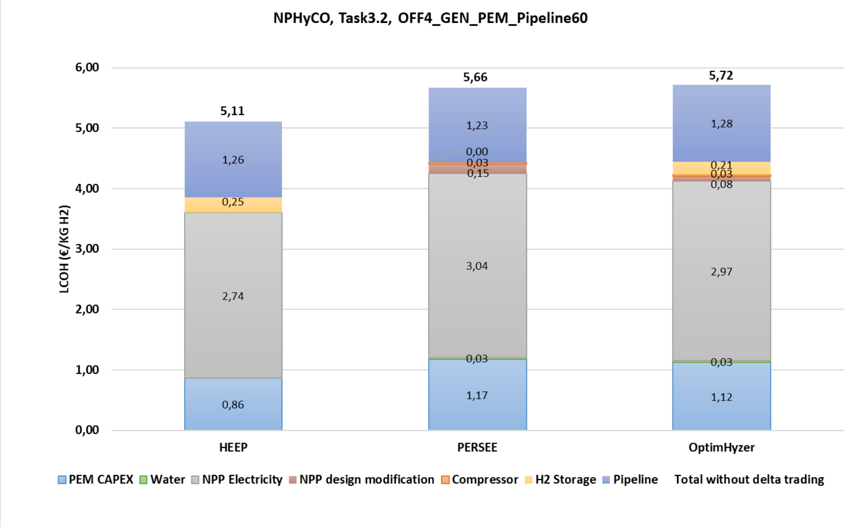
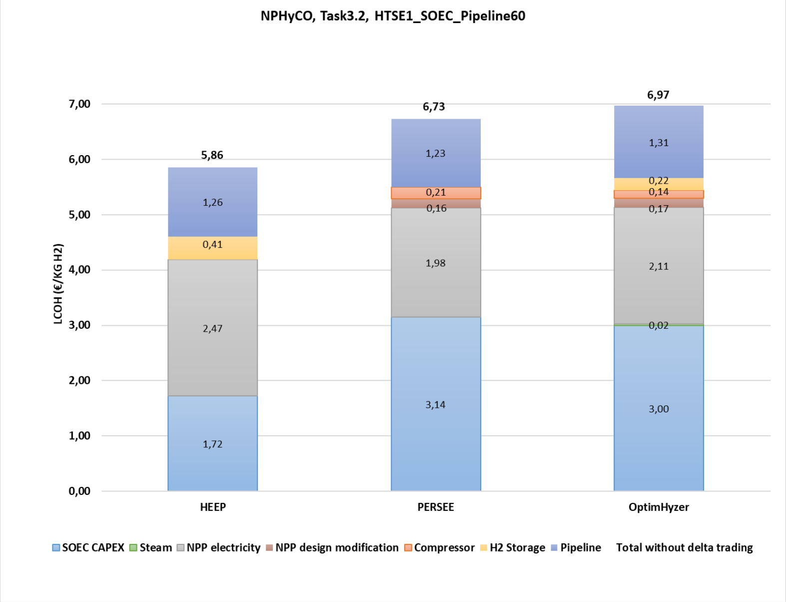
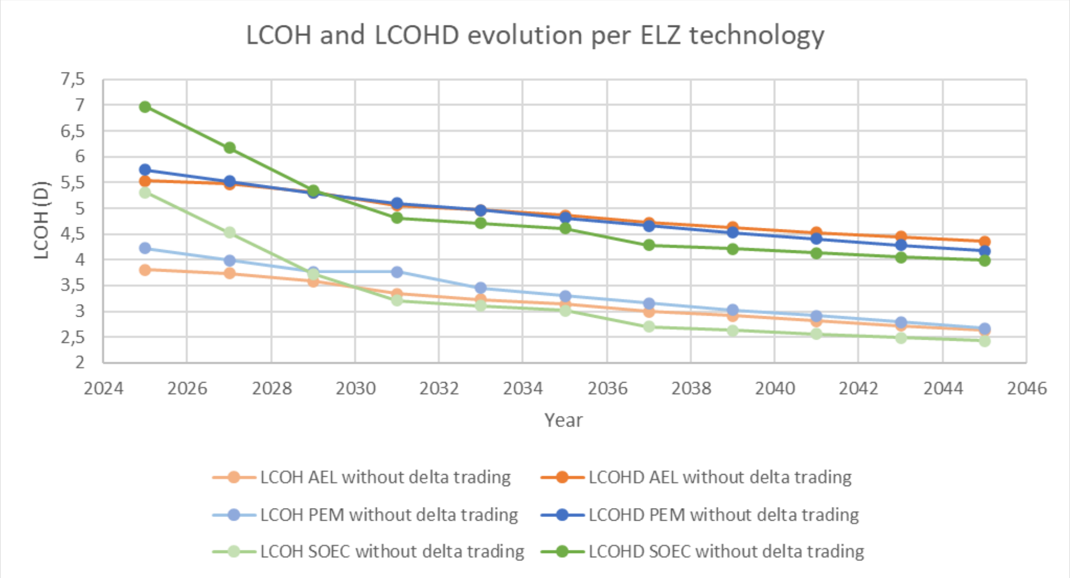
Sensitivity analyses. Some conclusions







- In case of LTE **(PEM and AEL), the most part of the LCOH weight is due to electricity consumption** made by the electrolyser. The water consumption cost is negligible. However, in case of **HTSE (SOEC), ELZ CAPEX represents the highest share of hydrogen generation costs**, and the electricity falls to a second position.

- **Currently the hydrogen produced with SOEC technology is more expensive than producing it with any of the LTE technologies**. However, according to calculations, is expected that by year 2029, SOEC is expected to reach the same level of prices as PEM technology and in year 2031, lower costs than both LTE technologies.

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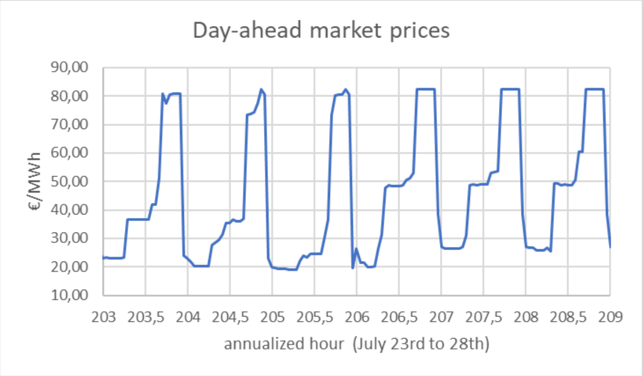
LCOH (D) is key for market competitiveness, but we need to go further…

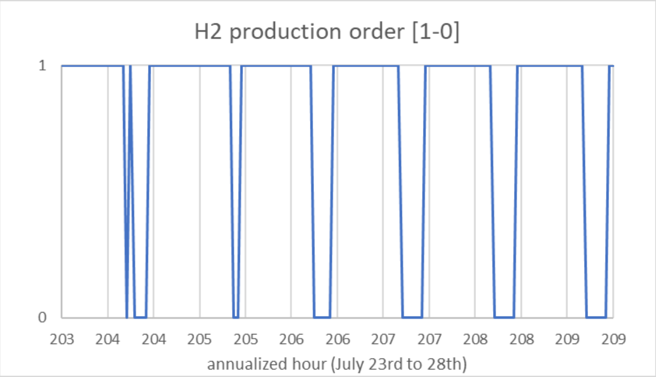
Other questions should be also answered in case a HPP coupling is envisaged to be done with an already existent NPP:

- **Is it better to continue selling electricity or also to produce hydrogen?**
- **Which is the hydrogen cost from which the benefits or the losses of the two business models are the same?**

Study case/Concept	H_2 not guaranteed. Continuous production	H_2 not guaranteed. Price-based strategy
LCOHD	5,72 €/kgH_2	6,44 €/kgH_2
"Delta trading"	1,19 €/kgH_2	0,06 €/kgH_2
LCOHD + "delta"	6,91 €/kgH_2	**6,5 €/kgH_2**



- ➢ The hydrogen production strategy combined with the type of supply contract is crucial for maximizing benefits in a hybrid system.
- ➢ In case of not penalties or delivery restrictions, produce hydrogen when electricity prices drop low and switch back to electricity whenever they rise up is the strategy that maximizes the benefits. Otherwise, produce whenever is possible.



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Financial assessment

Which is the hydrogen selling price for obtaining certain level of profitability?

Which are the conditions for making nuclear-hydrogen production competitive and besides, economically feasible from a hybrid system standpoint?

Financial assessments performed (PEM and SOEC technologies):

1. Prices and subventions calculation methodology
2. CO_2 avoided monetization impact
3. Production rate and technological progress impact
4. Lifetime moment of the plant (LCOE)
5. Secondary regulation market participation impact
6. Determination of possible conditions for economic feasibility

End use	Technology to be replaced	Break-even price (€/kg)
Oil refining	Use of hydrogen as feedstock produced in SMR with natural gas as input	3,9 - 8,1
Heavy-duty trucks	Use of diesel in internal combustion engines for long-distance heavy-duty trucks	3
Primary steel making	Primary steel produced in blast furnace with basic oxygen furnace with coking coal as reducing agent	1,2 – 2,2
Maritime applications	Use of Very Low Sulphur Fuel Oil in two or four stroke conventional marine combustion engines	2,4 – 5,8

Selling price ($€/kgH_2$)	Subvention ($€/kgH_2$)	IRR	Payback	Levelized production (ton H_2)	Operative annual hours (avg year 1)
Hydrogen not guaranteed. Price-based strategy. LCOHD = 6,44 $€/kgH_2$, "Delta trading" = 0,06 $€/kgH_2$					
3	6	21,43%	5		
3,5	5,5	21,67%	5		
4	5	21,91%	5		
6,7	-	12,63%	8	21.971.728	6.492
8	-	19,32%	6		
8,5	**-**	**21,75%**	**5**		
9	-	24,14%	4		
Hydrogen guaranteed with penalties (8 $€/kgH_2$). Continuous production. Hydrogen rate guaranteed: 455 kgH_2/h. LCOHD= 6,16$€/kgH_2$, "Delta trading" = 1,2 $€/kgH_2$					
3	6	20,06%	5		
3,5	5,5	20,38%	5		
4	5	20,69%	5		
7,2	-	12,26%	8	27.016.775	7.914
8	-	17,52%	6		
8,5	**-**	**20,52%**	**5**		
9	-	23,54%	5		

IRR >20%
H_2 selling price 2,5 - 3 €/ kgH_2

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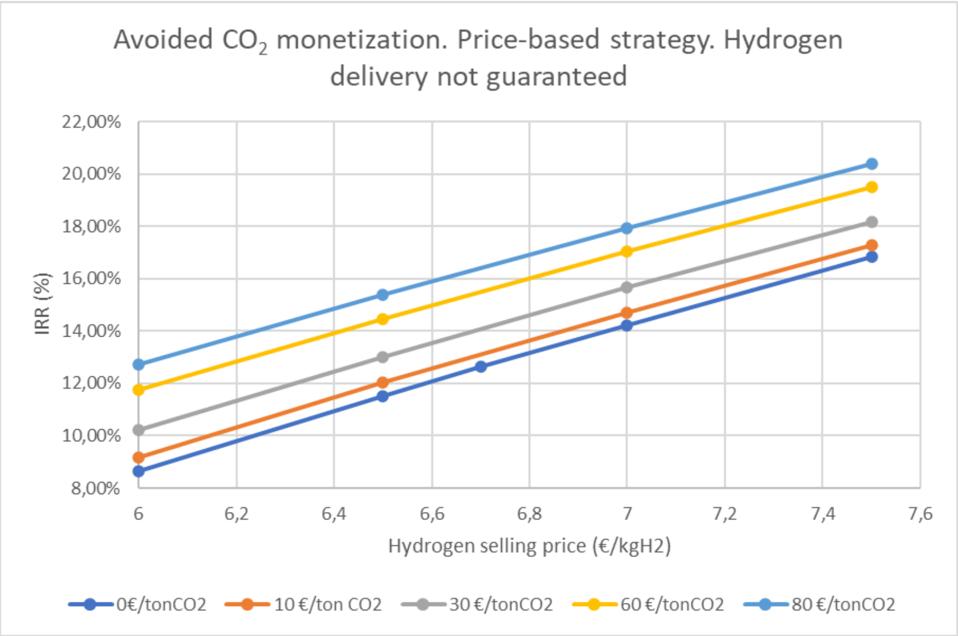
Financial assessment- CO_2 avoided monetization

Price of emissions allowances traded on the EU ETS evolution
(€/ t CO_2 equivalent)



- An increase of 10 €/ ton $CO_{2\ eq}$ in the price of emissions allowances report a reduction of 0,1 €/kgH_2 in the hydrogen selling price for obtaining constant IRR.
- This analysis has been performed for a 30MW PEM electrolyser (2026) and it has not been verified for other hydrogen production rate/ conditions.

Financial assessment- H_2 production rate and technology maturity (PEM)

- COMPLETE VALUE CHAIN ANALYSIS: PRODUCTION, COMPRESSION, STORAGE AND TRANSPORT

Hydrogen not guaranteed. Price-based strategy

IRR> 20%									
Year	2026	2028	2030	2032	2034	2036	2040	2045	2050
Production rate (kgH_2/h)	Hydrogen production cost and delivery (LCOHD) (€/kgH_2) "Delta trading" =0,06- 0,05 €/kgH_2								
494	6,46	6,25	6,00	5,80	5,63	5,47	5,14	4,70	4,46
1.976	4,9	4,67	4,45	4,26	4,12	3,98	3,7	3,41	3,11
6.000	4,58	4,35	4,14	3,95	3,8	3,66	3,39	3,08	2,79
16.000	4,47	4,24	4,02	3,83	3,69	3,55	3,28	2,97	2,68

H_2 selling price
>=6,5 €/kgH_2
6 €/kgH_2
5,5 €/kgH_2
5 €/kgH_2
4,5 €/kgH_2
4 €/kgH_2
3,5 €/kgH_2
3 €/kgH_2

Hydrogen guaranteed with penalties. Continuous production

IRR> 20%									
Year	2026	2028	2030	2032	2034	2036	2040	2045	2050
Production rate (kgH_2/h)	Hydrogen production cost and delivery (LCOHD + penalties) (€/kgH_2) "Delta trading" = from 1,2 to 0,87 €/kgH_2								
494	6,16	5,93	5,69	5,5	5,35	5,21	4,92	4,61	4,32
1.976	4,87	4,63	4,43	4,24	4,11	3,99	3,74	3,48	3,21
6.000	4,62	4,38	4,17	3,99	3,86	3,74	3,49	3,21	2,95
16.000	4,52	4,28	4,08	3,9	3,77	3,65	3,4	3,12	2,86

H_2 selling price
>=7 €/kgH_2
6,5 €/kgH_2
6 €/kgH_2
5,5 €/kgH_2
5 €/kgH_2
4,5 €/kgH_2
4 €/kgH_2

- Lower costs are detected as long as the hydrogen rate is increased, and the time passes, and the technology become more mature.
- The combination of hydrogen contract supply + production operational strategy is key for obtaining the optimum profitability in the business case
- In case the selling break-even price is set to 3 €/kgH_2, subventions would be required in almost all the cases analyzed if a 20% IRR is needed.
- The lowest selling price obtained is 3 €/kgH_2 for starting operating year 2050, hydrogen rate from 6.000 kgH2/h, hydrogen not guaranteed with price-based strategy. That is, if hydrogen selling price is set to 3 €/kgH_2, no subventions would be required in this case.

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Financial assessment- H_2 production rate and technology maturity (PEM)

- **ONLY HYDROGEN PRODUCTION**

  Hydrogen not guaranteed. Price-based strategy

IRR> 20%	40,12€/MWh								
Year	2026	2028	2030	2032	2034	2036	2040	2045	2050
Production rate (kgH_2/h)	Hydrogen production cost- LCOH (€/kgH_2)								
494	4,48	4,27	4,02	3,85	3,68	3,52	3,21	2,87	2,54
1.976	4,09	3,86	3,65	3,48	3,34	3,2	2,93	2,65	2,36
6.000	4,06	3,83	3,61	3,44	3,3	3,17	2,90	2,60	2,32
16.000	4,05	3,82	3,60	3,43	3,29	3,16	2,89	2,59	2,31

H_2 selling price	
	>=5 €/kgH_2
	4,5 €/kgH_2
	4 €/kgH_2
	3,5 €/kgH_2
	3 €/kgH_2
	2,5 €/kgH_2

- As there are many references, news and other sources where the target of competitive hydrogen generation costs is established in 1-1,5 €/kgH_2, it has been considered important to perform the analysis without transportation costs.
- A hydrogen selling price of 2,5 €/kgH_2 is envisaged for year 2050 for hydrogen rates from approximately 1.976 kgH_2/h.
- The cost reduction due to higher hydrogen rates is not substantial if only LCOH is considered, the technology maturity projection reports higher impact in costs values.

Financial assessment- LCOE assessment (PEM)

	New plants operating	LTO 10 years	LTO 20 years	LTO + 20 years
LCOE (€/MWh)	146,06	40,12	36,50	27

- ONLY HYDROGEN PRODUCTION

Hydrogen not guaranteed. Price-based strategy

IRR> 20%	36,5€/MWh								
Year	2026	2028	2030	2032	2034	2036	2040	2045	2050
Production rate (kgH_2/h)	Hydrogen production cost- LCOH (€/kgH_2)								
494	4,21	4,01	3,77	3,61	3,44	3,29	2,99	2,67	2,36
1.976	3,82	3,6	3,4	3,24	3,1	2,97	2,71	2,45	2,18
6.000	3,79	3,57	3,36	3,2	3,06	2,94	2,68	2,4	2,14
16.000	3,78	3,56	3,35	3,19	3,05	2,93	2,67	2,39	2,12

IRR> 20%	27€/MWh								
Year	2026	2028	2030	2032	2034	2036	2040	2045	2050
Production rate (kgH_2/h)	Hydrogen production cost- LCOH (€/kgH_2)								
494	3,5	3,33	3,11	2,96	2,81	2,67	2,41	2,12	1,84
1.976	3,11	2,92	2,74	2,59	2,47	2,35	2,13	1,9	1,66
6.000	3,08	2,89	2,7	2,55	2,55	2,32	2,10	1,85	1,62
16.000	3,07	2,88	2,69	2,54	2,42	2,31	2,09	1,84	1,6

H_2 selling price
>=5 €/kgH_2
4,5 €/kgH_2
4 €/kgH_2
3,5 €/kgH_2
3 €/kgH_2
2,5 €/kgH_2

- The minimum hydrogen cost reached is 1,6 €/kgH_2. It is constated that, approximately, from a LCOE of 27 €/MWh, it is possible to reach a target value of 1,5 €/kgH_2 at some point.
- It has been verified that NPPs with LTO conditions, that is, with lower LCOE values are the most favorable for obtaining lower hydrogen production costs.
- **The hydrogen selling values for obtaining certain level of profitability are exactly the same no matter the lifetime moment of the plant.**

Financial assessment- Secondary regulation electricity dispatching

ASSUMPTIONS CONSIDERED:

- The day-ahead market prices and the secondary regulation market prices (historical) were replaced in Rivne model for Spanish data because these inputs were freely available to perform the analysis.

- The electricity balancing markets are being integrated and standardized among all the European countries. The settlement process shall be based on a marginal pricing. Currently in Spain exists a quite similar remuneration mechanism that the one discussed for the European balancing markets. The secondary frequency reserve is paid through two concepts: availability and energy consumption

  - ➢ The availability is based on the marginal cost resulting from the product bidding. Currently in Spain, the same price is applied upward and downward reserve but in Q2 2024, 2 independent markets for each type of the reserves will be implemented.

  - ➢ The secondary regulation energy consumed has an assigned price equivalent to the tertiary regulation marginal price that would be necessary to be programmed in each hour, upward and downward, in order to replace the net energy use of the secondary regulation.

- **MODEL LIMITATION:** The hybrid system only participates on secondary regulation market, it cannot combine certain days DAM and other secondary regulation.

Financial assessment- Secondary regulation electricity dispatching

	Continuous production	Price-based strategy	Secondary regulation market
Hydrogen delivery not guaranteed			
LCOHD (€/kgH_2)	5,72	5,74	5,65
"Delta trading" (€/kgH_2)	1,28	1,28	1,27
LCOH + "delta trading" (€/kgH_2)	7,00	7,02	6,92
Levelized production (ton H_2)	28.106.570	28.050.030	14.143.807
Operative annual hours (avg year 1)	8.496	8.479	4.248

Selling price (€/kgH_2)	IRR	Payback	Levelized production (ton H_2)	Operative annual hours (avg year 1)
Hydrogen delivery not guaranteed. Continuous production (LCOHD= 5,72+ 1,28= 7 €/kgH_2)				
6	5,23%	11	28.106.570	8.496
6,5	9,39%	9		
7	**13,10%**	**7**		
7,5	16,54%	6		
8	19,80%	6		
Hydrogen delivery not guaranteed. Price-based strategy (LCOHD= 5,74+ 1,29 = 7,02 €/kgH_2)				
6	5,23%	11	28.050.030	8.479
6,5	9,39%	9		
7	**13,10%**	**7**		
7,5	16,50%	6		
8	19,76%	6		
Hydrogen delivery not guaranteed. Secondary regulation (LCOHD= 5,65 + 1,27 = 6,92 €/kgH_2)				
6	6,44%	10	14.143.807	4.248
6,5	8,50%	9		
7	10,45%	8		
7,5	**12,29%**	**8**		
8	14,07%	7		

- In the cost analysis was concluded that the secondary regulation participation reported the lowest LCOHD with respect other production strategies (continuous, price-based). Participating in balancing markets is translated to a lower hydrogen production as general term (50% in this case) but much higher selected and punctual electricity incomes. **HOWEVER,….**

- Despite a lower LCOHD, financial analysis results are less favorable with secondary regulation dispatching than with the other two strategies. It would be necessary to sell the hydrogen with a higher price to obtain similar profitability. The quantity of hydrogen produced and the associated number of hours the electrolyser is operating, negatively impacts the financial results.

Financial assessment- H_2 production rate and technology maturity (SOEC)

- COMPLETE VALUE CHAIN ANALYSIS: PRODUCTION, COMPRESSION, STORAGE AND TRANSPORT

Hydrogen not guaranteed. Continuous production

IRR> 20%									
Year	2026	2028	2030	2032	2034	2036	2040	2045	2050
Production rate (kgH_2/h)	Hydrogen production cost and delivery (LCOHD) (€/kgH_2) "Delta trading" = 0,94 – 0,75 €/kgH_2								
494	8,14	7,31	6,46	5,89	5,77	5,64	5,2	4,96	4,71
1.976	6,66	5,94	5,19	4,67	4,56	4,46	4,06	3,83	3,61
6.000	6,12	5,47	4,79	4,3	4,2	4,1	3,74	3,53	3,32
16.000	5,76	5,17	4,56	4,11	4,01	3,92	3,59	3,39	3,19

H_2 selling price
>=6,5 €/kgH_2
6 €/kgH_2
5,5 €/kgH_2
5 €/kgH_2
4,5 €/kgH_2
4 €/kgH_2
3,5 €/kgH_2
3 €/kgH_2

Hydrogen guaranteed with penalties. Continuous production

IRR> 20%									
Year	2026	2028	2030	2032	2034	2036	2040	2045	2050
Production rate (kgH_2/h)	Hydrogen production cost and delivery (LCOHD) (€/kgH_2) "Delta trading" = 0,94 – 0,75 €/kgH_2								
494	7,72	6,86	5,99	5,43	5,32	5,19	4,78	4,56	4,35
1.976	6,17	5,45	4,68	4,17	4,07	3,96	3,6	3,93	3,21
6.000	5,6	4,95	4,25	3,78	3,69	3,59	3,26	3,07	2,9
16.000	5,23	4,65	4,02	3,57	3,49	3,4	3,11	2,93	2,77

H_2 selling price
>=7 €/kgH_2
6,5 €/kgH_2
6 €/kgH_2
5,5 €/kgH_2
5 €/kgH_2
4,5 €/kgH_2
4 €/kgH_2
3,5 €/kgH_2
3 €/kgH_2

- In case of SOEC, price-based strategy has not been applied because a timestamp of 15 minutes would have been needed and the tools were not designed with this requirement.
- Lower costs are detected as long as the hydrogen rate is increased, and the time passes, and the technology become more mature.
- According to analysis performed in D3.2, approximately in year 2029, LCOH obtained with LTE technologies could reach similar cost values than SOEC technology. This behavior is constated in these Tables, where the LCOHD tends to be quite similar from both technologies from year 2030.
- The lowest selling price obtained is 3 €/kgH_2 for starting operating year 2050, hydrogen rate from 16.000 kgH_2/h, or 2045 and 6.000 kgH_2/h in case of hydrogen not guaranteed and continuous production. In case of PEM, this hydrogen selling Price is not obtained until 2050 and only applying Price-based strategy.

Financial assessment- H_2 production rate and technology maturity (SOEC)

- ONLY HYDROGEN PRODUCTION

Hydrogen not guaranteed. Price-based strategy

IRR> 20%	40,12€/MWh								
Year	2026	2028	2030	2032	2034	2036	2040	2045	2050
Production rate (kgH_2/h)	Hydrogen production cost- LCOH (€/kgH_2)								
494	5,46	4,68	3,88	3,35	3,25	3,16	2,76	2,57	2,38
1.976	4,94	4,25	3,55	3,07	2,97	2,9	2,54	2,37	2,2
6.000	4,63	4,01	3,38	2,93	2,84	2,77	2,45	2,29	2,13
16.000	4,37	3,81	3,24	2,82	2,74	2,67	2,39	2,24	2,08

H_2 selling price	
	>=5 €/kgH_2
	4,5 €/kgH_2
	4 €/kgH_2
	3,5 €/kgH_2
	3 €/kgH_2
	2,5 €/kgH_2
	2 €/kgH_2

- As there are many references, news and other sources where the target of competitive hydrogen generation costs is established in 1-1,5 €/kgH_2, it has been considered important to perform the analysis without transportation costs.
- A hydrogen selling price of 2 €/kgH_2 is envisaged for year 2050 for hydrogen rates from approximately 16.000 kgH_2/h. Comparing this result with PEM technology where the lowest hydrogen selling price was 2,5 €/kgH_2 by year 2050 and from 1.976 kgH_2/h, SOEC presents most promising results as this selling price is detected by 2040 (10 years before) for 16.000 kgH_2/h or by 2045 from approximately 1.976 kgH_2/h.

Financial assessment- LCOE assessment (SOEC)

	New plants operating	LTO 10 years	LTO 20 years	LTO + 20 years
LCOE (€/MWh)	146,06	40,12	36,50	27

- ONLY HYDROGEN PRODUCTION

Hydrogen not guaranteed. Continuous production

IRR> 20%	36,5€/MWh								
Year	2026	2028	2030	2032	2034	2036	2040	2045	2050
Production rate (kgH_2/h)	Hydrogen production cost- LCOH (€/kgH_2)								
494	5,25	4,48	3,69	3,16	3,06	2,97	2,58	2,39	2,22
1.976	4,73	4,05	3,36	2,88	2,78	2,71	2,36	2,19	2,04
6.000	4,42	3,81	3,19	2,74	2,65	2,58	2,27	2,11	1,97
16.000	4,16	3,61	3,05	2,63	2,55	2,48	2,21	2,06	1,92

IRR> 20%	27€/MWh								
Year	2026	2028	2030	2032	2034	2036	2040	2045	2050
Production rate (kgH_2/h)	Hydrogen production cost- LCOH (€/kgH_2)								
494	4,72	3,96	3,17	2,65	2,56	2,48	2,11	1,94	1,79
1.976	4,2	3,53	2,84	2,37	2,28	2,22	1,89	1,74	1,61
6.000	3,89	3,29	2,67	2,23	2,15	2,09	1,8	1,66	1,54
16.000	3,63	3,09	2,53	2,12	2,05	1,99	1,74	1,61	1,49

H_2 selling price
>=5 €/kgH_2
4,5 €/kgH_2
4 €/kgH_2
3,5 €/kgH_2
3 €/kgH_2
2,5 €/kgH_2
2 €/kgH_2

- The minimum hydrogen cost reached is 1,49 €/kgH_2, lower than in case of PEM technology where the minimum cost was 1,6 €/kgH_2. It is constated that, approximately, from a LCOE of 27 €/MWh, it is possible to reach a target value of 1,5 €/kgH_2 at some point.
- The lower hydrogen selling price to obtain and IRR> 20% is 2 €/kgH_2, while PEM case was 2,5 €/kgH_2.
- **The hydrogen selling values for obtaining certain level of profitability are exactly the same no matter the lifetime moment of the plant.**

NPHyCo
Nuclear Powered Hydrogen Cogeneration

Hypothetic scenarios for nuclear hydrogen economic feasibility

	PEM technology	SOEC technology
NPP LCOE	36,50 €/MWh	36,50 €/MWh
Hydrogen contract	Delivery not guaranteed	Delivery not guaranteed
Production strategy	Price-based strategy	Continuous production
Starting operating date	2030	2030
Hydrogen rate	6.000 kgH_2/h (352 MW)	6.000 kgH_2/h (224 MW)
CO_2 monetization	30 €/ton	30 €/ton
O_2 incomes	NA	NA
LCOH	3,39 €/kgH_2	3,24 €/kgH_2
Transport costs	0,49 €/kgH_2	0,44 €/kgH_2
"Delta trading"	0,31 €/kgH_2	1,11 €/kgH_2
LCOHD + penalties (if applicable)	3,7 €/kgH_2	3,68 €/kgH_2
IRR	20,91%	20,78%
Payback	5 years	5 years
Hydrogen price	2,5 €/kgH_2	2,5 €/kgH_2
Subvention	2,1 €/kgH_2	2,4 €/kgH_2

CONDITIONS FOR NUCLEAR HYDROGEN ECONOMIC FEASIBILITY (HORIZON 2030)

- NPPs are expected to operate in LTO conditions which is favorable to decrease LCOH values.
- By 2030, LCOH for PEM and SOEC technologies are expected to be similar for the same hydrogen production rate.
- Higher production rates decrease pipeline unitary costs and it is expected that electrolysers are technologically ready to be escalated.
- For the case analyzed, hydrogen could be sold with a price of 2,5 €/kgH_2 and with an approximate subvention between 2-2,5 €/kgH_2 , the investment return will be higher than 20%.

Conclusions

- Nuclear hydrogen is the only option that meets security of supply, CO2 non-emission, no price fluctuation, possibility of relevant hydrogen rates and promising production costs.

- There are still challenges and barriers to overcome but if we want to make a reality nuclear hydrogen production the moment for R&D, investment and policy makers is NOW. Low-carbon hydrogen needs a regulation framework, to be considered as part of the EU targets and to be awarded with the same benefits as renewable hydrogen (PPAs, auctions,..). Grey hydrogen cannot be a competitor in a Net Zero economy path.

- The hydrogen selling price offered could be competitive in the market in medium- term but it is necessary that **new projects developed are supported by subventions.** The NPPs have to get a reasonable profitability from its new business model in case they decide to invest in a hybrid system.

- The promotion of NPP LTO conditions will benefit the possibility of transitioning to hybrid systems, obtaining lower LCOH, but also new reactors could obtain same profitability levels because at the end, is not only a fact of lifetime of the plant but also the electricity market in which the NPPs are operating.

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