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TECHNOLOGY REVIEW AND SAFETY ASSESSMENT OF NUCLEAR-RENEWABLE HYBRID ENERGY SYSTEMS WITH LIGHT-WATER SMALL MODULAR REACTORS

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ABSTRACT

An increase of renewable energy share is expected in the next future to drive the energy transition towards a low-carbon future energy mix. However, renewable energy sources are intermittent and non-dispatchable by nature and could lead to grid stability issues. For this reason, the idea of coupling renewable energy sources with Nuclear Energy (in particular, Small Modular Reactors) in the so-called Nuclear-Renewable Hybrid Energy Systems has gained more attention during the past years. During the second half of 2022 a European project belonging to the Horizon Europe program, namely TANDEM, has started to investigate the safety aspects of Light-Water Small Modular Reactors when introduced in a Hybrid System scenario. This paper aims at summarizing some of the first outcomes of the TANDEM project regarding the technology assessment of a Nuclear-Renewable Hybrid Energy System with Light-Water Small Modular Reactors, with preliminary considerations about safety of nuclear cogeneration. To this purpose, the main components of a general Hybrid system are considered, i.e., Light-Water Small Modular Reactor, low and high temperature hydrogen production, thermal and electrical storages and seawater desalination, aiming at providing general rules to perform the future modelling of the system in the frame of the project.

Keywords: Nuclear Energy, Small Modular Reactors (SMRs), Nuclear Safety and Security, Nuclear Engineering

1. INTRODUCTION

In the last decade, EU Member States agreed on the global need of reducing carbon emissions by 2035, having the final objective of reaching a net-zero carbon energy mix by 2050 (see Fit for 55 package by EU).

In this frame, several technologies of Small Modular Reactors (SMR) have been investigated worldwide, ranging from the already assessed Light-Water technology to high-temperature reactors belonging to Generation IV, notably the so called Advanced Modular Reactors (AMR) [1]. The increasing interest in these technologies is mainly related to their advantages, ranging from the enhanced safety to the economical profitability, thanks to serial fabrication of components, modular construction and operational flexibility, also in relation to the multi-unit character of the Nuclear Power Plants (NPP) [2]. The latter feature has made the SMR/AMR one of the most suitable technologies to be envisaged as nuclear source in Nuclear-Renewable Hybrid Energy Systems (N-R HES), allowing a diversified usage of the nuclear power that would lead to the possibility of producing different economical valuable products (e.g., hydrogen or desalinated water). This will assure a stable and low-emission energy production [3], while producing nuclear power as constant as possible to limit economical penalties [4]. For this reason, the coupling between nuclear power and other electrical and thermal energy users within a N-R HES could lead to the capability of performing load-following by cogeneration [4], thus avoiding frequent and steep thermal power variations of the nuclear source, also in high penetration scenarios of intermittent renewable generators.

However, the definition of suitable technologies to be implemented in a future N-R HES is not trivial, since it depends on several factors such as the techno-economic feasibility of the system [3] as well as their Technology Readiness Level (TRL). Moreover, some regulatory hurdles may occur when the nuclear technology is foreseen in tightly coupled N-R HES, as the interface between nuclear and industrial processes may lead to several conditions that could influence the overall safety of the NPP [2].

At present time, different works can be found in literature concerning the techno-economic assessment of N-R HES, which consider different layouts and different technologies of the involved components. Moreover, depending on the available temperature of the supplied heat (i.e., the reactor technology), different non-electrical applications are foreseen to be introduced in a N-R HES for cogeneration purposes; among these:

- Hydrogen production (see, e.g., [4], [5], and [6]);
- Salty water desalination (see, e.g., [6], [7] and [8]);
- Hydrocarbons synthesis (see, e.g., [3], [9], and [10]);
- District Heating (see, e.g., [4]);
- Others (e.g., Ammonia production [10] or Plastic pyrolysis [4]).

In this frame, the EU TANDEM (Small Modular ReacTor for a European sAfe aNd Decarbonized Energy Mix) project [11] "proposes to address most specifically the SMR safety issues related to the SMR integration into hybrid energy systems. Considering a near-term deployment in Europe at 2030's horizon, the project is mainly focused on light-water technologies". The present paper aims at summarizing the preliminary outcomes achieved in the frame of TANDEM in two Work Packages (WP), i.e., WP1 and WP4. In particular, WP1 concerns the identification of the N-R HES to be studied in the project, while WP4 focuses on the safety characterization and analyses of the reference Light-Water Small Modular Reactor (LW-SMR) integrated in the N-R HES.

2. LITERATURE REVIEW ABOUT N-R HES TECHNOLOGIES

The topic discussed in this section is a summary of the initial work carried out in the frame of the EU Project TANDEM. In particular, the work referred to WP1, Task 2, whose main objective is to identify, through a literature review and expertise suggestions, the best technologies to be implemented in the N-R HES considered by TANDEM. Figure 1 shows a block diagram of the envisaged N-R HES, foreseen as an energy-hub, which is envisaged as a demonstration case for techno-economic assessment of a representative N-R HES layout for future EU energy mix. As it can be seen from the system depicted in Figure 1, several components are considered in the N-R HES, whose technologies must be defined in order to proceed to the modelling phase, which is ongoing at the present time. The reference design of LW-SMR is the one coming from another EU project, namely ELSMOR [12]. The direct coupling with the power conversion system (or Balance of Plant – BOP) through steam extractions serving a local or distributed heat network stimulates the interest into specific thermal energy uses, such as:

- Energy Storage;
- Hydrogen Production;
- Water Desalination;

and into a comparison of technologies based on a purely electrical input or a combination of electrical and thermal input.

Concerning the other blocks reported in Figure 1, these will be considered in the later phase of the project regarding the modelling of the N-R HES, thus they are not discussed in the present paper. In particular, the renewable blocks (i.e., photovoltaic and wind generators), might be modelled as an aleatory source, based on historical data series, embedded directly in the grid demand (i.e., by considering the net demand), or through more detailed models also taking into account also its inertia (e.g., for wind turbines). Moreover, the blocks indicated with "simplified" within those represented in Figure 1 are meant to be modelled in a simplified way (e.g., lumped parameter model with only their main dynamics parameters), leaving a more detailed system modelling to the other ones. The latter choice was made to find a compromise between accuracy and complexity of the global model.

The techno-economic assessment of the shortlisted technologies was performed by gathering the relevant data from several experts involved in the TANDEM project, which provided their own contribution to the description and technology assessment of each block of the N-R HES. The main objective of the work here described is to obtain a comprehensive overview of the most suitable technologies to be adopted in the N-R HES with respect to different Figure of Merits (FOM).

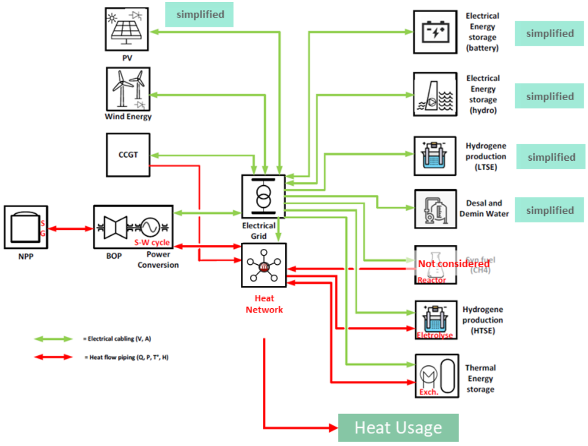

FIGURE 1: SCHEMATIZATION OF THE N-R HES.

2.1 Electrical Energy Storage

Electrical storage represents a useful component to be implemented in a N-R HES since it can have different applications such as power smoothing, i.e., decreasing the variability induced by renewable generators, or frequency regulation in future smart grids [13]. Devices that store electricity into chemical energy are herein considered, which can be divided into three main categories:

- Flow batteries, where the electrodes are constituted by two solutions, namely anolyte and catholyte, which are stored in two separated tanks. The anolyte and catholyte are continuously brought into the charging/discharging section through a pumping system [3]. Among the different technologies of flow batteries, the ones worth to be mentioned are the Vanadium Redox Batteries (VRB) [14], the Polysulfide Bromide Batteries (PSB) [15] and the Zinc-Bromine Batteries (Zn-Br) [15];
- Regenerative Fuell Cells (RFC), which are systems performable to produce electricity by using hydrogen and

oxygen as reactants, providing distilled water as output (i.e., reverse process of an electrolyzer) [16]. Regenerative Fuel Cells provide high specific energy and particularly good cycle capability. On the other hand, the RFC systems have higher capital costs with respect to other types of storage, lower round-trip efficiency (from 20 to 50%) and require further developments of materials for hydrogen storage purposes;

- Batteries, which are the most widespread technology used nowadays to store electricity in chemical potential energy. Usually, batteries consist in an electrolyte with two immersed electrodes that allow the dissociation of the chemical species in ions, storing or producing electricity [17]. As for the Flow Batteries, different technologies of battery systems can be considered as potentially usable for N-R HES applications, these include Lead-Acid Batteries (PBA) [17], Lithium-Ions Batteries (Li-Ions) [18] and Sodium-Sulphur Batteries (Na-S) [19].

Since in this case the reference applications are of a utility-scale, the FOMs can be identified as the power density, response time, self-discharge, round trip efficiency, lifetime and storage duration, costs (both capital and related to operation and maintenance, O&M) and maturity. Based on literature data (see, e.g., [14] [17] and [20]), the technologies chosen to be possibly embedded in the N-R HES are VRB, Na-S and Li-Ions. Table 1 lists the main FOM of the chosen technologies.

Parameter	**VRB**	**Na-S**	**Li-Ions**
Power Density (kW/m^3)	Up to 33	Up to 50	Up to 800
Response Time	>1/4 cycle	≈ 1 ms	≈ 1 ms
Daily Self-Discharge	negligible	negligible	≈1%
Cycle Efficiency	65-85 %	75-90 %	75-97 %
Lifetime	15-20 yrs	15-20 yrs	≈ 15 yrs
Storage Duration	Hours-months	Minutes–days	Minutes–days
Capital Costs ($/kWh)	150-1000	300-500	600-3800
O&M Costs ($/kWh/year)	70	80	negligible
Maturity	Developing	Commercial	Commercial

TABLE 1: FOM OF SELECTED ELECTRICAL STORAGES.

However, it is not trivial to predict which technology among those still under the Research and Development phase could be the driving one for utility scale applications in the short- or medium-term future. According to the International Energy Agency [21], the most promising battery technology at 2030-2040 timeline is the next generation of Lithium batteries, namely Lithium Iron Phosphate batteries, where Lithium-metal is used as anode and Sulphur as cathode.

2.2 Thermal Energy Storage

Thermal Energy Storage (TES) technologies accumulate thermal energy in diverse ways, embedding a further thermal capacity in the system beyond direct energy production in cogenerating systems. Presently, several works can be found in literature that consider thermal energy storages coupled with nuclear power generation systems in N-R HES, showing their importance in helping to avoid thermal stresses in the reactor while maintaining good load-following capabilities (see, e.g., [8]). With the current technologies, three different macro groups of thermal energy storage can be considered to be possibly implemented in a N-R HES: sensible heat storages, which store heat as sensible heat by heating up a medium; latent heat storages, which store thermal energy as latent heat; and thermochemical storages, which store thermal energy as chemical energy. Some of the different technologies of sensible heat storages are mentioned hereafter:

- Two-tank systems (TS), which use a fluid as heat storing medium (e.g., water or thermal oils). As the name suggests, these systems are composed by two tanks that store the hot and cold medium separately, which are connected via pumping systems to two heat exchangers: one for charging the storage, connected with the heat source, and the other one for the discharging phase, connected to the heat sink [22];
- Thermocline system (TC), which follows the same principle of the two-tank heat storage (i.e., storing/discharging heat via two heat exchangers by heating/cooling a fluid), but exploiting the thermal stratification in one single tank that stores the thermal medium [22] (the portion of medium with higher temperature is naturally separated by the colder one by the density difference), thus reducing the capital cost and avoiding any pumping need. The thermocline tends to lead to lower efficiency due to the unavoidable heat diffusion occurring along the vertical direction, which could be limited by using insulated plates [23].

Concerning latent heat storages, the majority of technologies allow to store heat via fusion latent heat through Phase Change Materials (PCM), which can be of different nature, from organic to eutectic [24]. Latent heat storage has greater capacity than sensible heat storages, hence they are less costly although more complex from the point of view of system layout.

Parameter	**TS**	**TC**	**PCM**
Operating T (°C)	≈ 300	≈ 300	≈ 400
Average Capacity (kWh/m^3)	≈ 70	≈ 70	100 - 420
Round Trip Efficiency (%)	75 - 80	50 - 65	85 - 99
Applicability for LW-SMR	Yes	Yes	Uncertain
Heat-usage applications	Yes	Yes	No
Load-Following capacity	Yes	Yes	No

TABLE 2: FOM OF DIFFERENT THERMAL STORAGES.

Finally, thermochemical storages allow to store heat in chemical bound through endothermal reactions, e.g., the dehydration of calcium hydroxide $Ca(OH)_2$ in calcium oxide CaO, producing water vapor [22]. Differently, when the stored thermal energy is needed, the reverse exothermal chemical reaction is favored (i.e., hydration of CaO). Thermochemical storages have large energy density and negligible thermal losses. However, the very low cyclability of the chemical reactions, the intrinsic complexity of the chemical reactor [22] and the lack of economic competitiveness [25] make this technology hard to be included in future applications.

To choose the best suitable technology to be implemented in the N-R HES with LW-SMR, the considered FOM are operating temperature, storage capacity, round trip efficiency, applicability for LW-SMR, usage in load-following operations and possible usage for heat user applications. Table 2 lists the value of the main parameters considered in the FOM for some TES technologies.

Considering all the mentioned parameters, referring to different literature works (e.g., [22], and [25] [26]), a two-tank system with a thermal oil (e.g., therminol66 [26]) is foreseen to be implemented in the N-R HES. For the sake of completeness, Figure 2 (taken from [26]) shows a schematic layout of a possible implementation of a two-tank system in a Nuclear Power Plant. The load-following, in the present case, is made by a changing power of the hot tank extracting pump, thus providing a changing additional steam mass flow rate to the turbine while the reactor is operating at rated power.

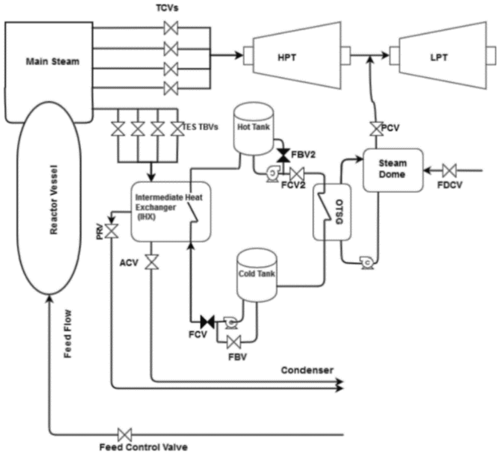

FIGURE 2: TWO-TANK THERMAL STORAGE EMBEDDED IN A NUCLEAR POWER PLANT [26].

2.3 Hydrogen Production

Hydrogen is foreseen to be a real important player of the future energy transition, as it is currently considered as the reference vector to decarbonize the hard-to-abate energy sectors, from industry to automotive [5]. At present time, most of the hydrogen production is supplied by fossil fuels (i.e., natural gas and coal) [27]. However, several greener ways of producing hydrogen have been investigated so far, e.g., electrolysis supplied by renewable energy sources [28]. Another technology which gained increasing attention for the production of hydrogen is nuclear energy (delivering "pink hydrogen"), thanks to its low-carbon intensity and high stability [5]. Moreover, producing hydrogen with nuclear power could be also helpful for future hybrid systems, being hydrogen a mode of energy storage, which would help the reliability of the entire system and provide economic benefits.

At present day, several ways of producing hydrogen can be envisaged, e.g., steam reforming of natural gas, catalytic decomposition of natural gas, partial oxidation of heavy oil, coal gasification, water electrolysis, thermochemical cycles and so on. However, being the present discussion focused on light-water nuclear-based hydrogen production, the following technologies are considered to be implemented in the considered N-R HES:

- low-temperature electrolysis, which uses only electricity from the grid;
- high-temperature steam electrolysis, which uses heat (i.e., steam) and electricity produced by the nuclear reactors.

Low-temperature electrolysis uses electricity exclusively to split water molecules into hydrogen and oxygen. The current low-temperature electrolysis technologies include:

- Alkaline Electrolysis (AE), which uses two electrodes submerged in an alkaline solution, normally of potassium hydroxide KOH or sodium hydroxide NaOH. The two regions with electrodes are separated by a membrane permeable to ions. Although this technology is mature and already used in industry, it does not allow to be connected to fluctuating power sources since the pressure at anode and cathode must be kept as constant as possible. The latter is to avoid dangerous diffusion of hydrogen and/or oxygen through the diaphragm leading to their mixing [29].
- Proton Exchange Membrane (PEM) electrolyzers, which are PEM Fuel Cells operating in reverse mode, i.e., producing hydrogen from water using electricity. Differently from AE, PEM does not work with liquid solutions, leading to a cost decrease due to the design simplification. PEM electrolyzers are well-suited to be coupled with a NPP in a N-R HES due to their high current density (i.e., it can sustain rapid power changes) and, for the same reason, it can be also used as system to control the grid frequency [30].
- Anion Exchange Membrane (AEM) technology, which can be considered as a bridge between the two already described (i.e., AE and PEM). In fact, AEM working principle is a blending between an Alkaline electrolyzer and a reverse Fuel Cells. The reactants of the AEM technology, indeed, are water and electricity as for the PEM technology, but in this case the global reaction of hydrogen production is divided into two reactions. First, water molecule is split into Hydrogen (H^+) and Hydroxyl ions (OH^-). Then, OH^- ions flow through the AEM towards the anode, where they are recombined giving water and oxygen [31].

In order to select the most suitable technology to be implemented in a N-R HES with LW-SMR, the considered FOM are maturity, operating temperature, hydrogen purity, efficiency, and suitability for coupling with nuclear energy. Basing on data available in literature (see, e.g., [32], [33] and [34]) and taking into account the defined FOM, the chosen technology is the PEM electrolyzer.

Regarding the High-Temperature Steam Electrolysis (HTSE) technology, it was considered relevant for the objectives of the TANDEM project as the physical inputs of the HTSE system are electrical power (which will be taken from the grid) and steam, whose production may be made, at some extent, by using the LW-SMRs. The considered technology to be introduced in the N-R HES is the Solid Oxide Electrolyzer (SOE), which is the most common one for these kind of applications [35]. SOE usually operates in the range of temperature from 700 °C up to 900 °C. However, this technology has a relatively low maturity compared to PEM electrolyzers. Moreover, some issues exist at present time, e.g., the high degradation of the electrolyzer cells due to the high operating temperature [35]. Nevertheless, some works can be found in literature which assess the interaction between a NPP with Light-Water Reactors and a HTSE (see, e.g., [36]), achieving interesting results in terms of benefits for the Nuclear facility with different Hydrogen market conditions. To conclude, it must be mentioned that HTSE technology can be considered relevant for both the short-term and long-term scenarios. In fact, based on its maturity level, SOE is expected to further evolve and improve in terms of efficiency and effectiveness, although this would lead to make hypotheses during the project that may be modified along with the technology evolution.

Table 3 lists some of the considered FOM for different hydrogen production technologies.

Parameter	**AE**	**PEM**	**AE**	**SOEC**
Maturity	Mature	Early	Pilot	Pilot
Operating T (°C)	70 - 90	50 - 80	40 - 60	≈ 800
H_2 purity (vol%)	99	99	99	N/A
H_2 production (Nm^3/h)	Up to 700	30	1	N/A
Efficiency (%)	56 - 64	56 - 64	56 - 64	40 - 50
Coupling with LW-SMR	Uncertain	Yes	Yes	Yes

TABLE 3: FOM OF DIFFERENT HYDROGEN PRODUCTION TECHNOLOGIES.

2.4 Water Desalination

Nowadays, more than 97% of the water sources is saline or brackish water [37]. Moreover, since water shortage is foreseen to be a prominent issue in the next future, technologies for production of fresh water from salty/brackish sources have gained more attention during the past years. In this frame, nuclear energy is considered one of the most promising technologies to achieve a massive freshwater production since it is a stable and low-carbon energy source. Moreover, nuclear energy is also economically competitive with respect to fossil fuel-based desalination plants [37]. Furthermore, most thermal desalination processes operate at a temperature level which is very suitable to the waste heat a nuclear power plant produces. Therefore, coupling a nuclear power plant with a desalination plant would increase the thermal efficiency, hence the profitability, of the entire system.

At present time, the most common technologies used for sea-water desalination can be divided into three macro groups [38]:

- filtration processes, e.g., Reverse Osmosis (RO) or Electrodialysis (ED); they rely on the osmotic pressure to separate water from salt and, generally, they only need electricity to operate;
- evaporation and condensation processes, e.g., Multi-Effect Distillation (MED) or Multi-Flash Desalination (MFD); the idea these technologies rely on is evaporation/condensation of water to remove the salt, hence they need also thermal energy to operate at the prescribed temperature, commonly around 100°C;
- crystallization processes, e.g., Hydration (HY); the latter relies on the formation of crystals made of water and a gas (e.g., carbon dioxide) leaving the salt behind; after, the gaseous molecules are separated from the water through heating, obtaining fresh water. However, these technologies are still in the development phase.

The most mature and suitable technologies used for desalination processes to be coupled with a Light-Water Nuclear Power Plant in a N-R HES are RO, MED and MSF [39], hence only these three are here discussed:

- Reverse Osmosis represents the most used technology for desalinating salty and brackish water. It relies on the principle according to which solute can be removed by a solution through a semi-permeable membrane if the solution is pressurized to compensate the osmotic pressure. Therefore, Reverse Osmosis plants use only electricity as energy source to supply the pumps that pressurize the salty water and send them to the membranes. Some ways could be envisaged to recuperate part of the brine pressure, e.g., by using a Pelton turbine [38].
- In Multi Effect Distillation, sea/brackish water is preheated in several heat exchangers, then sprayed in distinct stages of the system. In each stage, sprayed sea water exchanges heat with the hot vapor coming from the previous stage (see Figure 3). The heat lets the seawater evaporate, leaving a highly concentrated solution. The first stage of the system, being the one with the higher operating temperature, is supplied by steam coming from a boiler (typically using fossil fuels [40]) but it can also be coupled, in the frame of N-R HES, with a NPP using Light-Water Reactors.

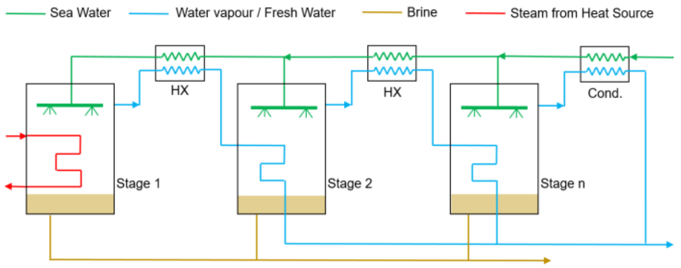

FIGURE 3: SCHEME OF MED PROCESS.

- The Multi-Stage Flash working principle is similar to the MED one, except for the fact that in MSF the evaporation of sea water is made by flashing (i.e., by depressurization). Feedstock water is first preheated in a heat exchanger supplied by steam from a heat source (HS). Then, hot sea water is depressurized through a laminarization valve and immitted in the first stage of the system, where it evaporates. The clean vapor condenses by exchanging heat with the cooler tubes containing the sea water, then the condensate is collected and sent to the next stage, while the remnant brine is collected on the bottom (see Figure 4).

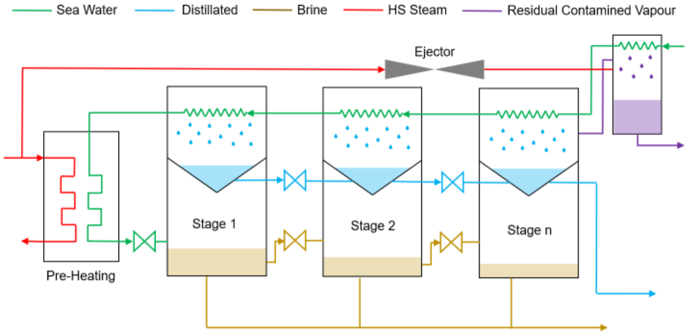

FIGURE 4: SCHEME OF MSF PROCESS.

Table 4 lists some parameters, taken from literature (i.e., [38], [40] and [41]), of the three selected desalination technologies. The considered FOM are operating temperature, energy consumption, recovery ratio (i.e., the ratio between output freshwater volume and input feedstock water volume), Total Dissolved Solids (TDS) in both feedstock and product water and costs.

Parameter	RO	MED	MSF
Temperature (°C)	Max 45	Max 120	90-110
Electricity Consumption (kWh/m^3)	3-5	1.5	3.5
Thermal Consumption (kWh/m^3)	-	28-61	44-83
Recovery Ratio	30-60 %	≈ 65 %	25-50 %
TDS Feed Water (mg/l)	Up to 48,000	Up to 180,000	Up to 180,000
TDS Product Water (mg/l)	< 500	< 10	< 50
Capital Costs ($\$/m^3$/day)	900	900	1000
O&M Costs ($\$/m^3$)	0.14	0.08	0.08

TABLE 4: FOM OF SELECTED DESALINATION TECHNOLOGIES.

As a final consideration, it must be highlighted that some works are focusing on hybrid desalination systems to achieve a consistent water production [42]. In this configuration, Reverse Osmosis and Thermal Desalination Plants would work together, being the RO connected only to the electrical grid and the Thermal Plant coupled with the Balance Of Plant of the NPP through an exchange of steam. For instance, Reverse Osmosis can be used to produce fresh water by using a low TDS water source, while the brine produced by RO can be used as feedwater for Thermal Desalination Processes [42]. Another example could be to thermally couple both the Reverse Osmosis and Thermal Desalination Plant with the Nuclear Power Plant, basing on the fact that the permeability of the membranes grows with increasing temperature [43].

3. REVIEW ABOUT NUCLEAR COGENERATION SAFETY

The present section discusses the outcomes provided by WP4, Task 1, of the TANDEM project, aiming at reviewing the status of reports about “safety analyses in Europe from the operational flexibility and cogeneration viewpoint”. Of course, there is a direct link between WP4 and WP1, since any safety assessment shall be carried out considering the ultimate definition of the reference N-R HES. The work was carried out by several international partners and Technical and Scientific Support Organizations (TSO), which provided their own insights about the addressed topic.

The available literature about nuclear cogeneration safety, carried out in Europe, regarding LW-SMR was found to be limited. However, some EU projects can be mentioned (i.e., EUROPAIRS [44], NC2I-R [45] and GEMINI + [46]) that cover cogeneration issues using AMRs, in particular (Very) High-Temperature Reactors, (V)HTR. Moreover, different reports can be mentioned by WENRA, IAEA and SMR Regulators’ Forum, to preliminary set up a safety assessment methodology when dealing with nuclear cogeneration, trying to translate the outcomes of the mentioned projects from the point of view of Light-Water applications. In the following subsections, the main outcomes from all the mentioned projects and literature survey are summarized, while a preliminary draft of a safety margins assessment methodology for cogeneration with LW-SMR is presented at the end.

3.1 Outcomes from EU Projects

The considered EU projects cover safety issues of nuclear cogeneration by adopting (V)HTR coupled with different industrial processes. In particular, Deliverable 1.2 of EUROPAIRS project [47] considers safety and licensing issues of cogeneration with High Temperature Gas Reactors (HTGRs). In the reference work, different safety objectives are considered, among which the fact that the coupled facility shall not fall under the nuclear regulation. Moreover, quite intuitively, is stressed the fact that the general risk must not be increased by the introduction of the NPP within the N-R HES. As a matter of fact, interactions between the two systems (i.e., NPP and Industrial Process) cannot be avoided, but the design of the coupling must assure that those interactions do not decrease the general safety level of the NPP compared to the stand-alone operation. More in detail, the following issues are considered in the reference work.

- The nuclear power plant shall be appropriately separated by the coupled facility. Nevertheless, this objective must be optimized by considering also the physical constraints, e.g., thermal losses through the coupling pipes;
- The contamination of the coupling fluid must be of particular concern when dealing with a safety analysis. In this regard, particular attention is given to Tritium contamination. The latter could be avoided by introducing an additional barrier between the NPP and the coupled facility (e.g., an intermediate heat exchanger);
- Radioprotection of workers of the coupled facility must be carefully considered;

- It is highlighted the fact that for HTRs the evacuation area could be discarded, something that may or may not have a counterpart for LW-SMR, depending on the design and the analyses of possible large early releases during accidents;
- Concerning the security aspect, it is stressed the fact that workers of the coupled facility should be conditioned by the same security clearance of the NPP in case there is a discrete proximity of the two plants;
- Ability of the NPP to follow the energy demands, as well as to cope with the scheduled operations of the coupled facility (e.g., maintenance periods), without being influenced too much by the induced transients.

In particular, incidents and accidents which may impact the third barrier of the defense-in-depth (i.e., control of accidents within the design basis) must be carefully considered. Moreover, transients induced by the N-R HES on the NPP which may bring to the depletion of the second barrier (i.e., control of abnormal operations and detection of failures) must be carefully investigated.

Considering the NC2I-R and GEMINI+ projects, different documents can be taken into account to cover nuclear cogeneration safety (i.e., [48], [49], [50] and [51]). The general considerations about nuclear cogeneration safety are very similar to those coming from the EUROPAIRS project. In addition, the issue of the multi-units configuration is addressed by the project by reviewing the IAEA SSR 2/1 rev.1 [52], a safety guide for Light-Water Reactors. In particular, it is stressed that safety systems should be independent for each unit in order to limit common cause failures. Moreover, the potential risk of a shared control room for all the nuclear units should be considered and enough workforce must be assured to handle possible accidents concerning multi-unit configurations. Another interesting aspect of nuclear cogeneration stressed in the reference projects concerns the proximity between the NPP and the coupled facility. In particular, the issue of possible chemical hazards and risk of explosion is considered. Finally, again the required flexibility of the Nuclear Power Plant is considered. In order to assess the latter characteristic, different scenarios are proposed the transients between each other are investigated as well:

- reactor operating at 100% of rated power with 90% dedicated to electricity generation and 10% to the coupled heat user;
- reactor operating at 100% of rated power with 75% dedicated to electricity generation and 25% to the coupled heat user;
- reactor operating at 25% of rated power dedicated to electricity generation;
- reactor operating at 25% of rated power dedicated to heat user.

Last but not least, the issue of continuity of electricity production on the grid to supply off-site power to the Nuclear plant is considered, which shall be carefully addressed when dealing with grids with high penetration of aleatory generators.

3.2 Further literature references

As for the EU projects, also literature about cogeneration with LW-SMR was found to be limited. However, various sources can be considered, mostly covering HTRs, as guidelines to put a first basis on the safety margins assessment methodology.

For instance, Igorevich et al. [53] discuss the applicability and sufficiency of the existing regulatory frameworks for SMRs. The issue of the possible relaxation of regulatory requirements with respect to large scale reactors, advocated by SMR proposers, is discussed. In this regard, it is proposed to avoid relaxing the safety criteria for the first SMR in order to assure the compliance of all the safety requirements.

A series of reports recently issued by the Small Modular Reactor Regulators’ Forum can be also considered (e.g., [54] and [55]), which discuss different aspects, e.g., multi-unit plants and passive safety systems adoption, as the ones that can play a role in cogeneration safety assessment.

A report by Oak Ridge National Laboratory (ORNL) [56] deals with the construction of a Phenomena Identification and Ranking Table (PIRT) to evaluate some of the most important phenomena that would impact the safety of cogeneration using VHTRs. In particular, the report deals with the coupling of a VHTR with a HTSE plant, addressing different aspects that may influence the nuclear safety such as Tritium contamination of the coupling fluid, possible dangerous releases from the chemical plant, rupture or malfunctioning of the intermediate heat exchanger and so on. An interesting aspect highlighted is the difference between safety requirements between the two plants. As a matter of fact, if nuclear plants tend to limit environmental releases, chemical plants are built in open environments to minimize the possibility of dangerous concentration of chemical substances.

A report by IAEA [57] was found to be interesting for setting up a preliminary methodology about safety margins assessment for cogeneration with LW-SMRs. The report considers some selected design features of SMRs (e.g., modularization, integral design, passive safety features, coupled facilities, protection against internal and external hazards etc.), important for updating the regulatory design safety requirements. For instance, some of the aspects (e.g., integral design) may raise issues of accessibility of the different components for maintenance. Moreover, passive features and natural circulation often suggested in SMRs designs may give rise to weak driving forces or phenomena of “passive failure of passive systems” (e.g., owing to ageing or clogging). In addition, regarding the coupling with other industrial facilities, it is mentioned that the coupling may have different adverse impacts, e.g., differences in the frequency occurrence of Anticipated Operational Occurrences (AOO). In summary, no specific feature of an SMR can be considered completely positive or negative in the ends of safety, thus an accurate screening of the specific plant and site characteristics must be performed.

Another report from Brookhaven National Laboratory (BNL) [58] discusses an interesting topic for nuclear safety, being the issue of implementing a NPP in a smart grid with high penetration of renewable energy sources. The discussion is mainly inspired by the General Design Criterion 17, in Appendix A to 10 CFR Part 50, related to the need to supply electricity to the NPP in a reliable and stable way. The latter problem, indeed, is considered as one of the most relevant in an electrical grid including intermittent sources, where the quality of the off-site power provided to the NPP may not be sufficient for nuclear standards. In this regard, also the low inertia provided to the grid by a high penetration of wind and solar energy generators is discussed.

3.3 Preliminary methodology for safety margin assessment

The main outcomes of the presented literature survey are that the methodology for safety margin assessment, especially related to nuclear cogeneration with LW-SMRs, must be made referring to works that are not specifically focused on the reference technology. While specific consideration will be developed in a subsequent phase of the project, when the related safety assessment methodology will be delineated from general considerations on the cogeneration applications envisaged by TANDEM, with the insights achieved from the current literature review it is possible to suggest a preliminary path for the assessment methodology.

A first investigation of potential issues can be performed by considering the WENRA safety objectives [59], i.e.:

O1 – Normal and abnormal operation and prevention;
O2 - Accidents without core melt;
O3 - Accidents with core melt;
O4 - Independence between all levels of defense-in-depth;
O5 - Safety and Security interfaces;
O6 - Radioprotection and waste management;
O7 - Leadership and management for safety;

and discussing which features of the cogeneration application impact on them. As previously discussed, the interaction with the N-R HES in general (i.e., electrical grid with high penetration of intermittent generators and heat users) may impact directly on the first safety objective. However, further assessments are needed to understand how the interfacing with the N-R HES could influence objectives 4, 5 and 6.

A second screening for possible concerns can be performed by considering the categories of issues mentioned by SMR Regulators' Forum [54], e.g., first-of-a-kind (FOAK), multi units and passive safety issues. In fact, although multi-unit issue could be the one directly involved in interfacing with cogeneration processes, the FOAK issue must be carefully considered due to the lack of experience and information in dealing with nuclear cogeneration with SMRs.

Another step could be to answer the question whether the interfacing with heat users could lead to a depletion of a particular barrier of the defense-in-depth. For instance, the changes in the frequency occurrence of AOOs could lead to an integrity issue of the first two barriers (i.e., prevention of abnormal operations and failures, and control of abnormal operations and detection of failures). In this regard, it shall be suggested that the operational flexibility of a nuclear reactor, i.e., load-following capability in environment with high penetration of renewable generators, has certainly the effect of increasing the initial conditions normally used to perform safety analyses.

To conclude, it must be highlighted that the EUROPAIRS project deliverable 1.2 [47] represents a very good example of a safety assessment of SMRs in cogeneration environments. Moreover, also the recent report by IAEA [57] represents a very authoritative source to be considered, helping in sketching the safety requirements for innovative nuclear reactors, comprehending SMRs. In particular, the step to be undertaken to set up a safety assessment for LW-SMRs could be similar to those indicated in the reference work (i.e., [47] and [57]):

- definition of the safety objectives;
- licensing requirements and their adaptation for cogeneration cases;
- assessment of influence that heat users have on the nuclear site;
- assessment of influence that nuclear site has on the heat users;
- licensing requirements and their adaption for cogeneration cases.

However, since the very work of adaptation of safety concepts and principles to SMRs is still underway worldwide, the further work to be performed in this regard will have to take into account the evolving context in which the safety of innovative nuclear reactors is being studied.

4. CONCLUSION

The present paper covered some of the initial outcomes of the EU TANDEM project. In particular, the results achieved in Task 1.2, covering a technology review of a N-R HES with LW-SMRs and Task 4.1, about a review of nuclear cogeneration safety with LW-SMRs are presented.

The results achieved in Task 1.2 define the most suitable technologies to be considered in future tasks of the project to perform the modelling of the N-R HES. More in detail, the technologies of several blocks of the N-R HES have been investigated (i.e., energy storages, hydrogen production and water desalination). Then, a literature review about safety of nuclear cogeneration is presented. Although the literature about cogeneration with LW-SMR was found to be scarce, several sources were found regarding cogeneration with VHTRs, allowing to present a preliminary and sketchy path that could be undertaken to build a safety margin assessment methodology for nuclear cogeneration with LW-SMRs.

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