Scenario Definition

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Abbreviations and acronyms

Acronym	Description
ASTM	American Society for Testing and Materials
HPP	Hydrogen Production Plant
HTSE	High Temperature Steam Electrolysis
HV	High Voltage
LTE	Low Temperature Electrolysis
LV	Low Voltage
MSR	Moisture Steam Reheater
MV	Medium Voltage
NPP	Nuclear Power Plant
SI	Safety Injection
SOEC	Solid Oxide Electrolysis Cell
PEM	Proton Exchange Membrane Electrolysis

Summary

The main objective of the Deliverable D1.2 of the project NPHyCo is to define the potential scenarios for integration of a Hydrogen Production Plant (HPP) into a Nuclear Power Plants (NPP). Definition of the scenarios is needed in order to be able to assess the feasibility and viability of the integration and establish the framework of the subsequent studies.

In the first section of the document (Section 2), the needs of a HPP have been investigated. The resources required for operation of a HPP have been gathered taking into account different electrolyzer-technologies (AEL, PEM and HTSE technology). These resources may be served by the already existing infrastructure of a coupled NPP in operation. Simplified HPP process flow diagrams for these three electrolyzer-technologies have been provided.

A list of 28 reactors of the European NPPs in operation from the 12 countries has been given in Section 3. These NPPs can be considered as potential plants for integration with a HPP.

Section 4 gives an overview of possible levels of integration of HPP into NPP. The good level of integration depends on the availability of the respective sources on NPP side, the induced impacts of such coupling and finally of the commercial benefit it creates. Obviously, there are two limiting scenarios with full integration, where all the HPP needs are served by NPP, and zero integration, where the HPP needs cannot be provided by NPP. On the other hand, there is a wide range of scenarios with partial integration and a lot of combinations for interfaces between HPP and NPP.

In Section 5, the possible modes of NPP operation which should be considered have been discussed.

The initial setup for the definition of realistic scenarios has been explained in Section 6. To derive reasonable scenarios for further investigations from the potential levels of integration it is helpful to take into account some considerations based on first results of the interface investigation or experiences of the consortium members. In addition, some assumptions need to be made to enable the start of the subsequent work within NPHyCo. In particular, such aspects as power capacity of the coupled HPP, its location related to the NPP (on-site or off-site), availability of the NPP resources required for HPP operation have to be considered. The impact of the NPP type on the scenario definition has been also discussed in this section.

Respective off-taker analysis and connection to the customer have been investigated. The results of the off-taker investigation showed that in most cases there is no close vicinity between NPPs and hydrogen consumers.

In Section 7, the 9 potential integration scenarios have been defined based on the investigation of the needs of a HPP, possible integration levels between NPP and HPP as well as off-taker analysis. The analysis of the 9 potential integration scenarios needs to be performed for the main three electrolyzer-technologies (AEL, PEM and HTSE technology). Additionally, the analysis should be performed for all the potential locations of HPP.

At the time of issuance of this document only the information regarding the two Ukrainian NPP sites were sufficient for further investigation. Therefore, detailed interfaces for the 9 scenarios for Khmelnitsky NPP have been prepared for further investigations.

The document provides also an Integration-Analysis-Matrix which shall summarize the results of the further investigations of the WP2, WP3 and WP4 and should support the decision concerning the final scenario for the pilot HPP plant.

1 Introduction

The transition to a low-carbon economy has increased the interest in hydrogen as a clean and sustainable energy carrier. In recent years, integrating nuclear power plants with hydrogen generation technologies has emerged as a potential solution, and in D1.1, various pathways for nuclear-powered hydrogen production were explored, and their advantages and disadvantages were analyzed. Based on the findings of D1.1, water and steam electrolysis technologies were chosen for further analysis, while technologies involving fossil fuel reforming and thermochemical cycles were excluded from the subsequent studies. Technologies that release CO_2, such as fossil fuel reforming, are not aligned with the project's objectives. Thermochemical water-splitting technologies, although very promising, are not expected to become commercially available within the near future. Thus, NPHyCo study will primarily focus on the low-temperature electrolyzers, represented by alkaline and proton exchange membrane (PEM) technology, as well as high-temperature electrolyzers, represented by HTSE (high temperature steam electrolysis)/SOEC (solid oxide electrolyser cell) technology.

NPHyCo is investigating the feasibility of producing low-carbon hydrogen with electrolysis-plants coupled to Nuclear Power Plants in Europe. Basic idea is that the use of existing infrastructure of a nuclear power plant may have additional benefits to produce hydrogen (compare D1.1 "Project Frame of Reference Report").

In this context there is a multitude of parameters to be considered:

- Type of Nuclear Power Plant (NPP)
- Type of Hydrogen Production Plant (HPP)
- Availability of infrastructure and media
- Distance between NPP and HPP
- Level of Integration
- Location

Plant-types (NPP and HPP) and the distance between the plants have influence on the level of integration. The location is defining the legal and the licensing framework and the market situation for hydrogen and electricity. All this is affecting the production cost of hydrogen and the potential achievable profits. In addition to the feasibility analysis NPHyCo is aiming to provide a decision matrix to enable decision makers in European countries to find the best spots and technical solutions for such a venture. Main criteria for such decision are

- Cost of produced hydrogen / Achievable price for hydrogen
- Price of electricity
- Location / Transport route to consumer of hydrogen
- Remaining lifetime of the NPP
- Hydrogen strategy of the country
- Interest of the operator of the NPP

To organize the investigations, it is necessary to define "scenarios" that cover respective combinations of the above-mentioned parameters. The following deliverable D1.2 "Scenario Definition" is going to describe the potential scenarios and explain which were selected for further analysis and why.

In the following the needs of a hydrogen production plant are described and the general possibilities how this needs may be served via the existing facilities of nuclear power plants. Respective levels of integration are defined. The analysis of site specific possibilities finally gives the list of scenarios that shall be investigated further in the other work packages of NPHyCo.

2 Needs of Hydrogen Production Plant

In order to define the possible scenarios for a coupled Nuclear Power Plant and a Hydrogen Production Plant, the needs of an HPP are essential to define. These needs represent a spectrum of technical, economical, and environmental considerations that collectively define the foundation for efficient and sustainable operation. In this Chapter, the main requirements of an HPP are defined, and the details of the general plant design and the special requirements of the different technologies are given in deliverable D2.1 of NPHyCo, “Analysis of viable interface within NPP environment for H2 generation”.

Figure 1 to Figure 3 shows a general plant design in the form of a simplified Process Flow Diagram according to the alkaline, PEM and high-temperature (HTSE/SOEC) electrolyzer technologies, and based on the findings of D2.1, the main needs of electrolyzer plant to produce hydrogen are the followings:

1. Electricity
   Electricity in DC is the energy source for the electrolysis process. As NPP are producing electricity this is available in abundance on NPP sites. The main objectives to analyze are how much electricity may be dedicated to the production of hydrogen, at which price and from which point in the internal grid will it be taken. The amount of electricity dedicated is highly dependent on the revenues to be gained with the production of hydrogen. But this is a result of the investigations of NPHyCo. In order to launch the analysis NPHyCo starts with the assumption of a nominal scale for the HPP plant of 30MWel (actual consumption of electricity is higher). And the availability of the respective amount of electrical power at NPP side. Later sensitivity analysis will show where the best scale from commercial point of view may be.

   The electricity needed by HPP is direct current which is not available in NPPs. Thus, respective rectifiers need to be integrated in the HPP plant.
   Depending on the voltage level of the electrical tie-in point in the NPP respective transformers may be needed as well.

2. Feedwater = Demineralized Water or steam
   Demineralized water with a high level of purity is the main consumable of the electrolytic production of hydrogen. As the water in the primary circuits of NPPs is demineralized water as well all NPPs have respective facilities to produce it, most likely with sufficient production margin to serve the needs of a HPP (if it is small enough). As many electrolyzers have very high requirements on the purity of the demineralized water, the available quality may not be sufficient and a feed water make-up unit may be foreseen to close the gap [6].

   In case of HTSE technology the feedwater is entered into the electrolyzer unit in the form of steam. Steam is in general available in NPPs but not superheated as needed for an HTSE. In order to do that, additional equipment is necessary (seeD2.1). On the other side this additional effort is paid back with higher efficiency of the electrolyzer.

3. Wastewater dump
   A feedwater make-up unit and some other process steps as well produce wastewater in the HPP which needs to find a sink. NPPs have water demineralization unit for own needs and the installed Waste Water Systems are designed to take wastewater from such desalination system. As feedwater make-up basically uses the similar technology most likely the

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wastewater conditions are acceptable for the HPP. In case of an HPP using alkaline technologies parts of the lye will be in the wastewater resulting in an increased pH-level (pH<12). In this case there might be a need for neutralization before tie-in. This needs to be checked with site-specific requirements case by case.

4. Component-Cooling
   The electrolyzer stack (especially PEM and Alkali) and other equipment (mainly the compressors) produce heat in operation and need cooling. All NPPs possess several cooling systems to be used for that purpose. It is important to choose a system with sufficient capacity to serve the additional load and which may have the least impact to NPP safety in case of disruptions. The hydrogen gas purification which comprises drying by cooling below dew point in a first step (adsorptive gel dryers etc. follow as a second step) needs respective cooling as well. This needs chilled water which is most likely not available in NPPs. Tus a chilled water unit needs to be integrated in the HPP which itself needs cooling water to operate.

5. Pressurized Air
   For safety reasons many drives for valves etc. are pneumatic to minimize ignition sources. Thus, the HPP needs pressurized air for the operation of this equipment and instruments. Pressurized air is available in all NPPs.

6. Nitrogen
   The HPP needs nitrogen for purging purposes i.e. to remove potentially explosive gas mixtures before specific operation mainly in maintenance. Nitrogen is in general available in NPPs as well for similar purposes of inertization.

7. Safety Environment
   As producing potentially explosible gases a HPP has a lot of safety features to avoid, mitigate and reduce effects of emergency situations. Thus, respective safety environment needs to be established. As NPPs per nature have the same requirements and facilities as respective co-use may be possible or is even mandatory e.g. signalization of fire, explosion …

8. Personnel
   It is intended to use HPP design that operates automatically with only little need for operators. Nevertheless, some activities may not be possible to avoid e.g. regular safety walk downs. And the operational parameters of the plant need to be shared with the control units of the NPP. NPP staff who have a high level of safety awareness may cover the personnel requirements of a HPP.

As described above, all needs of a HPP may be served by NPPs in operation. The conditions of use may vary from location to location depending on the plant type, plant age and local circumstances. It is necessary to clarify with operators in detail to which extent the integration of a HPP is possible. Potential levels of integration are described in the following in chapter 4.

Respective feedback from operators or research-results on NPPs is covered in D2.1 and is taken into account for the definition of scenarios. D2.1 and the derived scenario definition of D1.2 serve as a preliminary step for the subsequent work packages, particularly WP3, which focuses on evaluating the economic viability of nuclear-powered hydrogen production.

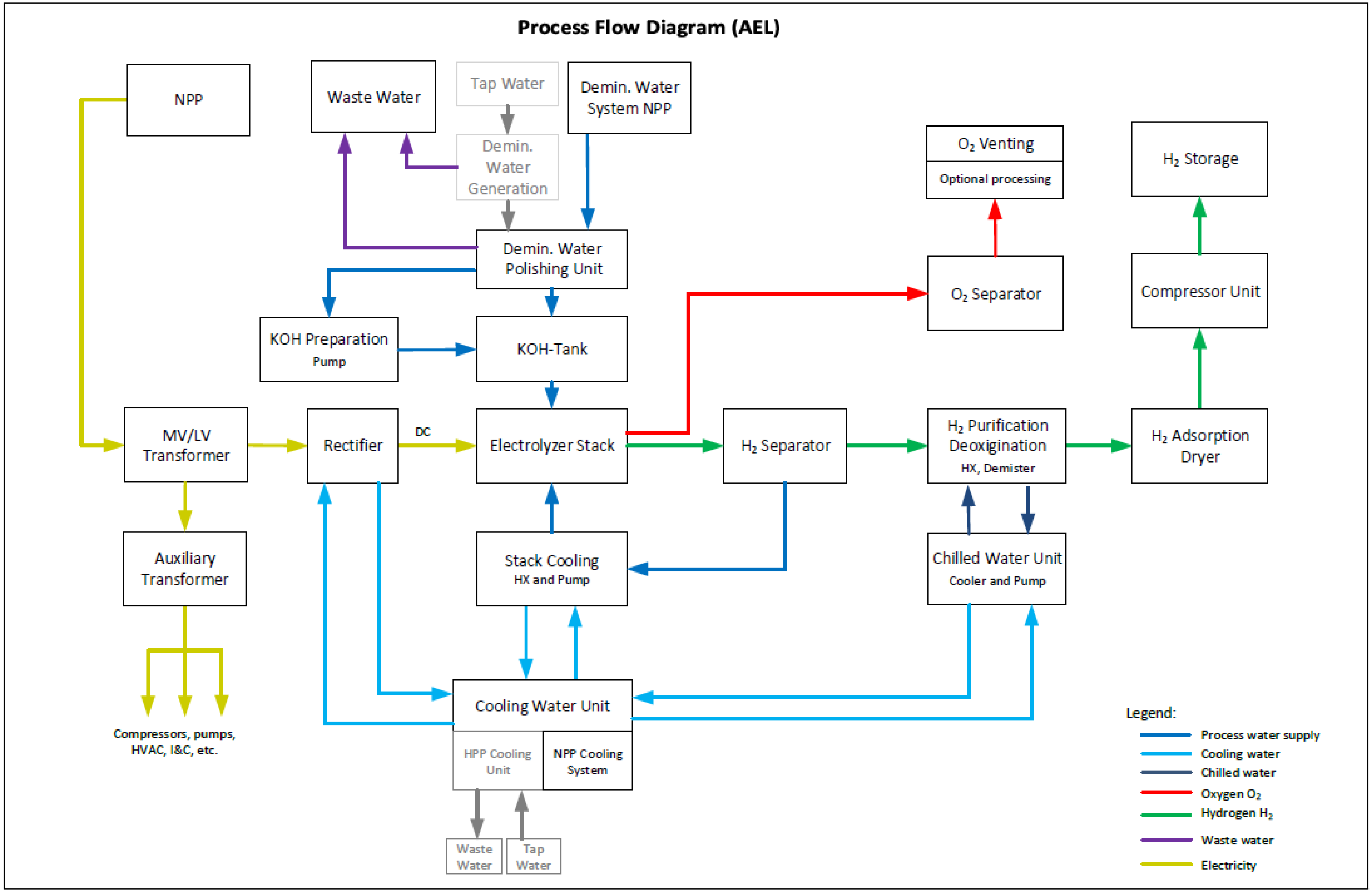

Figure 1: HPP Process Flow Diagram based on the AEL technology

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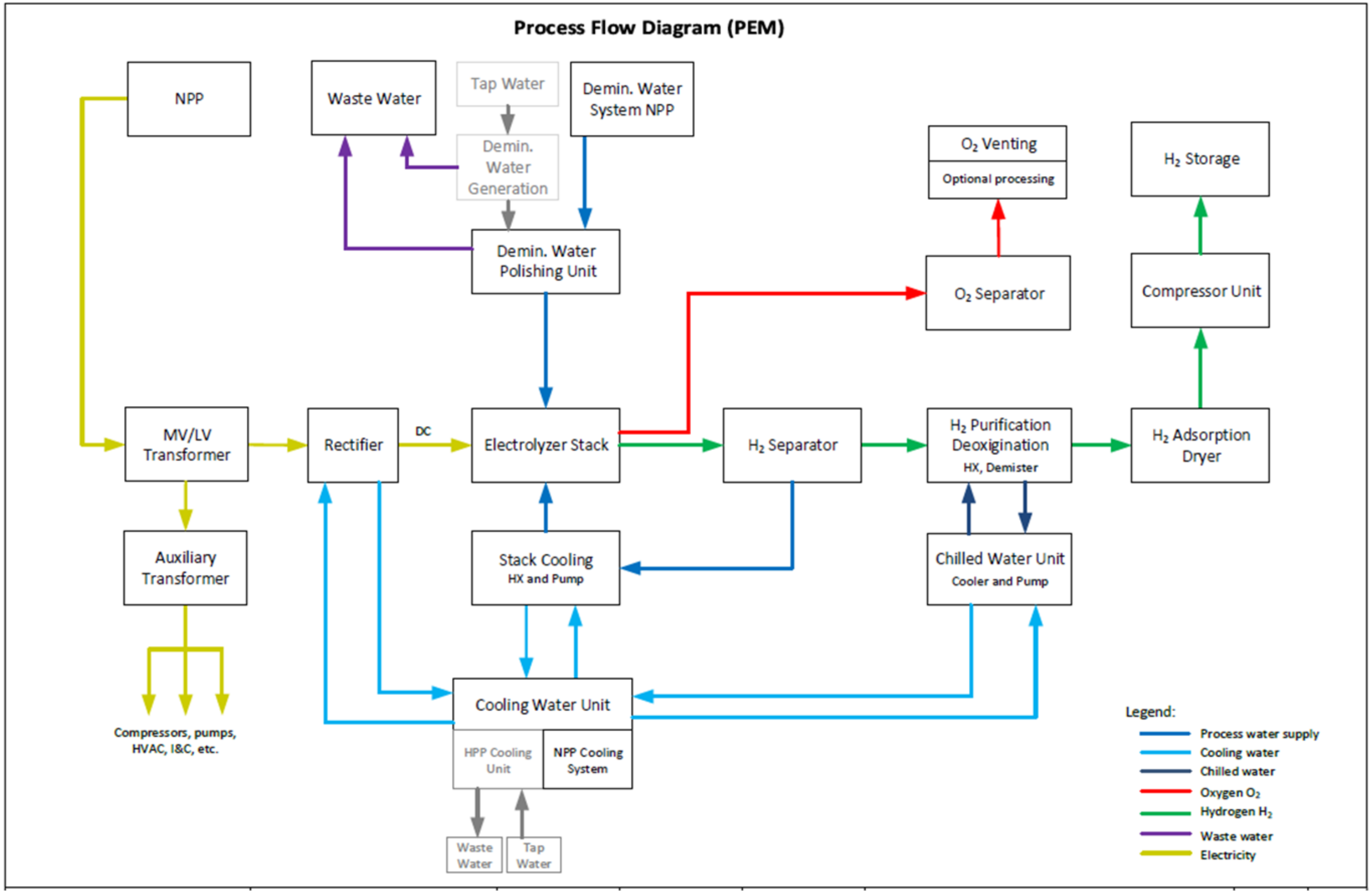

Figure 2: HPP Process Flow Diagram based on the PEM technology

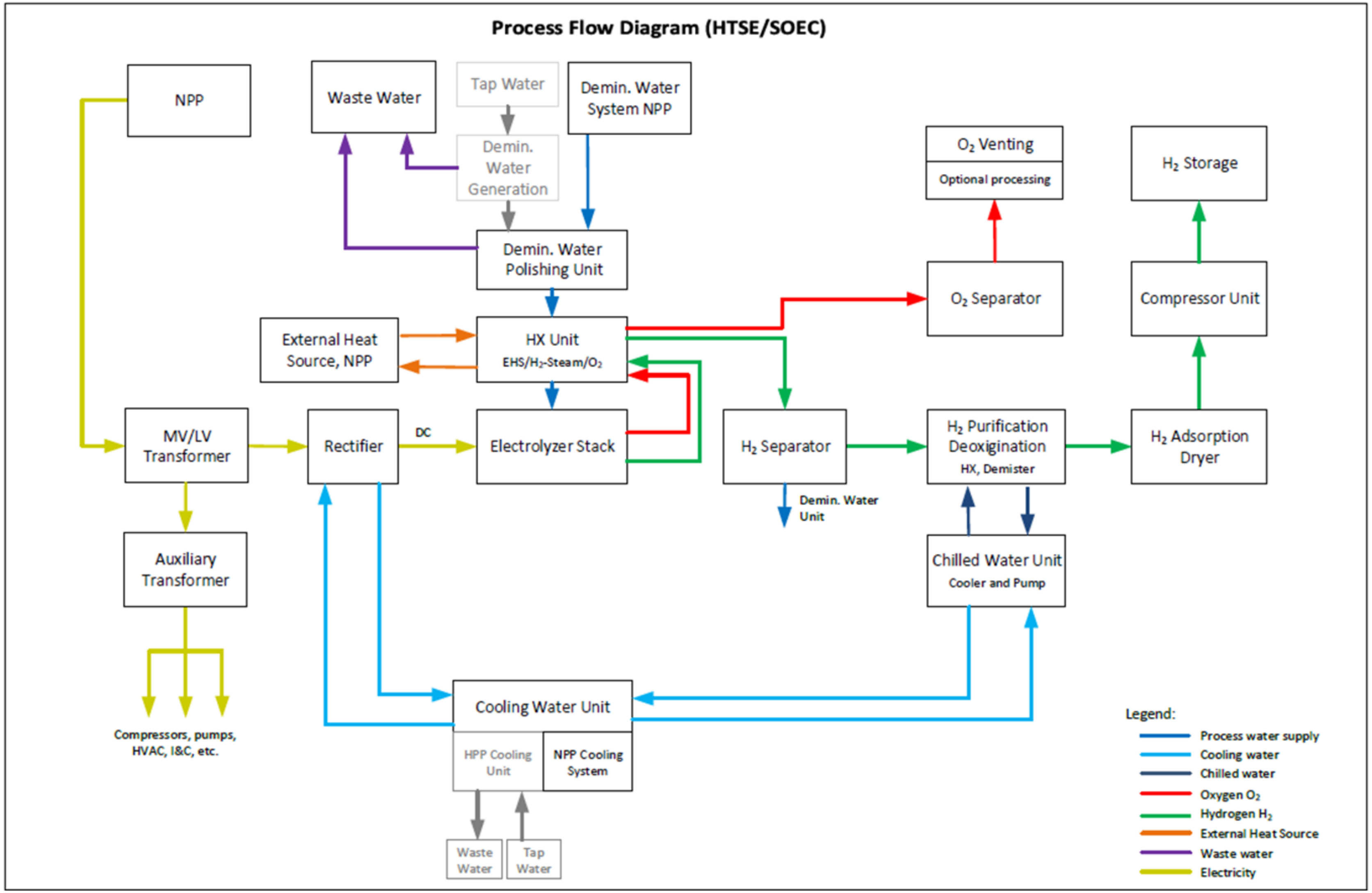

Figure 3: HPP Process Flow Diagram based on the HTSE/SOEC technology

3 European Nuclear Power Plants in operation

3.1 List of Power Plants considered

To identify the nuclear power plants to investigate the NPPs were screened after following criteria:

1. Focus: Europe
2. Type: Boiling water reactor (BWR), Pressurized water reactor (PWR) including VVER, Pressurized Heavy Water Reactor (PHWR)
3. Expected remaining Lifetime > 10 years. NPPs with periodical lifetime extension (every 10 or 20 years) are also considered.

The result, which is represented in Table 1, was to consider the following 28 reactors in 12 countries

Table 1: NPPs to investigate

Country	NPP	Reactor type
Ukraine	Rivne 1+2	PWR, VVER-440/213
	Rivne 3+4	PWR, VVER-1000/320
	Khmelnytsky 1+2	PWR, VVER-1000/320
	Zaporizhzhia 1-6	PWR, VVER-1000/320
	South-Ukraine 1-3	PWR, VVER-1000/302/338/320
Finland	Loviisa 1+2	PWR, VVER-440/213
	Olkiluoto 1+2	BWR, ABB-III/BWR-69-920
	Olkiluoto 3	PWR, Areva-EPR-1720
Slovakia	Bohunice 3+4	PWR, VVER-440/213
	Mochovce 1-4	PWR, VVER-440/213
Czech Republic	Dukovany 1-4	PWR, VVER-440/213
	Temelin 1+2	PWR, VVER-1000/320
Hungary	Paks 1-4	PWR, VVER-440/213
Bulgaria	Kozloduy 5+6	PWR, VVER-1000/320
Switzerland	Gösgen	PWR, KONVOI-1000
	Leibstadt	BWR, BWR-6-238-648-1200
	Beznau 1+2	PWR, Westinghouse M210-380
Spain	Trillo	PWR, KONVOI-1000
	Almaraz 1+2	PWR, Westinghouse M312-1000
	Asco 1+2	PWR, Westinghouse M312-1000
	Vandellós 2	PWR, Westinghouse M312-1000
	Cofrentes	BWR, BWR-6-218-624-1000
Romania	Cernavoda 1+2	PHWR, CANDU-6-700
Sweden	Ringhals 3+4	PWR, Westinghouse M312-1000
	Forsmark 1-3	BWR, ABB-III/BWR-69/75-1000
Belgium	Doel 4	PWR, Westinghouse M314-1000
	Tihange 3	PWR, Westinghouse M312-1000
Netherlands	Borssele	PWR, KONVOI-515

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The French plants are not included in the Table 1 because in France it is not allowed for NPP to produce anything else than electricity. In addition, from EDF's point of view, it makes more sense to produce the hydrogen close to the off-taker and not close to the electricity-provider as in France there is the same portion of nuclear power within the electricity grid anywhere and there is no variation of electricity prices in dependence on the portions of different power sources.

4 Levels of integration

Some of the needs of a HPP may be covered with already existing infrastructure of a coupled NPP. Thus, the systems of a coupled HPP are to some extent integrated into the systems of the NPP. The good level of integration depends on the availability of the respective sources on NPP side, the induced impacts of such coupling and finally of the commercial benefit it creates.

As it is indicated in Section 2 there is a group of systems that must be evaluated to define the level of integration. This is done in NPHyCo deliverable 2.1 and summarized in the following.

The Figures included below show the possible levels of integration.

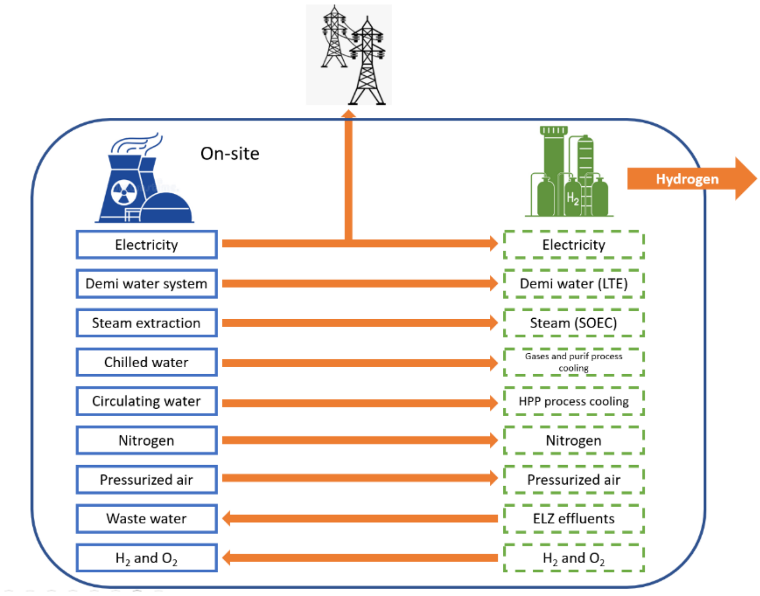

Figure 4 Full integration scenario

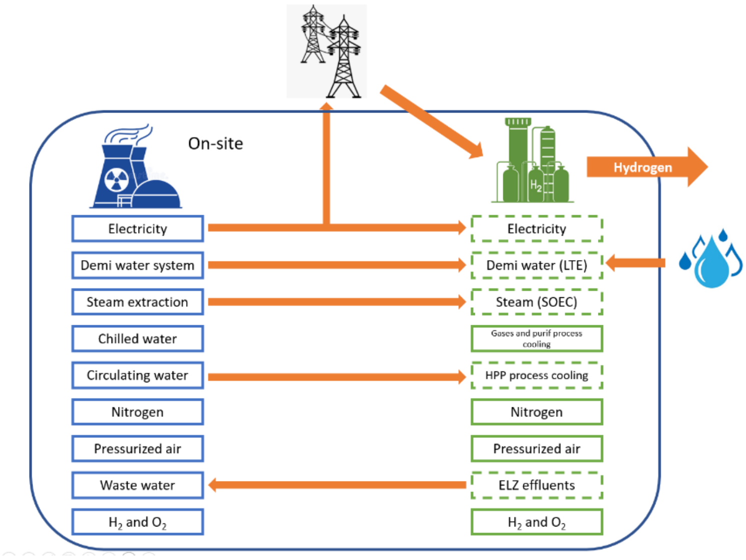

Figure 5 Partial integration scenario (on-site)

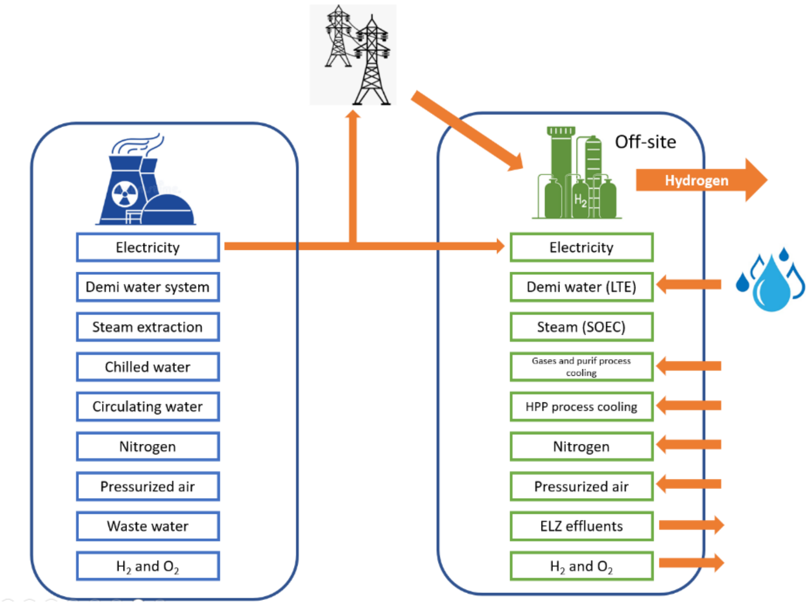

Figure 6 Partial integration scenario (off site)

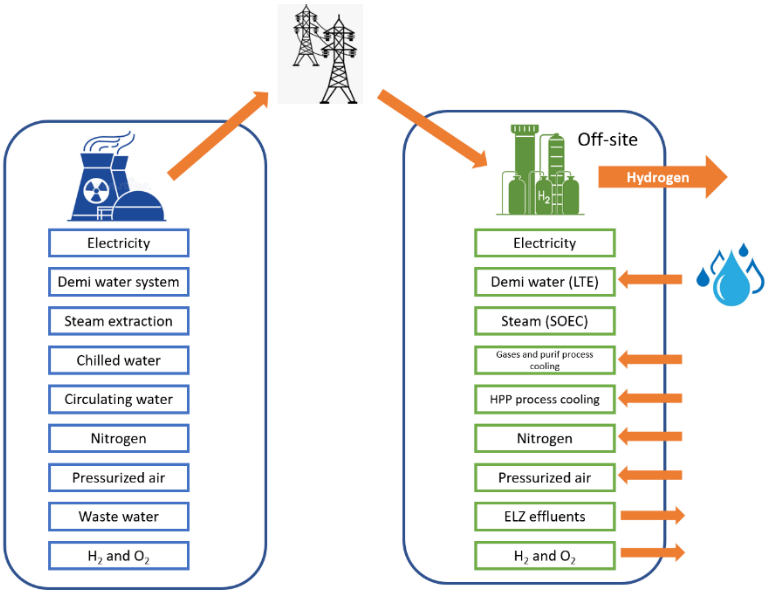

Figure 7 Zero integration scenario (off site)

4.1 Full integration

The Full Integration scenario is given if all needs of the HPP are served by NPP infrastructure. This is more a theoretical model as it is to be expected that any operating NPP or specific location will have at least some constraints that limit the integration.

4.2 Zero integration

The Zero Integration Scenario is the opposite theoretical model in which no needs of the HPP are served from NPP infrastructure. In the case of no coupling, there is no cogeneration at all. Nevertheless, this scenario is worthwhile being analyzed as it forms the benchmark for any plant coupling scenario. Whatever the level of integration may be, the respective production costs of the hydrogen need to be (significantly) lower than estimated for zero integration to make any sense.

In Zero Integration Scenario the electrical supply for the HPP is obtained from the external grid with the associated cost increase. Besides, the HPP is located outside the NPP site.

4.3 Partial Integration

Partial Integration scenarios are many. Figures 5 and 6 show only two examples. Which scenarios are to be investigated need to be decided based on the respective individual possibilities of a given site. The provision of electricity at a competitive price is understood as the minimal integration that any scenario should bear.

5 Operation Modes

Apart from the technical level of integration there are as well different modes of operation possible that need to be analyzed. Respective impacts on design, license and cost of installation and operation of HPP will be addressed in the work packages WP2, WP3 and WP4 accordingly.

5.1 Continuous Operation

The first operational scenario was permanent operation of the HPP at the designed capacity. This is possible in case the operator of the NPP is dedicating a certain amount of electricity and other sources permanently to the production of hydrogen. In this case the HPP is a constant additional consumer within the NPP surroundings and the production of hydrogen at a certain rate needs to be integrated in the operational licenses of the NPP. HPP starts and stops with the NPP.

5.2 Flexible Operation

As market prices for electricity and carbon-free hydrogen are constantly changing the operator may prefer an operational model in which the production of hydrogen is varying between no production and full capacity with respect to the achievable revenue. For example, the amount of hydrogen production will vary during the day. And nighttime or depending on the availability of regenerative electricity from solar or wind power. This operational mode involves frequent starts and stops of the HPP, possibly even several times in a day. Frequent starts and stops result in higher fatigue effects and need to be considered in the design of the plant. Depending on the level and detailed way of integration of the HPP into NPP systems, such frequent starts and stops may have an impact on the NPP as well. Flexible operation needs to be considered in the design of the plants and with respect to the operation license both of which have impact on the cost of the HPP installation, the cost of operation.

6 Initial setup for the definition of realistic scenarios

To derive reasonable scenarios for further investigations from the potential levels of integration it is helpful to take into account some considerations based on first results of the interface investigation or experiences of the consortium members. In addition, some assumptions need to be made to enable the start of the subsequent work within NPHyCo. These considerations are explained in the following subchapters.

6.1 Capacity of the coupled H2 plant

The price of the produced hydrogen depends on the size and capacity of the plant of the HPP. CAPEX and OPEX increase or decrease with size and production capacity. Which HPP-scale would be the commercial optimum shall be a result of the respective investigations of NPHyCo and therefore is not known at the start. To enable the investigation of the possibilities of integration a size must be known though to define the needs. Thus, a reasonable size of $30MW_{el}$ is assumed as a starting point. Depending on the selected technology of electrolysis and again assumed 8000h/a of continuous operation this resembles a production capacity in the range of 4.500t/a.

6.2 Onsite/Offsite

The investigations carried out with operators of existing NPPs and from public available sources showed very early on that it is not possible to operate an industrial plant of any kind directly on the site of an NPP or in very close vicinity. In some countries this was not legal (Hungary, France) in other countries there is a safety distance to be kept. In Ukraine the so-called sanitary protection zone is 2.5km to 3km depending on the location. On the other side it was said that respective exemptions may be possible to be granted if the feasibility and especially the safety of such coupled plants can be shown. This means that on-site scenarios shall not be excluded from the start. The benefits of integration are expected to be higher with lesser distances of on-site solutions. The results of the analysis will show whether the higher obstacles can be overcome and whether it is commercially beneficial to undergo this more difficult path. Respective further analysis is performed in the subsequent tasks of work packages WP2 (technical roadmap), WP3 (commercial roadmap) and WP4 (licensing roadmap).

6.3 Nitrogen Supply

With respect to the supply of nitrogen the need for the HPP (at least in the targeted size) is so low that it seems to be easier and cheaper to not connect to NPP systems but simply provide the NPP with a stand-alone nitrogen-supply via gas bottles. A cost estimation will be performed to prove that assumption, but the integration of nitrogen supply most likely will not be pursued in the scenarios.

6.4 Chilled Water Supply

First feedback from operators indicates that most likely there will not be sufficient supply for chilled water in NPPs as they normally do not use cooling water in this temperature range. Chilled water is mainly used for the HVAC systems with only small capacities. Thus, a stand-alone chilled-water set will be foreseen within the NPP.

6.5 Electricity Price

The price of electricity is the main parameter for the production cost of hydrogen from electrolysis. As described in D1.1 one assumed major benefit from coupling H2 production to nuclear electricity production was the potential to define the HPP as a part of the NPP and the respective electricity consumption as own consumption or home need. This would allow for respectively low electricity prices as there was no need for grid fees in this case. Whether this view is accepted by operators and regulators is not secured. Thus, NPHyCo shall perform its evaluation with both potential electricity prices. That is at home need cost rate and with external consumption cost rate.

6.6 NPP-type Impact on Scenarios

As the need investigation shows, all types of NPPs could possibly cover the needs of a HPP in general. Yet depending on the type of NPP the integration may lead to different issues e.g. with respect to safety. The installed capacity of demineralized water and cooling water thus the buffer of availability of it when serving the HPP need might be different. As the safety architecture of the NPP types is different the sensitivity to impacts resulting from disruption in a coupled HPP will be different as well. NPPs have containments and civil structures to protect sensitive systems and equipment from mechanical impacts such as airplane crashes or explosion pressure waves or fire. These structures are different for the types in question (VVER-440, VVER-1000, KONVOI, etc.). This will have influence on the possibilities for the selection of the location of a potential HPP. Respective investigations will be carried out in WP2 and WP4 (impact analysis) and taken into account with the site-specific analysis.

At the current stage there is no impact that asks for a general exclusion of specific scenarios based on NPP type except the integration of a HTSE plant with a BWR reactor. BWRs can provide only radioactive steam as heat source and a tie-in point was close to the reactor. This does not mean that it is impossible, but the technical solution and the impact on the NPP seem unreasonably extensive.

6.7 Advanced reactor types

The circumstances regarding the use of hydrogen as a promising contributor to realize decarbonization and climate goals are rapidly evolving worldwide. So are the plans to find ways to serve the respectively growing demand of green hydrogen [8] (compare D1.1).

To reach large scale production capacities, the use of nuclear power plants mainly or fully dedicated to the production of hydrogen is one investigated route [9]. Especially when planning and designing new power plants with advanced and new reactor types the co-generation of hydrogen is taken into account already in early phases. The NPHyCo consortium partner Ansaldo for example did an investigation of coupling a GenIV+ nuclear power reactor of ALFRED type (Advanced Lead-cooled Fast Reactor European Demonstrator) with high temperature electrolysis of SOEC type with promising results [7].

Another route is the use of SMRs i.e. Small Modular Reactors dedicated to the power supply of hydrogen production facilities [10]. This approach is investigated in EURATOM projects such as Gemini2.0 or TANDEM. Also, there is two-to-three-year pilot project FIRST aimed at demonstrating the commercial-scale production of clean hydrogen and ammonia from small modular reactors in Ukraine using solid oxide electrolysis [5].

Nevertheless, advanced reactor types are not taken into account for the scenario definition. NPHyCo sets its focus on the currently operating nuclear power plants in Europe as it is intended to identify a possible location for a subsequent pilot plant project in case the results show co-generation with existing power plants as possible and commercially beneficial. Therefore, SMRs or future nuclear reactor models were not integrated in the selection of scenarios to be investigated.

6.8 Storage and transport (impact of off-taker analysis)

The produced co-generated hydrogen needs to reach the consumer finally. Thus, it is necessary to identify the potential off-takers of (green) hydrogen in Europe and compare the location of the main consumers with the location of the nuclear power plants. Respective off-taker analysis is part of NPHyCo tasks and respective information is given in D2.1 as the connection to the customer is a very important interface to be covered in the interface report.

The sectors and industrial fields consuming significant amounts of hydrogen are chemicals, refining, aerospace, electronics, metals, and glass (compare D1.1 and D2.1). Some of them use hydrogen as direct feedstock. Others like use it as energy-carrier especially in case direct use of electric energy is not favorable.

With respect to scenario definition, the results of the off-taker investigation show that in most cases there is no close vicinity between NPPs and H2 consumers. Figure 8 to Figure 12 give an overview.

Figure 8: Overall map of Europe with important locations

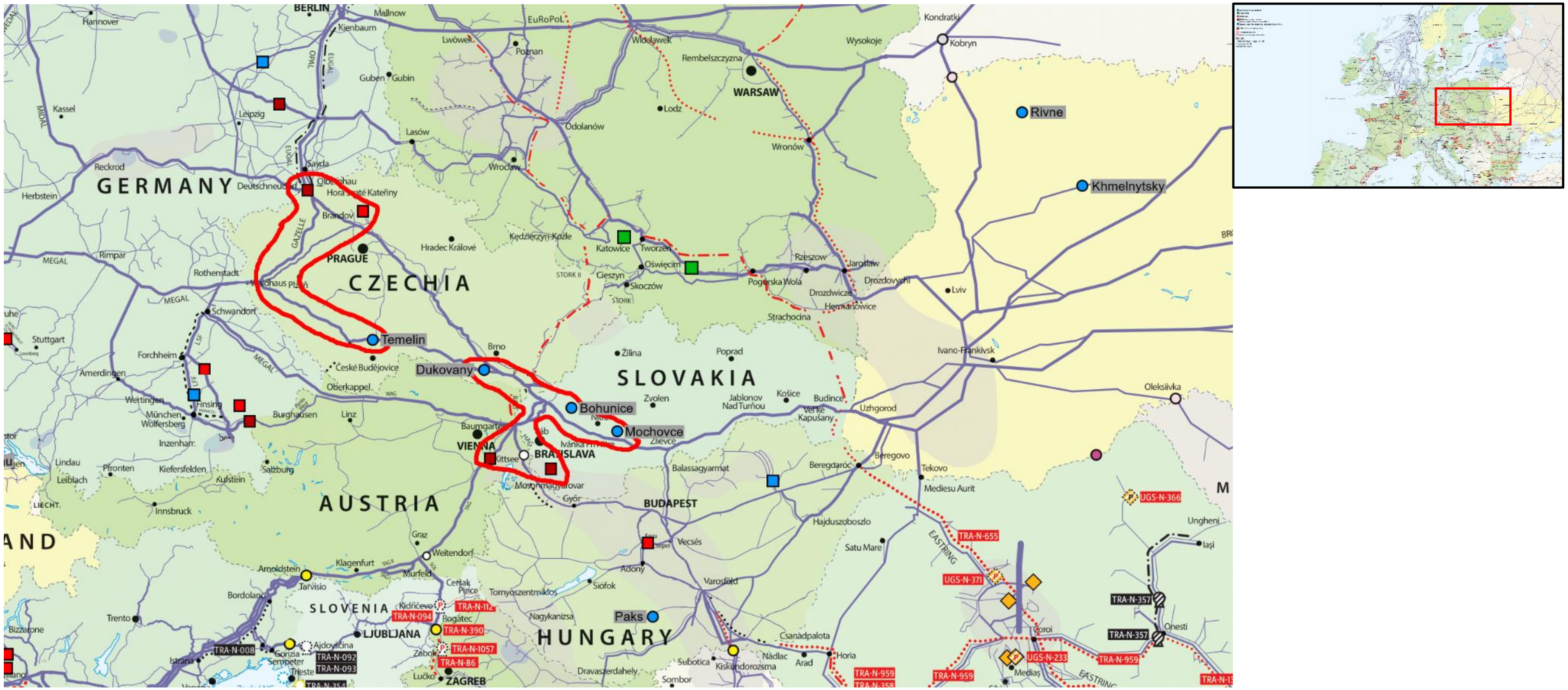

Figure 9: Central Europe Cut Out

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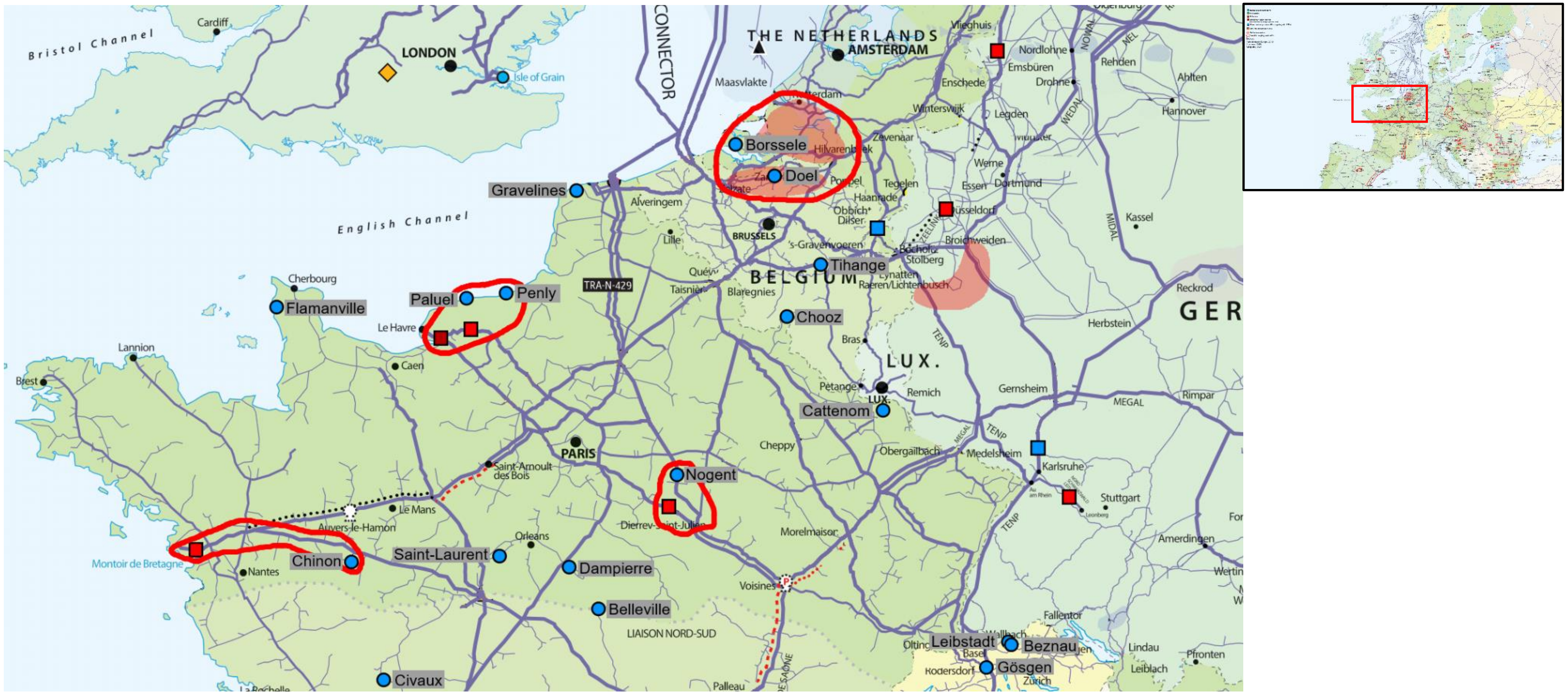


Figure 10: North France and Netherlands Cut Out

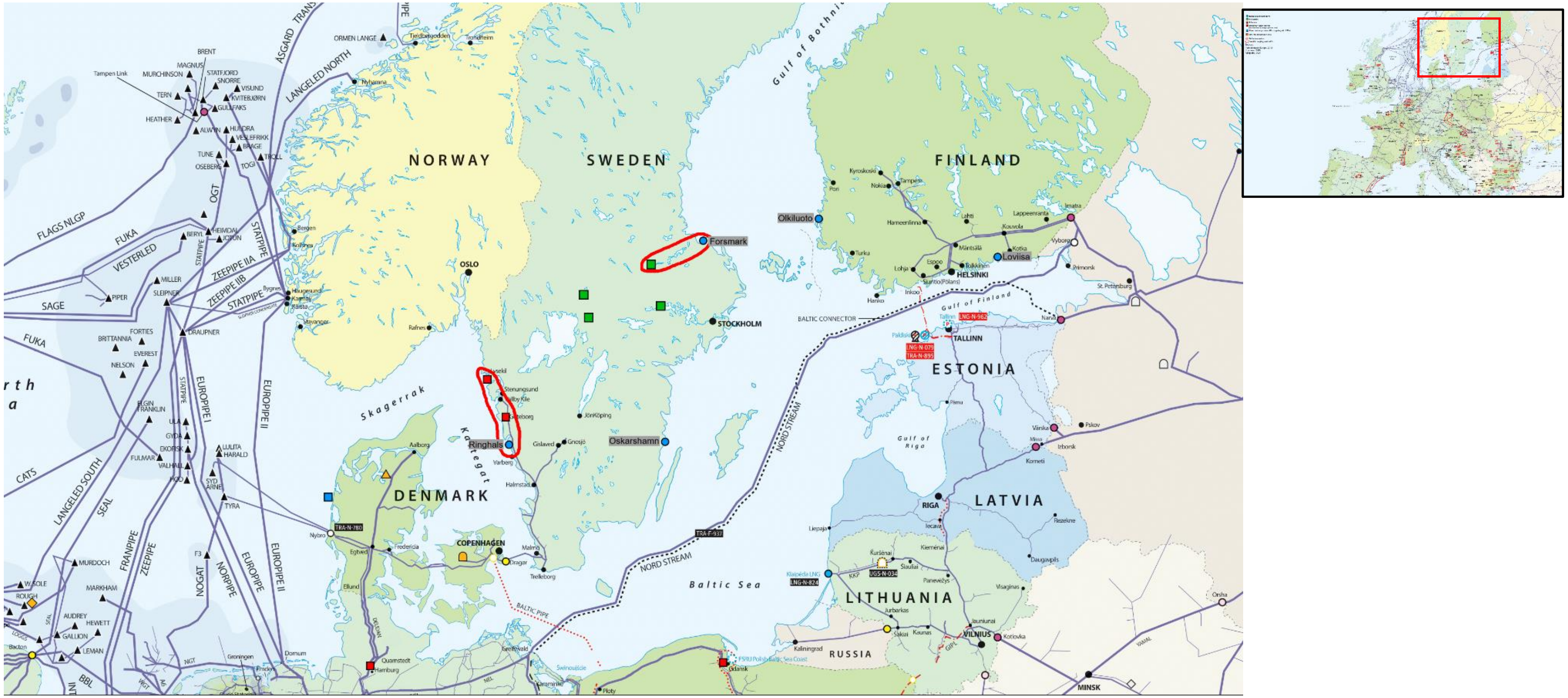


Figure 11: Scandinavia Cut Out

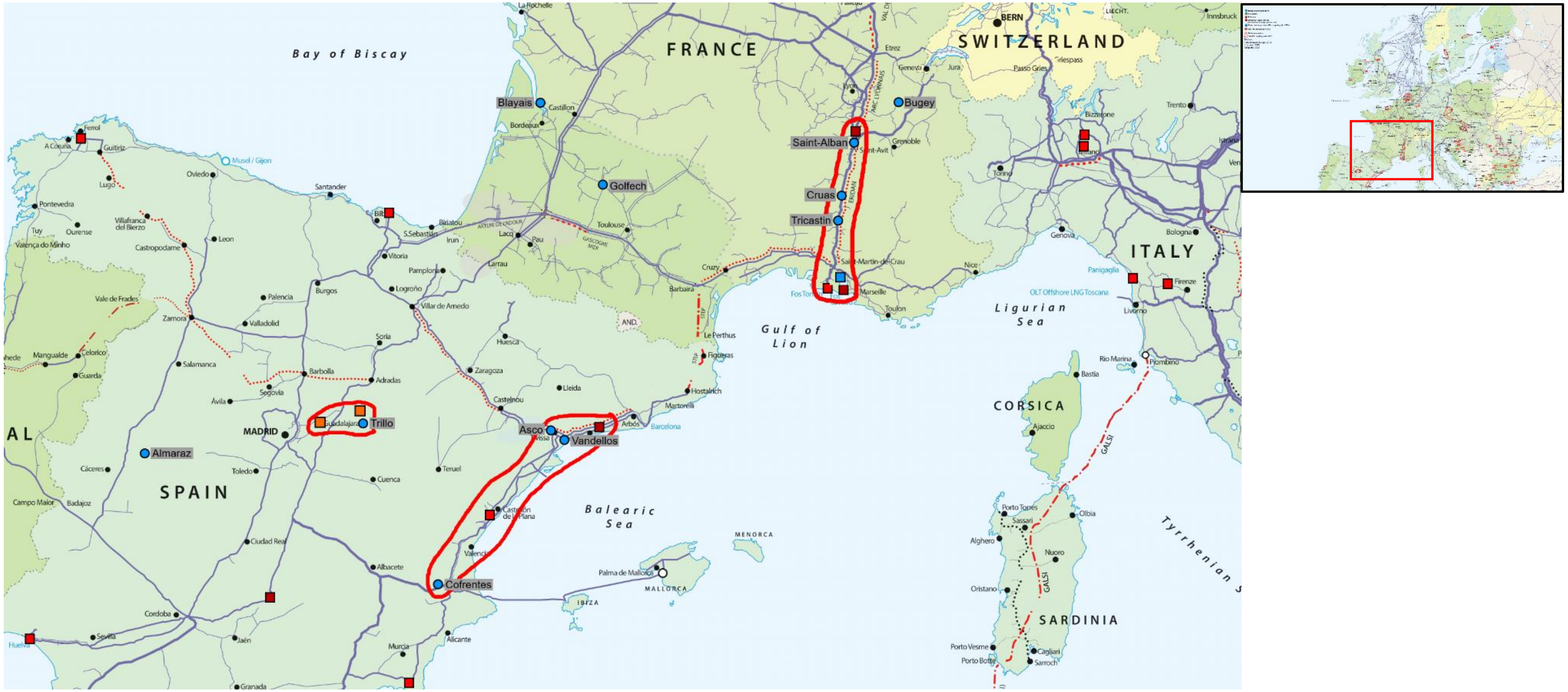


Figure 12: Spain and South France Cut Out

This is partly due to the nature of NPPs and their safety requirements. In most European countries there are regulations that do not allow any industrial production facilities within a specific safety range around a NPP (compare D4.1). This is even more true for facilities that bear safety risks of their own. Thus, the scenarios must consider that transportation of the produced hydrogen is needed. Which way of transport is the most beneficial again depends on the specific location. Generally, the three main possibilities (per pipeline, truck or ship) shall be taken into account.

D2.1 gives more information on the off-taker situation for the European countries and the transportation possibilities.

7 Scenario Definition

7.1 9 pre-selections

The considerations above result in the following cases to be analyzed i.e. scenarios for any NPP site/location in discussion.

Onsite Solutions

1. Onsite solution with full integration except chilled water with electricity at normal price (grid)
2. Onsite solution with full integration except chilled water with electricity at reduced price (home need)
3. Onsite solution with integration of electricity and cooling water only normal price
4. Onsite solution with integration of electricity and cooling water only reduced price

Offsite Solutions

(3 km distance as a starting point)

1. Offsite solution with integration of electricity and cooling water (elaboration of break-even distance for cooling water integration) with electricity at normal price (grid)
2. Offsite solution with integration of electricity and cooling water (elaboration of break-even distance for cooling water integration) with electricity at reduced price (home need)
3. Offsite solution with integration of electricity only at normal price
4. Offsite solution with integration of electricity only at reduced price
5. Offsite solution with zero integration as benchmark i.e. normal price (grid)

These pre-selected scenarios are intended to be analyzed for each operating NPP and location and the different technical solution linked to it.

Feedback from operators is needed to cover the real-life situation and circumstances at each site as this may not be fully available in public sources. Thus, the detailed analysis can be carried out only for NPPs for which sufficient data can be obtained. Respective feedback will be entered in D2.1.

According to the investigations and talks carried out so far it seems likely to achieve this for the following subset of NPPs:

- NPP Rivne
- NPP Khmelnytsky
- NPP Trillo
- NPP Temelin
- NPP Paks
- NPP Gösgen

It is intended to perform the analysis at least for one type of NPPs exemplarily i.e. for one example of VVER-440, VVER-1000, BWR and PWR. With the feedback of Energoatom regarding Khmelnytsky NPP and Rivne NPP the both VVER types are covered.

Trillo in Spain could cover PWR (Konvoi), in case additional information regarding possible modifications of the NPP can be achieved. This will be entered in D2.1 also.

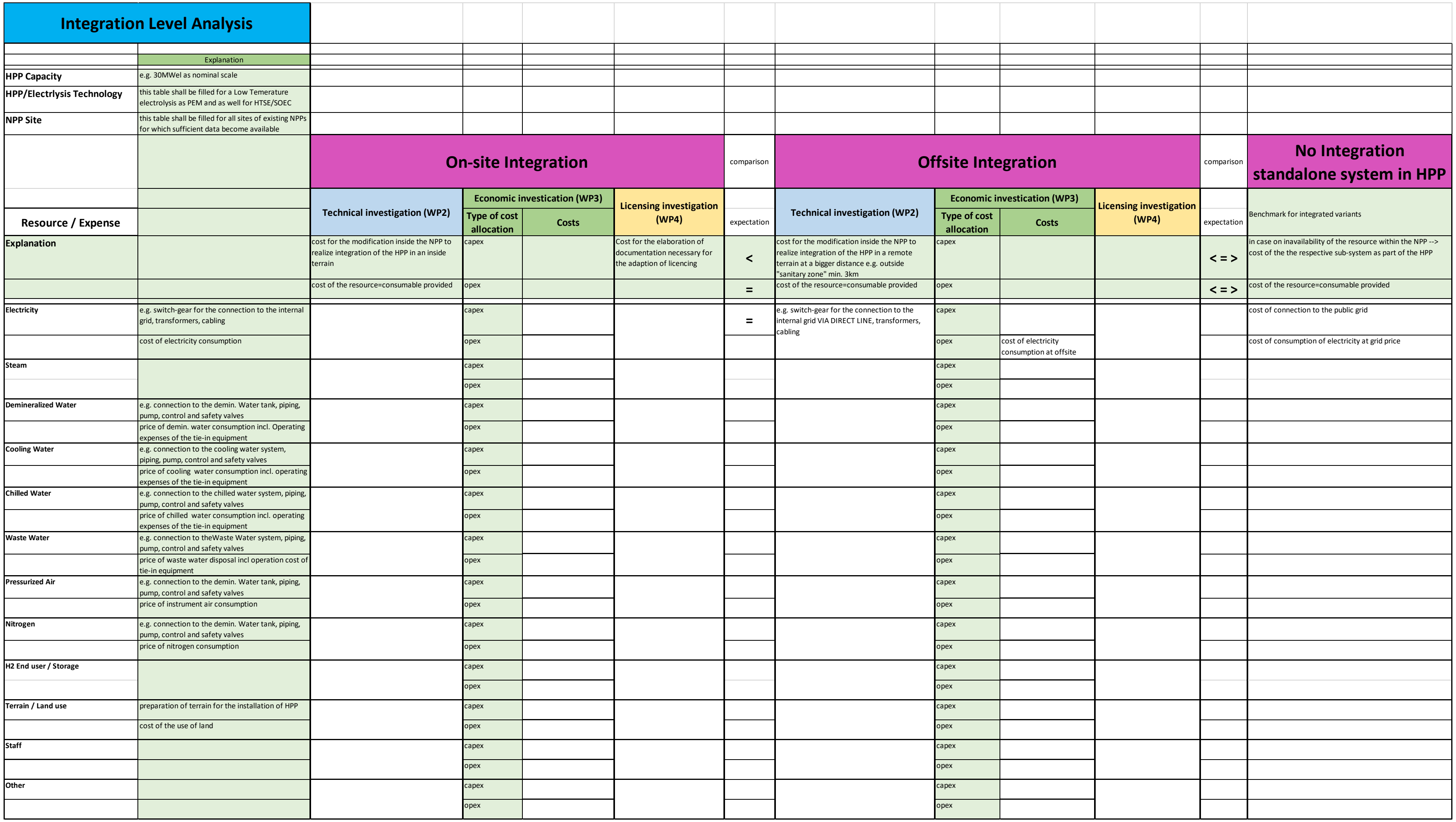
BWR will be even more difficult.

In case the missing information cannot be obtained in time NPHyCo will fill the gaps with assumptions e.g. postulate the same distances and technical solutions for tie-in identified for the Ukrainian plants and transfer them to the different market situation in Spain or Switzerland.

For each location all three electrolyzer-technologies (AEL, PEM, HTSE) shall be considered (except HTSE technology for BWR).

The first step is to describe the potential modifications on NPP side and estimate the related cost. Alternatively, the costs of nonintegrated stand-alone solutions within the HPP need to be estimated. With this information optimal integration levels shall be detected by performing respective simulations. Effort linked to rework of documentation to gain licensing shall be considered as well.

Such analysis may follow the logic visualized in the Integration-Analysis-Matrix (see Figure 13 and Annex 10.1). Therefore, analysis shall consider the technical (supported by WP2), economical (supported by WP3) and licensing (supported by WP4) aspects of the pre-selected scenarios. The analysis results summarized in the Integration-Analysis-Matrix should support the decision concerning the final scenario for the pilot HPP plant. Form of this Integration-Analysis-Matrix can be modified and improved according to the progress of investigation.



Integration Level Analysis												
	Explanation											
HPP Capacity	e.g. 30MWel as nominal scale											
HPP/Electrlysis Technology	this table shall be filled for a Low Temerature electrolysis as PEM and as well for HTSE/SOEC											
NPP Site	this table shall be filled for all sites of existing NPPs for which sufficient data become available											
		On-site Integration				comparison	Offsite Integration				comparison	No Integration standalone system in HPP
		Technical investigation (WP2)	Economic investication (WP3)		Licensing investigation (WP4)		Technical investigation (WP2)	Economic investication (WP3)		Licensing investigation (WP4)		
Resource / Expense			Type of cost allocation	Costs		expectation		Type of cost allocation	Costs		expectation	Benchmark for integrated variants
Explanation		cost for the modification inside the NPP to realize integration of the HPP in an inside terrain	capex		Cost for the elaboration of documentation necessary for the adaption of licencing	<	cost for the modification inside the NPP to realize integration of the HPP in a remote terrain at a bigger distance e.g. outside "sanitary zone" min. 3km	capex			< = >	in case on inavailability of the resource within the NPP --> cost of the the respective sub-system as part of the HPP
		cost of the resource=consumable provided	opex			=	cost of the resource=consumable provided	opex			< = >	cost of the resource=consumable provided
Electricity	e.g. switch-gear for the connection to the internal grid, transformers, cabling		capex			=	e.g. switch-gear for the connection to the internal grid VIA DIRECT LINE, transformers, cabling	capex				cost of connection to the public grid
	cost of electricity consumption		opex					opex	cost of electricity consumption at offsite			cost of consumption of electricity at grid price
Steam			capex					capex				
			opex					opex				
Demineralized Water	e.g. connection to the demin. Water tank, piping, pump, control and safety valves		capex					capex				
	price of demin. water consumption incl. Operating expenses of the tie-in equipment		opex					opex				
Cooling Water	e.g. connection to the cooling water system, piping, pump, control and safety valves		capex					capex				
	price of cooling water consumption incl. operating expenses of the tie-in equipment		opex					opex				
Chilled Water	e.g. connection to the chilled water system, piping, pump, control and safety valves		capex					capex				
	price of chilled water consumption incl. operating expenses of the tie-in equipment		opex					opex				
Waste Water	e.g. connection to theWaste Water system, piping, pump, control and safety valves		capex					capex				
	price of waste water disposal incl operation cost of tie-in equipment		opex					opex				
Pressurized Air	e.g. connection to the demin. Water tank, piping, pump, control and safety valves		capex					capex				
	price of instrument air consumption		opex					opex				
Nitrogen	e.g. connection to the demin. Water tank, piping, pump, control and safety valves		capex					capex				
	price of nitrogen consumption		opex					opex				
H2 End user / Storage			capex					capex				
			opex					opex				
Terrain / Land use	preparation of terrain for the installation of HPP		capex					capex				
	cost of the use of land		opex					opex				
Staff			capex					capex				
			opex					opex				
Other			capex					capex				
			opex					opex				

Figure 13: Screenshot of Integration-Analysis-Matrix

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7.2 Selected scenarios

At the time of issuance of this document only the information regarding the two Ukrainian NPP site were sufficient for further investigation. Thus, the following scenarios were defined to start the subsequent work of NPHyCo. The scenarios will be extended to other sites in analog manner as soon as necessary information is provided.

7.2.1 Location Khmelnitsky & PEM technology

1. **BENCHMARK Scenario** i.e.
    a. location in about 3km distance of the NPP
    b. no integration to the NPP
    c. all subsystems standalone within the HPP (in WP3 we need to estimate the capex and opex for this standalone systems)
        i. Connection to the Ukrainian electrical grid
        ii. Standalone Demineralized water production system from tap water
        iii. Standalone Cooling Water system run with water from a river
        iv. Standalone Chilled Water System
        v. Instrumentation Air system (small compressor unit and buffer tank)
        vi. Nitrogen supply via a bottle station and some internal piping
        vii. Wastewater disposal to Ukrainian canalization
2. **Scenario Offsite1** is what I call the minimal-integration-offsite-scenario
    a. Location about 3 km distance to the NPP
    b. Integration of electricity via direct line of the NPP (with the price given by Energooatom or **with 2 alternative assumptions = grid price and reduced price**))
    c. All other subsystems standalone as in scenario 1
3. **Scenario Offsite2** is
    a. Location about 3 km distance to the NPP
    b. Integration of electricity via direct line of the NPP
    c. Integration of demineralized water supply (a 3 km piping connection for demineralized water seems unreasonably expensive, but a stand-alone demineralized water system is expensive as well. We may check it roughly at least)
    d. All other subsystems standalone as in scenario 1
4. **Scenario Offsite3** is
    a. Location about 3 km distance to the NPP
    b. Integration of electricity via direct line of the NPP
    c. Integration of demineralized water system (a 3 km piping connection for demineralized water seems unreasonably expensive, but a stand-alone cooling water system is expensive as well. We may check it roughly at least)
    d. Integration of cooling water system (a 3 km piping connection for cooling water seems unreasonably expensive, but a stand-alone cooling water system is expensive as well. We may check it roughly at least)
    e. All other subsystems standalone as in scenario 1
5. **Scenario ONSITE1** is the full integrated onsite solution
    a. Location as indicated by Energoatom
    b. Integration of electricity with the price given by Energoatom (or **with 2 alternative assumptions = grid price and reduced price**)
    c. Integration of all other subsystems
6. **Scenario ONSITE2** is the probably best integrated onsite solution
    a. Location as indicated by Energoatom

b. Integration of electricity with the price given by Energoatom (or with 2 alternative assumptions = grid price and reduced price)
c. Integration of all subsystems for which the cost estimation of the modification of the NPP is significantly lower as for standalone systems (this should be true for the cooling water connection of an onsite scenario and the wastewater connection

The analysis of the above given scenarios needs to be repeated for AEL and HTSE technology and then all that needs to be repeated for the other locations. Temelin and Dukovany are of VVER type as well thus the next location shall better be another NPP type.

8 Conclusion

The project NPHyCo investigates the feasibility of producing low-carbon hydrogen via electrolyzers coupled with European NPPs currently in operation.

To assess the feasibility and viability of the integration of HPP into NPP and establish the framework of subsequent studies, scenarios of such integration need to be defined.

In order to define these potential scenarios, a brief investigation of the needs of an HPP, the possible levels of integrations and locations, the operational modes, and the potential assumptions are done in this document.

The main needs of HPP plant to produce hydrogen are the followings:

- Electricity in DC is the energy source for the electrolysis process.
- Demineralized water with a high level of purity is the main consumable of the electrolytic production of hydrogen. In case HTSE/SOEC technology the steam is entered into the electrolyzer unit.
- Cooling water and chilled water are required for cooling of the components and for hydrogen gas purification process.
- Wastewater treatment is needed to remove the wastewater resulting from hydrogen production unit.
- Pressurized air is used in HPP for operation of many pneumatic drives for valves etc.
- HPP needs nitrogen for purging purposes.
- A respective safety environment needs to be established in HPP

Some of the needs of a HPP may be covered with already existing infrastructure of a coupled NPP. The good level of integration depends on the availability of the respective sources on NPP side, the induced impacts of such coupling and finally of the commercial benefit it creates.

Obviously, there are two limiting scenarios with full integration, where all the HPP needs are served by NPP, and zero integration, where the HPP needs cannot be provided by NPP. On the other hand, there is a wide range of scenarios with partial integration and a lot of combinations for interfaces between HPP and NPP.

Which scenarios shall be investigated needs to be decided based on the respective individual possibilities of a given site. The provision of electricity at a competitive price is understood as the minimal integration that any scenario should bear.

To derive reasonable scenarios for investigations from the potential levels of integration it is helpful to take into account some considerations based on first results of the interface investigation or experiences of the consortium members.

The price of electricity is the main parameter for the production cost of hydrogen from electrolysis. A major benefit from coupling hydrogen production to nuclear electricity production is the potential to define the HPP as a part of the NPP and the respective electricity consumption as own consumption or home need.

The investigations carried out with operators of existing NPPs and from public available sources showed very early on that it is not possible to operate an industrial plant of any kind directly on the site of an NPP or in very close vicinity. On the other hand, it was reported that respective exemptions may be possible to be granted if the feasibility and especially the safety of such coupled plants can be demonstrated.

That means that both on-site and off-site scenarios shall be investigated. The benefits of integration are expected to be higher with lesser distances of on-site solutions.

The produced cogenerated hydrogen needs to reach the consumer finally. Respective off-taker analysis and connection to the customer is a very important task to be covered in the interface report.

The sectors and industrial fields consuming significant amounts of hydrogen are chemicals, refining, aerospace, electronics, metals, and glass industry. Some of them use hydrogen as direct feedstock. Others use it as energy-carrier especially in case if a direct use of electric energy is not favorable.

The results of the off-taker investigation showed that in the most cases there is no close vicinity between NPPs and hydrogen consumers.

Based on the investigation of the needs of a HPP, possible integration levels between NPP and HPP as well as off-taker analysis, 9 potential integration scenarios have been defined.

At the time of issuance of this document only the information regarding the two Ukrainian NPP sites were sufficient for further investigation. Therefore, detailed interfaces for the 9 scenarios for Khmelnitsky NPP have been prepared for further investigations.

The analysis of the 9 potential integration scenarios needs to be performed for all three electrolyzer-technologies (AEL, PEM and HTSE technology). Afterwards, the analysis should be performed for all other potential locations of HPP. The analysis shall consider the technical, economical and licensing aspects of the pre-selected scenarios based on the feedback and required data provided by NPP operators.

The results of the analysis shall be summarized in the Integration-Analysis-Matrix which should support the decision concerning the final scenario for the pilot HPP plant.

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10 Annexes

10.1 Annex 1 - Integration-Analysis-Matrix

The Integration-Analysis-Matrix shall summarize the results of the investigations in WP2, WP3 and WP4 and should support the decision concerning the final scenario for the pilot HPP plant.

Table 2: Integration-Analysis-Matrix

Link to open the table: NPHyCo_integration-matrix_D12_12-10-2023_FIN.xlsx