“Requirements that need to be fulfilled by the H2 plant to be coupled to a NPP”

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Explanatory Note

This spreadsheet contains requirements or parameters that are necessary, favourable or of other importance to the hydrogen cogeneration via coupling of a hydrogen production plant HPP to a nuclear power plant NPP.

This first part of the table focuses on the requirements from a point of view on the needs of the HPP .

There is a second similar spreadsheet focussing on the modifications to be done on a NPP to allow the cogeneration. This is given with Deliverable D2.4.

Where distinct values are given they relate to a HPP with a 30MWel scale.
As there was no pre-defined optimal HPP plant size in NPHyCo project 30MW were taken as example for a reasonable size of a pilot plant to better understand the order of magnitude of the paramters. This are mainly the technical needs for hydrogen production. For other parameter it is not possible to give distinct values as there are too many variables influecing them. Mostly it is the strong dependency of parameter on the specific local circumstances of a given site.

The requirements are categorized in the following classes:

- T for technical requirements
- C for commercial requirements
- L for licencing requirements
- O for other requirements

All this requirements/parameters listed were taken into account in the subsequent workpackages e.g. WP3 (economical roadmap), WP4 (Licensing roadmap) and especially in the decision matrix elaborated in WP5 (implementation roadmap)

List of Abbreviations

HPP	Hydrogen Production Plant
NPP	Nuclear Power Plant
OPEX	Operational Expenditures
CAPEX	Capital Expenditures
LCOH	Levelized Cost of Hydrogen
HTSE	High Temperature Steam Electrolysis
SOEC	Solid Oxide Electrolysis Cell
LTE	Low Temperature Electrolysis
PEM	Proton Exchange Membrane
AEL	Alkaline Electrolysis

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Classification	Number	Designation of Requirement	Relevance of Requirement	Significance (with respect to LCOH) S1 = very significant S2 = significant S3 = less significant parameter	Typical values Low Temperature Electrolysis PEM or AEL	Typical values High Temperature electrolysis SOEC
		Product Definition				
T	001	Hydrogen product amount	not a requirement but the definition of objective it depends on availability of resources and the contractual agreements with the customer the wanted production capacity defines the plant scale and thus influences the cost of erection and operation of the HPP and finally th LCOH the values given in column H are expected capacity of a 30MWel plant scale	very significant in the sense of defining the HPP scale	540 kg/h for an assumed 30MWel HPP	700 kg/h for an assumed 30MWel HPP
T	002	Hydrogen product quality	not a requirement but the definition of objective it depends on electrolyzer technology used and contractual agreements with the customer the wanted product quality defines the gas purification part of the plant and thus influences the cost of erection and operation of the HPP and finally th LCOH the values given in column H are expected for many customers	very significant in the sense of defining the kind and cost of HPP gas purification unit	>99.9% Hydrogen 1-32 barg	
C	003	Hydrogen Production Cost (LCOH)	Not requirement but the objective of coupling the levelized cost of hydrogen is a result of the technical solution and integration level choesen the target value depends on the market i.e. the country and various other paramters	very significant	LCOH should allow a sales-prices that is competitive (lower) than marketprice of (green) hydrogen in the respective country	
T	004	Oxygen byproduct amount	Oxygen is a byproduct of hydrogen production. The production amount is fixed with the production capacity.	less significant	approx. 4320 kg/h with an assumed 30MWel HPP	
T	005	Oxygen byproduct amount and quality	Not a requirement, but a potentially favourable parameter. In most hydrogen production facilities the byproduct oxygen is dismissed to tha ambient air. In case there was an additional customer for oxygen as well, this would support the possibility of hydrogen co-generation as i may give additional revenue and thus reduces LCOH. Potential requirements with respect to quality of oxygen cannot be given in general but a gas purification or gas drying step may be envisaged.	less significant because of unlikelyness may become signifcant if revenues are possible	depends on the potential use	
C	006	Oxygen byproduct cost and sales price	As oxygen is a by-product it does not have initial production cost, but a likely purification / drying unit and its amortisation and operational cost have to be taken into account and weighed against the sales revenues.	less significant because of unlikelyness may become signifcant if revenues are possible	depends on the potential use and the related purification if needed	
		Energy supply (Electricity & Steam)				
T	007	Availability of Electricity dedicated, depending in grid needs, depending on market price	Electricity is the main energy-supply to drive the electrolysis. Thus the availability of electricity is a MUST for any electrolysis plant. The LCOH is highly depending on the cost of electricity and on the amount of operational hours of a HPP during a year; thus the concept of electricity supply is crucial. This may be a fixed amount of electricity dedicated for the hydrogen production. Another concept is to run HPP as a flexible load for the NPP and the NPPs electricity is sold either the electricity-market or used for hydroigen production in dependance on the market prices for electricity and hydrogen. In the latter case the amount of available electricity defines the scale of the hydrogen production plant. In case the whole range of load flexibility of a NPP was supposed be covered, the HPP should have a scale of approx. 10% of the NPP capacity.	very significant	not applicable	
T	008	amount of electricity input DC	the need amount of electricity is defined by the scale of the H2 production and the electrolysis technology used. The efficiency of the different eletrolyzer technologies span from 60% (AEL and PEM) to 90% (SOEC). It is important to understand that in addition to the energy consumption of the electrolysis other consumption e.g. efficiency of AC-DC-conversion, other consumer as compressors or feed water make-up systems need to be taken into account. Comparisons of plant efficiencies need to be done carefully with respect of system boundaries.	very significant	4.3 to 6.3 kWh/Nm³ of Hydrogen 50 to 60 kWh/kg Hydrogen	
C	009	price of electricity input DC	As electricity is the main energy source for the process the LCOH is highly depending on it. For LTE where electricity is the only energyp source and the overall efficiencies are low the electricity price is the most significant paramater regaring cost of hydrogen production. For HSTE (SOEC) where steam is used as additional energy source and higher efficiens are reachable the electricity price is only the second important cost parameter. The high efficiency has to be paid for with lower stack lifetimes and thus the stack replacement cost become more significant (compared to LTE). The coupling of HPP to NPP bears the opportunity that the price for electricity may be comparably low when the hydrogen production is regarded as own consumption of the electricity producer. On the ther side large consumers may be granted reduced prices even if there was no direct coupling. This is depending on the elecricity provider and needs to be taken into account.	very significant	depending on the country and market situation, no price indication given	

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T	010	Steam input amount	In case of HTSE (SOEC) the feedwater is processed in form of steam at temperatures of approx. 800 ºC. In case steam is availabe in the coupled plant as it is given for NPPs it can be used to pre-heat the process water and support the evaporation step. Any kind of steam with temperature above approx. 150°C may be used. Another pre-heat step is performed by using the heat of the process gases. the missing gap of energy is coveed by an electrical heater in the evaporator. This optimzed use of external steam and internal excess heat contributes to the better efficiency of HTSE technology.	significant	not applicable	any amount of steam with T>150°C may be used for preheating. typically HTSE plant cover 25% of the overal energy input with external steam, but more or less is technically feasible if commercially useful.
C	011	Steam input price	the contribution of the steam supply to the LCOH depend on the price for the external steam (incl. the amortisation of the connection line). significance is defined by price and amount.	significant	not applicable	price for the steam supply is depending on the respective plant and the amortisation of the efforts for building and maintaining the supply connection (insulated piping, valves) which again is depending on the distance between tie-point and NPP
		Water supply				
T	012	Demin Water supply amount	Demineralized Water (or demineralized water with lye) is naturally the input source for hydrogen production via electrolysis and needs to be available in the sufficient amount. The overall water consumption is in some locations/countries a very significant paramert as the water is sometimes a rare resource (Spain)	very significant	stoichiometric value: 9 kg water/kg hydrogen technical values: 12 to 14 kg water/kg hydrogen (incl. high purity water production) i.e. approx. 7.300l/h for a 30MWel plant scale or 58.000 m³/a	
T	013	Demin Water for ELY Quality	Electrolzers need a high purity water. Even if there is demin. water available in the most NPPs it is mostly not clean enough to be used directly for electrolysis. Thus water make-up units need to be installed or even complete high purity water production units in case the available amount can not be provided. The requirements differ a bit from electrolyzer supplier. Column H gives typical values.	very significant	Conductivity µS/cm < 0.1 Sodium mg/l < 0.32 Iron µg/l < 6.0 Silica µg/l < 18 Aluminum ppb w/w < 126 Copper ppb w/w < 0.42 Chloride ppb w/w < 42 O2 mg/l Saturated CO2 ppb w/w < 16 TOC µg/l < 62.1 Turbidity NTU < 1 pH - 6.9 to 7.1 Total salinity mg/l < 0.1 (TDS: total dissolved solids) Total hardness °dH < 0.11	
C	014	Demin. Water Price	The price of the demin. water is depending on the necessary make-up or production facilities and thus depending on specific local circumstances. But availablility is probably more important than the price.	less significant		
C	015	Tap Water Supply amount and price	in case there is no demineralized water available on NPP the process water needs to be produced from tap water. In this case the tap water price feeds into the demin. water price. Tap water amount is bigger than demin water amount as water purification produces waste water. Depending on the used technology (mostly reverse osmosis) and quality of plant the efficency is to be expected between 70% to 90%	very significant	Efficiency of high purity water production is to be expected between 70% to 90%	
		Cooling supply				
T	016	Cooling Water	AEL and PEM produce waste heat that needs to be removed from the electrolyzer system via heat exchanger and connection to cooling water system of NPP. in case the cooling water can not be served by the NPP cooling water system, as dry cooling tower unit needs to be installed instead. In best case there was a possibility to use this heat e.g. for district heating; however most likely heat pumps are necessary to allow this. With HTSE the heat of the gaseous product stream is used to maintain the high operation temperatur and to pre-heat the feed water before evaporation. Cooling of the stacks via a cooling water circuit is not needed. But as the product gas temperature is much higher some excess heat may needed to be removed before or during gas purification even if the gas stream is cooled via the water pre heaters. In addition to the electrolyzer cooling, water is as well needed for process water preparation or polishing unit, the power electronics and the compressor unit.	significant for LTE less significant for HTSE	approx. 1.5 MW_th of heat to be removedfrom stack by cooling water for a assumed 30MWel HPP: approx. 800m³/h 600m³/h for stack cooling 160 m³/h for power electronics (transformers and rectifiers) 40 m³ /h for compressor, chiller, other	as there are three possible modes to run a HTSE i.e. exotherm, endotherm or thermo-neutral the amount of cooling varies very much from supplier to suppler thus cannot be given in distinct values here. The cooling needs for equipment of the BOP are the same as for LTE.

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T	017	Quality of Cooling Water	The heatexchangers of the HPP can be designed according to the quality of available cooling water of the respective coupled NPP. Thus the characteriscs of the cooling water are no very crucial. We give typical values as example.	less significant	Demin Water or 50% Glycol-mixture 50 to 100 µS/cm range • PH: 7.0 to 9.0 • Chloride content: < 20 PPM • Nitrate content: <10 PPM • Sulfate content: <100 PPM • Total solids: <250 PPM • Total hardness: < 250 PPM of calcium carbonate PH: 7.0 – 7.5	
T	018	Price of Cooling water	The cost of cooling are part of the operational cost, in case the cooling water is provided by the NPP the respective price needs to be taken into account.	significant for LTE less significant for HTSE	depending on the specific cost at the respective NPP site	
T	019	Chilled Water	Hydrogen product quality is reached via gas purification which is mainly the removal of water from the hydrogen gas. This is done in a first step by cooling the gastreeam below the dewpoint to condensate the contained vapour. Inorder to achieve this chilled water is necessary. Chilled water is most likely not available in NPPs. A chiller unit needs to be installed to cover this need. The chilled water unit needs to transfer the excess heat again to the cooling system of the NPP or to the air via dry cooling fans.	less significant	40-60m³/h with an assumed 30MWel HPP	
C	020	Price of chilled water	The cost of chilled water is part of the operating cost for the hydrogen purification.	less significant	???	
		Other supply				
T	021	Nitrogen for ELY supply line parameters	Nitrogen is used to flush hydrogen containing systems in emergency case or before maintenance operations may be carried out. In case there is a nitrogen supply system available the HPP may be connected to it. Whether this is worthwhile is depending on the distance between tie-in point and HPP location. As a standalone nitrogen station with nitrogen gas bottles are not very expensive this is likely to be the commercially better solution.	technically a MUST commercially less significant	1,7 Nm3/h per 10 MW (continuous flow) and 8.4 Nm3/h per 10 MW (Intermitent) Grade 4.8 (99.998%)	
C	022	Price for Nitrogen supply	whether provided by existing systems of NPP via connecting piping or via standalone unit of the HPP, the price for the needed nitrogen is part of the operational cost.	technically a MUST commercially less significant		
T	023	Instrument Air for ELY supply line parameters Line to NPP: DN12, PN10	In order to minimize ingnition sources that could spark an explosion in case of hydrogen leakages most valves in hydrogen bearing systems are pneumatically operated to avoid electrical actuation. Thus a supply of pressurized air is needed. Instrument air is likely to be available at NPPs. Thus the supply may come from there or via a standalone compressed air production unit which is not very costly.	technically a MUST commercially less significant	13 Nm3/h Per 10MW Electrolyzer 5-8 bar NPP line connection DN12, PN10	
C	024	Price for instrument air supply	whether provided by existing systems of NPP via connecting piping or via standalone unit of the HPP, the price for the needed instrument air is part of the operational cost.	technically a MUST commercially less significant	depending on the specific cost at the respective NPP site	
T	025	Waste water and sewage parameters	Water preparation and make-up and gas purification produce some waste water that needs to be removed from the HPP. In case of connection to NPP waste water system the respective allowed parameters need to be kept. Eventually a correction f pH-value is needed. Other opertions are not to be expected.	less signifcant	approx. 2m³/h for an assumed 30MWel HPP	
		Other requirements				
C	026	Frequency of Replacement of Electrolyzer Stacks	Electrolyzer stacks degrade with operation time. This is why performance values are always givenfor BOL (begin of live) and EOL (end of live) state. This means that the efficiency becomes worse over time and at a certain age is so low that stacks need to be replaced. Frequency of replacement is depending on electrolyzer technology and supplier. HTSE stacks degrade much faster than L'TE stacks.	very significant	PEM stacks has been estimated to have a lifetime of approximately 60.000h currently and by 2035 the expected lifetime will reach 95.000h. In case of AEL the current lifetime seems to be a little bit higher than PEM due to operating conditions, that is, 65.000h aprox but by 2035, the expected life will reach 80.000h (a little less thanPEM technology). This information is extracted from Deliverable 3.1.	SOEC electrolysers currently have relatively low durability and thus a low overall lifetime. In Deliverable 3.1 has been assumed around 30.000h for current lifetime, 60.000h lifetime expected for 2035 and 85.000h by 2050.

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C	027	Cost of Replacement of electrolyzer Stacks	frequency and cost of stack replacement are a significant parameter with respect to the operational cost and thus contribute significantly to the LCOH.	very significant	Current stack replacement costs are estimated in one third of the direct capital costs. In case of PEM technology these costs should be reduced by 2035 up to 15% due to new stacks designs where the repleacement tasks are easier. However, for AEL electrolysers is not expected a variation in the percentage assigned to stack cost replacement.	HTE suffers from much shorter stack longevity than LTE and conequently, the OPEX and stack replacement costs parameters have a significant influence on the final hydrogen production cost alongside the electricity price and CAPEX. The references analysed establish the stack replacement costs as a 30% by approximately 2035. The current stack replacement costs are considered to be higher than 30% currently, that is, around 39% in 2023.
T	028	Operational Parameters of electrolyzer	In a coupled hydrogen co-generation scenario the operation of the electrolyzer needs to be harmonized with the operational modes of the NPP esp. with the mode of supplying electricity. The start-up/shut-down time scales or ramp-up/dramp-down transients need to be harmonized. The electrolyzer design needs to be chosen to allow the wanted flexibility. Or vice versa the operational modes need to respect the possibilities of the electrolyzer. The parameters relevant in this context are given in the following lines.	very significant technically significant commercially		
T	029	ELY as a provider of flexible operating modes	There are three types of flexible operating modes: primary and secondary frequency regulation. In order to replicate or improve the performance of a NPP hybrid system compared with a NPP, it is necessary to consider the values and requirements currently accomplished by the NPPs. Control range and ramps are dependent on the NPP rated power.	very significant if regulation services are required to be provided. Less significant in other cases.	Technically, LTE can meet primary frequency control, but they need to be designed for such purpose. The studies that conclude this, are focused on one-digit MW so, it seems that for low power NPPs the coupled electrolyser could meet the primary frequency requirements but in case of higher power, further analysis and technical development is required. The secondary frequency control requires less critical dynamic characteristics than for FCR, but longer duration. There are demonstration projects with PEM electrolysers qualified for providing services in secondary frequency control.	Available information in the literature about HTSE to operate under flexible is still scarce due to the still low TRL of this technology. According to Deliverable 2.2. Part b, the war-up start-up time is significantly higher than LTE and ramp-up and ramp-down frequencies are also lower compaerd with AEL and PEM. Therefore, this technology is not found suitable to be operated under flexible load but under baseload mode.
T	030	Control concept of H2 production	Depending on the H2 delivery contract that the NPP hybrid system have signed with the consumer, different H2 production modes could take place. For example, in case of delivery not guaranteed, that is, to deliver as much as hydrogen is possible to be produced, the most convenient H2 production mode from economic perspective is price-based strategy, that is, to produce hydrogen when the day-ahead market price is low and to stop the production when the prices are high. However, if a contract with penalities is signed, the best strategy is produce 24h no matter the price of the electricity, to avoid penalties.	very significant	It has not been analysed from a technical point of view the run/stop limitations of electrolysers. However, it seems that are less demanding than the case of flexible operation so, it is thought that LTE electrolysers could perform H2 production strategies different than continuous production.	Production H2 strategies in case of HTSE seems to be more difficult to be applied. As previous line, the information about flexible operation in the literature is scarce so, in this case, it is advisable to operate in continuous mode.
T	031	Building Area Space availability Location	The HPP needs some suitable area to be erected, as well the potentially needed hydrogen storage. There a re several criteria to be taken into account. The area needs to be big enough to bear all the necessary equipment. The location is to be chosen carefully: as close as possible to the tie-in points of the connected systems to minimize connection cost. At the same time potentially dangerous parts of HPP (stacks and even more storage tanks(need to be placed far enough from sensitive NPP installments to ensure explosion risk at an acceptable level. This is depending on site specific circumstances. In some cases on-site scenarios may not be possible t all. Or HPP and hydrogen storage need to be separated locally. Apart from that the soil conditions must allow for the foundations.	very significant	80x60m for a 30MW PEM plant area needs to be suitable for the erection of a HPP. loads to the soil or civil structures depend on technology and supplier	HTSE needs more space than PEM due to the more complex equipment and the higher amount of heat-exchangers/ pre-heaters etc.
T	032	Storage solution	There are several storage solutions available for hydrogen - above ground or under ground. Most commonly used is storage of hydrogen gas under pressure. Liquification was an alternative or LOHC or adsorption to metalhydrides. The most suitable solution is depending on the customer and transportation solution. Pressurized storage is the most likely solution for 30MW scale production and pipe duct transportation. When hydrogen is transported in tube trailers, high pressure vessels in the range 350-700 bar are used in gas terminals.	significant		

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T	033	Required Hydrogen Storage Capacity (Storage Days)	Storage capacitiy is depending on the customer requirement regarding availability of supply and the transport solution. Storage capacity should cover possible periods of non-production due to the general operational mode chosen plus outages of NPP, maintenance on HPP. It is not possible to give a general number of storage size.	significant		
T	034	Compressor Package specifications	Depending on the electrolyzer technology, offtaker and transport solution a compressor station is needed to increase the product pressure to the needed pressure for tranportaiton or use. Thus the needed pressure increase is very site specific and cannot be given in general. To give a order of magnitude we may state the delivery pressure of LTE lies in a range from ambient pressure to 30bar. Transportation with gas ducts is performed in a range of 70 to 100 bar and transportation with tube-trailers is performed in a range of 250 to 550 bar.	significant	When hydrogen is transported with gas ducts centrifugal multistage compressors are used. When hydrogen is transported by tube-trailers a gas terminal for loading hydrogen into trailers is required. In gas terminal the use of reciprocating multistage compressors is suggested	
L	035	Construction permit	Before a construction permit can be granted, the environmental impact of the construction phase as well as the operating phase has to be assessed (EIA), the possible adaptation of the land-use plan has to be accepted and the overall design has to fulfill all building-/construction requirements.	significant for the erection of the plant and contribution to the cost of design documentation i.e. CAPEX		
L	036	Operating permit	Before an operating license can be granted, the actual installation has to be commissioned; showing to be according design and fulfiling all safety and operational requirements. An update of the safety assessment report , the final SAR, has to be submitted and the regulator has to approve this.	significant for the erection of the plant and contribution to the cost of design documentation i.e. CAPEX		
C	037	Local market prices for H2	This is not a requirement but the main paramter for the calculation of the commercial benefit of hydrogen production. The co-generated hydrogen must be competitive with the market price for hydrogen. This very much depending on the country and is changing rapidly. It is important to note that hydrogen from co-generation with nuclear energy needs to be compared with other low-carbon hydroge as e.g. from regenerative energy.	very significant		
C	038	Local funding for green H2	Currently the production of low-carbon hydrogen is more expensive than conventional produced hydrogen from fossile sources. But as there are efforts to decarbonize the industries there are respective programms to foster the development of low-carbon hydrogen production. If there were respective fundings in a given location at a given time this could reduce the cost for nuilfing respective HPP or reduce the production cost. E.G. is the Inflation reduction act in the U.S. that is granting significant tax reduction to the production of hydrogen from nuclear energy.	very significant		
T	039	Lifetime of HPP	The lifetime of the HPP is an important parameter to calculate the cost of hydrogen production. This is a design parameter to be decided on in the planning phase.	very significant	10 to 30 years i.e. 80,000 h to 240.000h of operation	
O	040	Available customers for oxygen	as mentioned above the potential of selling the by-product as well is a parameter for chosing suitable locations	less significant		
C	041	CAPEX Hydrogen Production Plant (stack + BoP)	HPP CAPEX is the second more important cost from LCOH point of view in case of LTE and the most important cost in case of HTSE. So, it is a relevant parameter. Obviously, the lower this value, the better. Up to date, the costs are high but for all technologies is expected a decrease in prices thanks to technological progress.	very significant	The current PEM cost is approximately 1200 €/MW and the projected cost for 2030 is expected to decrease to 900 €/MW. In case of AEL, current cost is cheaper than PEM, 1100 €/MW and the projected cost for 2030 is approximately 650€/MW. By 2050 the projected cost for both technologies should be quite similar, around 200 €/MW	Current cost for SOEC technology is much more higher than LTE. Currently, it is around 2800 €/MW and the value projected for 2030 is 900 €/MW. The cost decrease expected is really high.
T	042	Degree of integration HPP/NPP (electrical systems, water systems...)	According to analysis performed in Deliverable 3.2, there is a clear economic benefit in case of electrical integration. However, no decisive conclusion about water systems integration has been made. More detailed analysis is needed on these last systems integration. In case of steam, it is also a promising integration for HTSE.	very significant	As it is stated, electrical connection is a clear benefit but not final conclusion has been obtained regarding the water systems integration.	Electrical connection and steam utilization is clearly a benefit. Besides, as the SOEC CAPEX is expected to experiment a big decrease, high temperature electrolysis is envisaged as a promising technology.

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C	043	NPP cost modification	The NPP cost modification is dependent on the degree of integration. The relevant key point here is not the total cost of the modification but if the total cost is covered by the savings obtained using shared resources.	significant	According to analysis performed in D3.1, the cost modification needs to consider also licensing requirements (documentation modification, training, etc). The electrical connection has a medium complexity but as long as the integration is higher, also de associated costs.	The NPP modification for steam extraction is expected to be higher than no matter the case with LTE. However, the efficiency of the electrolyzer is higher so, the key element here is to evaluate if leveraging the steam compensates the cost of the modification
C	044	HPP OPEX - Fix	The OPEX fix is not considered a relevant value for LCOH weight. In this OPEX replacement costs are not included. In any case, as other costs, the lower the better. OPEX fix is usually defined as a percentage of the CAPEX. For HTSE OPEX is more relevant value than for LTE.	less significant	Most of the studies establish PEM OPEX between 1-3% of the PEM electrolyser CAPEX.It has been assumed for PEM cost model a target of 2% by 2030 and a target of 1% by 2050. The maintenance costs for AEL are lower than those detailed for PEM electrolysers due to its operating conditions. It has been assumed a currently value of 2% and a target of 1% by 2030.	For case of SOEC, it has been assumed a value of 3,5% of direct capital costs. The percentage is higher than in case of LTE and besides, the amount per year will he higher due to CAPEX higher.
C	045	OPEX - Variable	The OPEX variable is not considered a relevant value for LCOH weight. Variable OPEX depends on yearly production. It is expected a decrease in this value for all technologies. As in the case of Fix OPEX, in case of HTSE this value is more relevant than in case of LTE.	less significant	The value assumed in Deliverable 3.1 for PEM technology is 35 € /(kg/day)/year. The forecasted value for 2030 is 22 € /(kg/day)/year. In case of AEL the values assumed are 43 € /(kg/day)/year (current value) and 36 € /(kg/day)/year (2030)	The value assumed in Deliverable 3.1 for SOEC technology is1905 € /(kg/day)/year. The forecasted value for 2030 is 46 € /(kg/day)/year.
C	046	Price of emissions allowances	As hydrogen is part of a sector considered at risk carbon leakage, installations can benefit from free allocation Emissions Trading System (ETS) allowances. These allowances are assumed to be possible to be traded in the EU ETS and this way, to be an additional stream revenue for low carbon hydrogen production facilities.	significant	Dependent on the value of Emissions Trading System (ETS).	
C	047	Duration of HPP construction (years)	It is directly connected with capital cost	significant	dependent on the specific situation of a NPP site	
C	048	Equity financing (%)	To raise capital for business needs, companies primarily have two types of financing as an option: equity financing and debt financing. Most companies use a combination of debt and equity financing.	significant	dependent on the specific situation of the investor	
C	049	Interest rate of debt (%)	parameter relevant for the calculation of production cost and amortisation of invest; very site specific thus not possible to be given in exact numbers	significant	dependent on the specific situation of the investor and financing entity	
C	050	Inflation rate (%)	parameter relevant for the calculation of production cost and amortisation of invest; very site specific thus not possible to be given in exact numbers	significant	Dependent on the countries	
C	051	Taxes (%)	parameter relevant for the calculation of production cost and amortisation of invest; very site specific thus not possible to be given in exact numbers	significant	dependent on the specific situation of a NPP site	
C	052	Discount rate (%)	parameter relevant for the calculation of production cost and amortisation of invest; very site specific thus not possible to be given in exact numbers	significant	dependent on the investor	
C	053	Hydrogen delivery guaranteed (most likely with penalties)	Hydrogen purchase agreements are not extended so far. The most part of the hydrogen production sites deliver as much hydrogen as it is produced. However, in case several producers are available, consumers could start to require certain delivery conditions. One of them could be a fixed quantity of hydrogen and in case of not delivering it, apply certain penalties. The cost od the penalties is a relevant value when LCOH is calculated and also really important when hydrogen production strategies are defined.	significant	Dependent on the agreement reached with the consumer	
C	054	Hydrogen Storage cost	Hydrogen gas storage cost increases as storage pressure increases. According to Argone National Laboratory “System Level Analysis of Hydrogen Storage Options” (2019) the pipe storage CAPEX per kilogram of stored hydrogen is USD 516 (100 bar). For the scenario presented in Deliverable 3.1 the CAPEX represents 95% of the annual storage cost and O&M represents the remaining 5%.	significant	According to the information presented in NPHyCo (Deliverable 3.1), the Total Installed Cost per kilogram of stored hydrogen for high pressure hydrogen storage in the range of 350 to 700 bar is in the range of USD 1544 to 2316 (2020)	

Classification	Number	Designation of Requirement	Relevance of Requirement	Significance (with respect to LCOH) S1 = very signifcant S2 = significant S3 = less significant parameter	Typical values Low Temperature Electrolysis PEM or AEL	Typical values High Temperature electrolysis SOEC
C	055	Hydrogen transport costs	The cost-effective approach for providing hydrogen depends on several factors, including the distance of transportation, the quantity of hydrogen needed, the end use of the hydrogen, and the availability of existing infrastructure. According to NPHyCo results there is only little chance to find a hydrogen offtaker in close vicinity to NPPs. Thus transport over larger distances is necessary in most cases. In mid- or long-term perspective hydrogen distribution should be accomplished via a grid of pipelines, the hydrogen backbone. This is today not yet existing. Thus hydrogen needed to be transported via tube-trailer to the offtaker.	very significant in case there is a need for transport oover longer distances	According to the information presented in NPHyCo (Deliverable 3.2), the estimated hydrogen transport cost (using Optymizer tool), for 30MW scale production, with the two different transport scenarios proposed is: - 100 km by pipeline (including compressor, storage and pipeline): 2,65 €/kg - 159 km by tube-trailer (including compressor, storage and trucks): 2,32 €/kg	
C	056	Waste treatment cost (including waste water)	process water preparation and make up produces some waste water that needs to be dismissed in a waste water system. Expenses for connection need to be taken as part of CAPEX, respective fees add to OPEX	less significant	independant of electrolyzer technology	
T	057	Remaining lifetime of NPP	NPHyCo investigates the possibilities to use existing NPPs for co-generation. Thus the remaining lifetime of the NPP limits the time-span in which the return of interest can occur. Thus this is a very important parameter for the commercial analysis and the seltion of a suitable site.	very significant		
T	058	Average yearly idle capacity of NPP Percentage of yearly hours that NPP operates at a loss	In case the operational concept of co-generation was to use only the capacity of the NPP that is not demanded by electricity production for the grid, this capacity defines the maximal operation time of the HPP. This is relevant for the production capacity and thus the OPEX calculation.	significant		
C	059	Day ahead electricity market price	In case the operational concept of the HPP is intended to produce hydrogen only if the revenue is better than for simple electricity sales the day-ahead electricity price is the most important parameter to decide to produce or not. Additionally, is important to calculate what is called " delta trading", that indicates if it is better to continue just producing hydrogen or change the business model to also produce hydrogen. Delta trading is what the NPP is not earning because they are using certain quantity of electricity to produce hydrogen. If the day ahead market prices are high, delta trading is higher and it is less convenient to change the business model.	very significant		
O	060	Minimum safety distance of HPP to sensitive parts of NPP	Some parts of the HPP bear a explosion risk. this needs to be taken into account when coupling a HPP to a NPP. The main aspect to reduce rsik to an acceptable level is to maintain respective safety distance between sensitive structures of NPP and potential sources of explosion. If this is not possible other mitigation measures might be used. This is analysed in the impact assessment in D2.2A	very significant for safe operation and thus for the licencing of the plant. respective distances or necessities for oter measures contribte to the cost of integration.	The minimum safety distances required to ensure that the worst-case accident scenario in the HPP does not jeopardize critical NPP structures and buildings depend on several factors. On the one hand, on the vulnerability of the NPP structures, which is expressed in terms of the structural fragility criterion (10 kPa), and on the other hand on the features of the pressure wave generated after a postulated hydrogen explosion (i.e., deflagration or detonation). The resulting pressure wave will depend on the combustion of the hydrogen-air mixture, which in turn is based on the vapour cloud, type of enclosure (e.g., container or building), and release features (i.e., leak size and orientation). According to the outcomes from the impact assessment summarized in D2.2A, a chemical explosion in the electrolyser facility would require a minimum distance of 85 m to comply with the 10 kPa criterion, whereas a physical explosion in the 30 kg buffer tank would require a minimum distance of 85 m. In addition, the explosion in the buffer tank would have the potential to generate missiles with a maximum flying range of 564 m. If the HPP is located in the centre of the proposed integration site in Rivne NPP, it would provide additional 44 m from the site boundaries. Based on the outcomes from the applied calculations, onsite integration of the electrolyser facility seems to be a feasible option from a safety perspective. However, additional calculations with plant specific data and high-fidelity computer codes are required. Contrarily, the 30 kg buffer tank should be located at an underground configuration or outside of the NPP perimeter to protect the standby diesel generators, cooling towers, and turbine building from possible missile impact. Finally, the high-pressure storage area needs to be placed outside of the NPP perimeter at a safe distance based on the storage capacity (energy) due to the large hydrogen inventory.	