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D5.1 LFR BOP Configurations analysis: definition of the final system configuration, equipment specifications and balance of plant

Authors: **Marcos Celador Lera, Alfonso Junquera Delgado, EAI**
Michele Frignani, ANN
Marco Ricotti, CIRTEN

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Lead author(s) & affiliation	Marcos Celador Lera, Alfonso Junquera Delgado, EAI Michele Frignani, ANN Marco Ricotti, CIRTEN
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Document Summary

The main characteristics of the secondary system of ALFRED demonstrator are introduced by assessing the possibility of integrating an energy storage system or cogeneration system. The first option is based on molten salts thermal storage that are used to produce low pressure steam to be turbined down producing an extra electricity output. The latter consists on a hydrogen production facility that generates hydrogen gas by means of Solid Oxide Electrolysis Cell (SOEC) high temperature electrolyzers using electricity and main steam produced in the nuclear plant.

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Authors: Marcos Celador Lera, Alfonso Junquera Delgado Michele Frignani Marco Ricotti	EAI ANN CIRTEN	13/03/2023
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List of Acronyms

ACC	Air Cooled Condenser
ALFRED	Advanced Lead-cooled Fast Reactor European Demonstrator
ANSELMUS	Advanced Nuclear Safety Evaluation of Liquid Metal Using Systems
BOP	Balance of Plant
BWR	Boiling Water Reactor
CSP	Concentrating Solar Power
ESS	Energy Storage System
FP	Full Power
FW	Feedwater
FWTCH	Feedwater Temperature Control Heater
HLM	Heavy Liquid Metal
HPT	High Pressure Turbine
HTS	Heat Transfer Systems
HTSE	High Temperature Steam Electrolysis
LFR	Lead Fast Reactor
LPT	Low Pressure Turbine
LTE	Low Temperature Electrolysis
NPP	Nuclear Power Plant
NSSS	Nuclear Steam Supply Systems
O&M	Operations & Maintenance
PWR	Pressurized Water Reactor
SG	Steam Generator
SGS	Steam Generation Systems
SOEC	Solid Oxide Electrolysis Cell
SPCEC	Solid Proton Conducting Electrolysis Cells
STG	Steam Turbine Generator
V-RES	Variable Renewable Energy Sources
YSZ	Yttria Stabilized Zirconia

1 Introduction

ANSELMUS project addresses the social and ethical impact of Heavy Liquid Metal (HLM) systems by assessing their integration in a low-carbon energy mix in a competitive and efficient way. ALFRED and MYRRHA projects are envisaged, as these are included in the roadmap for the development of advanced nuclear technologies in Europe. Specifically, ALFRED project is the main technological reference used, that has developed an advanced nuclear design based on Lead Fast Reactors (LFR) technology. This design enhances an intrinsic safety nature with respect to previous nuclear reactor generations, and reduces considerably the nuclear waste during the operating cycles.

It is important to develop a balance of plant (BOP) configuration that strengthens and extends the beneficial properties of the LFR technology by developing Power and Steam Conversion Systems that contribute to the reduction of global carbon emissions as the best low-emission back-up technology to the variable renewable sources (V-RES) production in the electric systems mix.

This report evaluates the feasibility and the potential of integrating a cost-effective energy storage system into ALFRED reactor, to achieve load-following performances while maintaining the reactor at high power levels minimizing power excursions. Two main technologies are envisaged to be assessed in the scope of this deliverable: molten salts thermal storage systems, and hydrogen production by High Temperature Electrolysis (HTE). Alternative low temperature thermal storage technologies are also presented.

These two technologies will be analysed to obtain the most suitable configurations for the balance of the plant, identifying the key design parameters that determine the system operation. This evaluation serves as input for ANSELMUS D5.2 deliverable “LFR BOP Main components definition: Definition and sizing of the main components, including sensitivity analysis of both BOP configurations”. It will provide the simulation of the configurations proposed, obtaining the sizing specifications of the main equipment as well as the performance parameters of the plant in terms of efficiency, availability of supply and quantity of heat stored or quantity of hydrogen produced.

The conceptual analysis of the mentioned solutions is based on information available about the reactor main operating parameters and design requirements as well as information about the reference site location, which is the nuclear platform from Mioveni, Romania.

2 Input data and assumptions

For this deliverable purpose, ALFRED demonstrator is used as the reference reactor. It is intended as an European demonstrator of LFR technology, and to reduce the lack of validation and operating experience, a staged operation approach will be implemented, by increasing progressively its thermal power, and consequently, the temperature and pressure of the generated steam: stage 1 – low temperature, stage 2 – medium temperature, stage 3 – high temperature [18], [19].

The investigation on Energy Storage and Cogeneration integration is limited to the plant commercial exploitation so the third stage is taken as the reference for this report. Indeed, it is the one that shall be attractive from an economic viewpoint and representative for commercial size LFR plant efficiency. The following input data [ID] have been considered for the purpose of this report:

[ID 1] The main parameters of the final commissioning stage of ALFRED reactor as shown in Table 1 [3].

Table 1 - Main parameters of the ALFRED reactor

Design data (nominal conditions)	Units	Stage 3
Thermal power	MWth	300
Primary System (Lead)		
Core inlet temperature	°C	400
Core outlet temperature	°C	520
Secondary System (Water / Steam)		
Mass flow rate	kg/s	192.6
Feedwater inlet temperature	°C	335
Steam outlet temperature	°C	450
SG outlet pressure	bar(a)	180

[ID 2] The minimum feedwater temperature at the Steam Generators inlet of ALFRED reactor is 335 °C, to ensure a minimum margin above lead freezing temperature (327 °C). This strongly limits the lower bound for the SG outlet pressure to ensure a minimum degree of under-cooling at the SG inlet (greater than 15 °C, corresponding to a saturation pressure of about 150 bar). Feedwater (FW) inlet temperature variation of ±5 °C at partial loads constraints is acceptable [3].

[ID 3] The following ambient conditions shall be considered (Table 2). The design conditions shall be used to specify equipment. The extreme conditions values should be taken into account only for operational limits [3].

Table 2 - Ambient conditions

Design Condition	
Nominal (yearly average)	12 °C at 60% RH
Summertime (maximum)	32 °C at 60% RH
Wintertime conditions (minimum)	-13 °C at 100% RH
Extreme Condition (verification only)	
Summertime extreme conditions	37 °C at 60% RH
Wintertime extreme conditions	-25 °C at 100% RH

[ID 4] The BOP design shall comply with Mioveni industrial water availability, currently set to 28 kg/s (goal) but extendable up to 56 kg/s (maximum) [3].

[ID 5] Target STG power ramp rate is ±15% FP / min. Minimum requirement is ±10% FP/min [3].

3 Load following capability of LFR in Europe

Nuclear technology has been diversifying along recent decades by adapting the power plant characteristics of the different electricity markets of the countries where they are installed [6]. Modern Light Water Reactors design provides capability of daily power regulations in the range of 50-100% full power (FP) at a rate of 5% FP per minute, once or even twice per day.

Despite the modern fleet load-following capability, baseload supply is so far the most attractive and profitable exploitation mode of nuclear energy. The cost-effectiveness of high loads factor (i.e., low O&M / capital cost ratio), the operational simplicity and reliability of rated power operations make load-following unattractive for nuclear utilities. The average low nuclear share in the country energy mixes, the relatively low penetration of intermitting renewable sources (V-RES), the interconnected electricity markets and the cost-effectiveness of Combined Cycle Gas Turbine peaked plants make baseload operation the most attractive option for nuclear at national grids level. It follows that, to date, the electricity markets for which it turns to be cost-effective using part of the nuclear fleet for daily peak-demand are those with high nuclear share, such as France (70%) and Belgium (47%). Former German nuclear energy policy required enhanced built-in load-following capability to its PWR and BWR fleets since 1970s, achieving remarkable power ramp rates of 10% FP per minute [7].

Under a technical perspective, the current nuclear fleet is suited to daily duck-curve load-following (i.e., one or two power cycles per day). The future high V-RES penetration markets will ask for a significantly higher grid flexibility, on daily and hourly basis, the latter neither achievable nor profitable with current NPP design. The high penetration of V-RES will therefore require a paradigmatic change in nuclear power plants design, licensing and construction approach as well as deep investigation on economic sustainability and profitability of future nuclear load-following option. To date, there is a general consensus on the technical feasibility of designing new units for flexible, safe, reliable and efficient operations. However, under the economic perspective, the power flexibility will cause capital and O&M costs increase, requiring policy makers to leverage on financial incentive to attract future plant owners and designer to load-following option.

In this frame, the integration with Energy Storage Solutions is raising interest in the development of advanced reactor designs, as a potential solution that combines the full power operation technical and economic benefits with load-following capabilities.

An Energy Storage facility will essentially decouple, to some extent, the plant electrical output from the reactor power, keeping the latter at rated values and modulating the first according to grid demand. This solution may be of particular interest in the case of Heavy Liquid Metal Fast Reactors, where additional constraints – to be furtherly investigated - related to primary fluid inertia (for pool type reactor only), the thermal-fatigue due to the high temperature difference experienced by the in-vessel components as well as the lack of operational experience, might make steady-state operation on primary side preferable.

Based on the above considerations, this document investigates the possible balance of plant configurations for integrating a thermal storage system or cogeneration of hydrogen in ALFRED reactor and identifying the key aspects of each technological solution.

4 Secondary systems integration with Nuclear Island

4.1 Nuclear Steam Supply System

ALFRED (Advanced Lead-cooled Fast Reactor European Demonstrator) is the name given to the project that develops the commercialization of a first of a kind LFR (Lead-cooled Fast Reactor) under the FALCON Consortium, having a power range in the SMR (Small Modular Reactor) domain. LFR reactor is one of the 6 reactor technologies selected by the Generation IV International Forum (GIF), which coordinates research and development on Generation IV nuclear systems and promotes the innovative design of new safe, secure, sustainable, competitive and versatile nuclear reactors. This technology aims a better fuel cycle sustainability, maximum safety standards that exclude domino effects in case of incident or accident in the primary side, and economic competitiveness compared to current nuclear reactors, being optimum for multi-unit sites facilities.

To achieve these goals, a staged approach for ALFRED will be implemented by increasing progressively its thermal power and consequently, the temperature and pressure of the generated steam, as explained in ANSELMUS Deliverable D1.2 “ALFRED reference design and initiating events” [18]. The present document focuses on the Stage 3 of the implementation process [3], in order to get to a BOP configuration that is attractive from an economic viewpoint and representative for commercial size LFR plant efficiency.

The reactor design has three Steam Generators of the bayonet tube type, that provide a constant nominal flow rate of superheated steam at any power rate (including stages). The feedwater goes to the bottom of the SGs and rises up removing the thermal power from the liquid lead, which goes downwards towards the core inlet, in a counter-current configuration. Isolation valves are installed at the inlet (feedwater isolation valves) and the outlet (steamline isolation valves) of the reactor working in open position during normal operation. Safety relief valves are located upstream the steamline isolation valves to protect the system from overpressure events. (see ANSELMUS Deliverable D1.2 for more information on the Steam Generators and the Reactor Coolant System of ALFRED reference design [18]).

One of the main requirements for the secondary side design is to keep the feedwater temperature at the steam generator inlet at 335 °C in order to ensure that the lead is always over its melting point [ID 2]. As stated in [ID 1], the steam generators will produce high superheated steam at 450 °C and 180 bar(a). This high pressure is required to guarantee liquid conditions of the feedwater at the steam generators inlet and will largely determine the overall performance of the plant as well as the operation and nature of the installed equipment.

4.2 Steam and Power Conversion Systems

The main objective of this report is to study the feasibility of coupling the Nuclear Steam Supply System (NSSS) of ALFRED reactor and the Steam and Power Conversion Systems for electric generation by integrating an Energy Storage or Cogeneration System. For any of the technological solutions presented in this report, there are some common features that are predefined for the secondary system of the plant.

The main steam produced in the Steam Generators (SG) located in the reactor vessel is superheated steam at 450 °C and 180 bar(a). A conventional single reheat Rankine cycle with regenerative preheating is selected as more convenient for these steam conditions and power. Preliminary, the cycle shown in Figure 1 is used as a starting point for the ongoing analysis.

A High Pressure Turbine (HPT) expands the steam up to slightly wet or saturated conditions (to be determined in future steps). This will determine if the steam is introduced in a Moisture Separator or goes directly to the reheating cycle, formed by two stages. Afterwards the steam is expanded again in a Low Pressure Turbine (LPT) and is driven by backpressure from its exhaust to the condenser. The possibility of having two separated Steam Turbine Generators (STG) will be studied in the next deliverable of the project (D5.2), as this might give some flexibility to the Energy Storage configuration to be installed. The condenser will be dry Air-cooled Condensers (ACC) in order to largely reduce the need of water in the heat sink of the cycle.

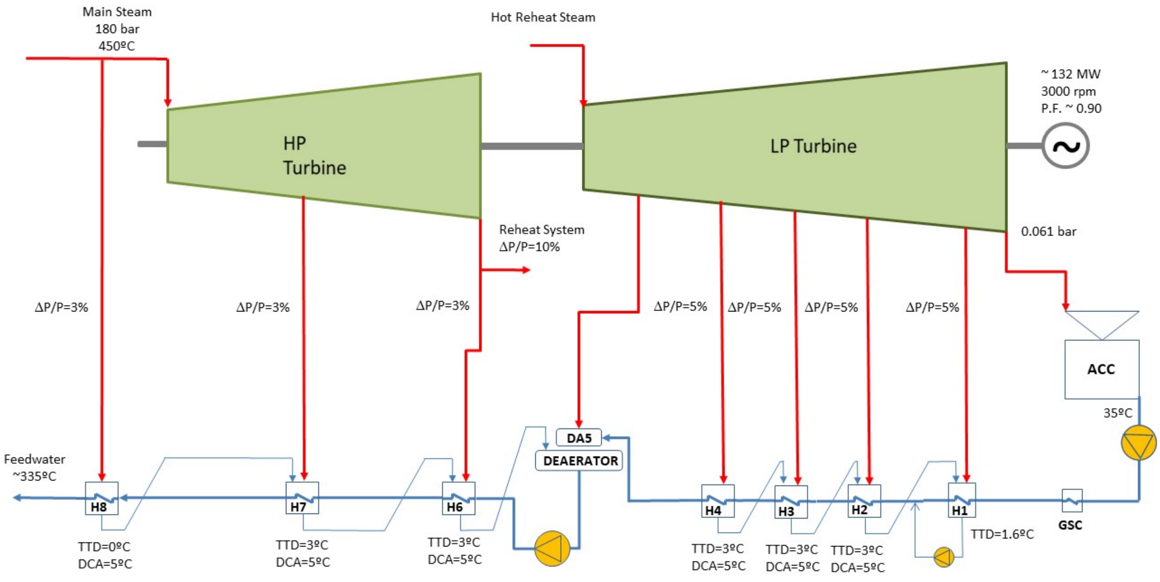

Figure 1 - Secondary System General Balance of Plant Schematic

A series of heat exchangers preheat the feedwater before entering the SGs of the reactor up to the required feedwater temperature of 335 °C. They are fed by steam extractions and exhausts of the HPT and LPT, and the condensed water is redirected to previous steps of preheating in cascade to take advantage of the higher enthalpy conditions. Although a first approach is depicted herein (Figure 1), the final configuration on how many preheaters shall be installed and from which points of the cycle are fed shall be determined in the following deliverable (D5.2, EAI, R, PU, M12).

In any case, all the preheaters shall be cascade drain type, with two exceptions: the deaerator and the first preheater H1. The Deaerator is a direct contact heater and the drain is pumped by the feedwater pumps into the high pressure preheaters. The first preheater H1 shall be pump-forward drained, as the condensate cannot be gravity driven into the ACC condenser.

An extra heater (Feedwater Temperature Control Heater – FWTCH) fed with main steam is located upstream the SG Feedwater inlets to maintain, during any transient or mode of operation, a feedwater temperature of 335 °C, as shown in Figure 1, represented as preheater H8. This equipment is considered an essential part of the balance of plant, as was already depicted in [2].

Between the low pressure and high pressure preheaters is the Deaerator. There are also 2x100% feedwater pumps which supply the SGs with water having a low oxygen and carbon dioxide concentrations to protect them against corrosion.

A 100% turbine bypass system is included, allowing direct transfer of main steam from the steam generator to the condenser, giving the plant total power variability during possible thermal load transients. There is desuperheating feature in the bypass valves using cold water coming from a condensate pumps outlet connection.

As it is described in this section, there are several parameters of the water and steam cycle that are open for further analysis in the following deliverable. This will offer some flexibility when determining how the thermal storage systems can be coupled to the cycle. Some of these parameters are the following: steam conditions at the HPT exhaust, reheat process operating pressure, number of preheaters and their steam extractions configuration or LPT backpressure and condensing temperature.

5 Energy Storage and Cogeneration Systems

Electricity markets are changing due to the V-RES penetration increase such as wind and solar energy. These energy sources are non-dispatchable, creating volatile electricity prices. To adapt nuclear power plants to this new electricity market behavior, the feasibility of integrating an Energy Storage or a Cogeneration System in the BOP to vary the power plant production or transmission is evaluated.

The goal is to keep the reactor at constant base load while the electric power given to the grid varies depending on the electricity market. When electricity prices are set low (or even negative), part of the produced steam is used to store energy in thermal or chemical form, while the turbine operates at minimum load. When electricity prices are set high, all the steam produced by the reactor is used to produce electricity in the turbine, and also, an extra electric energy could be produced by using the energy from the Energy Storage System (ESS). In case of the Cogeneration option, the generated product can be stored and sold when it is economically convenient.

The main overall requirements that the Energy Storage or Cogeneration Systems must fulfill are: thermodynamic compatibility with the main steam produced by the steam generators (superheated steam at 450 °C), daily basis storage time capacity, good thermal overall efficiency, and competitive economic costs. The feasibility of implementing different energy storage solutions that are being developed or investigated nowadays and their compatibility to ALFRED reactor main requirements are analyzed.

The two main alternatives for plant load-following in ANSELMUS project are the molten salt energy storage systems and the production of hydrogen by means of high temperature steam electrolysis [1]. These two options are analyzed in the following chapters.

Moreover, alternative forms of low temperature thermal storage technologies are overviewed for information purposes in Section 5.3.

5.1 Molten salts thermal storage

The basis of this energy storage system applied to the ALFRED demonstrator is to heat up molten salts with part of the main steam produced in the SGs and store them so that the hot salts are used to produce steam back and obtain the extra load requested. The reactor power would remain constant at full load conditions independently from the plant final output, at least whenever no partial loads are required by the primary side operating requirements.

5.1.1 Technological solution

5.1.1.1 Heat transfer Fluid

The use of liquid salt coolants as working fluid in the Heat Transfer Systems (HTS) offers a series of important benefits such as:

- High volumetric heat capacity
- Low vapor pressure and high boiling point
- Appropriate thermal conductivity
- Good chemical stability within the operating range
- Non-flammable and non-toxic
- Optical transparency during inspection operations.

Several types of molten salts mixtures can be used as heat transfer fluid for this application: fluorides, chlorides and nitrates (mainly Hitec - NaNO3-NaNO2-KNO and the so-called solar salts). From these types of salts, the nitrates ones are cheaper, but also much less corrosive than fluorides and chlorides [4]. Among them, solar salts are selected due to their high commercial display and availability as they are commonly used in Concentrating Solar Power (CSP) facilities. The selected solar salts are composed by a mixture of 60% weight of Sodium Nitrate ($NaNO_3$) and 40% of Potassium Nitrate (KNO_3).

The melting point of the mentioned mixture is 222 °C, but it can start crystalizing at around 238 °C [4]. Assuring that the molten salts are always over the melting temperature is one of the main challenges of this technology. For safety reasons, margins have to be applied so the minimum operating temperature of the salts during all operation modes should be kept over 290 °C.

To accomplish this requirement, all molten salt piping and related equipment or devices should be designed to include a heat tracing system to keep the piping walls at the required temperature for all the operation modes of the plant, as well as insulation. Additionally, the Storage System of the plant will be equipped with electric heaters to assure the minimum operating temperature. It is also recommended not to reach 600 °C to prevent thermal degradation, so the upper limit operating temperature can be 565 °C, although it shall be set to a maximum of 400 °C, for constructive reasons, as it is explained below.

Some composition requirements must be fulfilled for the operation with molten salts. The salts mixture shall have a minimum nitrates concentration of 99 weight percent and a maximum chloride ion concentration of 0.1 weight percent. Other contaminants concentrations such as sulfates, nitrites or carbonates shall be controlled and limited as well.

It should be noted that the above described heat transfer fluid requires high demanding design conditions for the piping and equipment due to the high levels of corrosion and the high operating temperatures.

5.1.1.2 Thermal Storage Systems

The Thermal Storage System has the goal of accumulating the heated salts in the most efficient way so that the least energy is lost during the storage time. The molten salts are pumped from the storage system by means of several vertical pumps from the atmospheric pressure to the HTS. Due to operative reasons, there is a minimum amount of salts that can be stored in the tank serving as sump volume. Several configurations can be chosen for this function:

- ***Two storage tanks.*** The most commonly used technology to fulfil this objective, usually applied in all CSP plants, is the installation of two storage tanks, one dedicated to store the hot salts and the other one the cold salts. In Figure 2, a configuration for CSP using two storage tanks is illustrated. The tanks are vertical cylinders made up of carbon steel and insulated in order to minimize the heat loss through the walls and ceiling. The tanks are maintained at atmospheric pressure by means of atmospheric vents. The hot tank operating temperature shall not exceed 400 - 420 °C in case of carbon steel tanks, in order to avoid constructive problems, as these have been detected in several installations of this type. Using a more expensive material such as alloy or stainless steels would increase considerably the costs of the storage system, and the temperature increase available in this case study is too short to compensate the investment.

Each of the tanks has additional equipment to be installed for the correct functioning of the system:

- Salts circulation pumps: these are vertical pumps submerged in the tanks with outboard electric motors with variable speed drives supported by an independent platform outside the tanks
- Tempering pumps used during startups and transients of the plant
- Electric heaters are installed at the bottom part of both tanks in order to maintain under any circumstances the salts over their freezing point, keeping the fluid over the minimum operating temperature. They shall be placed under a minimum molten salts volume that is defined for operability reasons
- Salts distribution rings are used to receive and distribute the molten salts in each of the tanks. Usually, they are located at the bottom of the tank and are fed by a vertical collector of the same diameter
- Other auxiliary and safety minor equipment such as overpressure protection devices, vents and drainage lines.

Figure 2 – Thermal storage tanks in Termosol 1 CSP Plant of 50 MW in Badajoz, Spain [11]

The size of the tanks is determined by the hours of storage intended in the design but it is also considered the minimum salts volume for pumps submergence as well as the salts volume in heat exchangers and piping of the whole thermal storage system for the total emptying.

- ***Single storage tank.*** Recent projects are studying the feasibility of installing one single thermocline-like storage tank where the hot salts (located at the top part) are separated from the cold salts (located at the bottom) by a stratification or thermocline zone in between (see Figure 3). The thermocline zone moves upwards and downwards during discharging and charging of the tank, respectively.

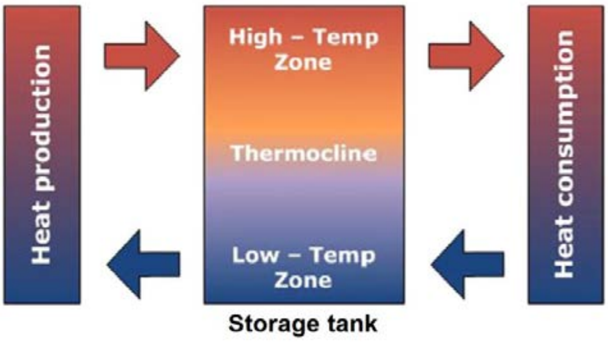

Figure 3 – Thermocline storage tank operational principle [5]

This technology offers several benefits compared to two tank systems, as follows:

- High reduction of heat losses
- Reduction of capital costs
- Reduction of required space
- Reduction of the unused sump salt volume.

There are different approaches for the single tank molten salt system with regard to the technology used for the thermocline zone. There can be natural stratification, moving barrier, packed beds or solid filler materials. Among these options, the one using refractory filler materials is the most promising technology. It offers a reduction of thermal stress between filler and wall tank, as well as adjustable flow distribution by checker geometry design.

There are several disadvantages of single tank solution with respect to the two-tank one. A technical one is related to a drop in the outlet temperature of the hot salts at the end of its discharging process. This issue has a direct reduction of the efficiency of the whole plant performance. Nevertheless, there are ongoing developments in the state of the art to counteract this temperature drop by introducing at the top and bottom of the tank an additional phase change material layer that stabilizes the outlet temperature of the salts due to its high phase change enthalpy at constant temperature.

Another disadvantage of this solution is the immaturity of the technology, as its readiness level is still in the simulation phase, which uses relevant environments but not real scaled locations. Although the commercial display of the technology has some uncertainties at this moment, there are promising ongoing projects that could have relevant advances in the following years.

Regarding the previous analysis of both technologies, in the next deliverable one of these systems will be selected for the thermal storage system of the molten salts energy storage configuration. In any case, the differences regarding the heat and mass balances of the plant are not significant in a conceptual design phase and the system can be simulated with no much interference.

5.1.1.3 Heat Transfer Systems

The HTS of the plant is in charge of transferring the thermal power from the main steam produced in the Nuclear Steam Supply System (NSSS) to the cold side of the molten salts circuit to heat up the salts and store them in the hot reservoir, corresponding to the Loading operating mode (see Section 5.1.2).

The main steam is desuperheated, condensed, and subcooled in a succession of heat exchangers so that the subcooled liquid is returned to the water-steam cycle again, and the heated salts are stored in the hot reservoir.

In Section 5.1.2.1 the possibility of replacing the loading side of the HTS by electric heaters fed by the Steam Turbine Generator of the plant is introduced.

The Heat Transfer Systems are also in charge of transferring the heat from the hot molten salts circuit to the liquid water of the Feedwater System of the plant, during the Unloading operating mode (see Section 5.1.2).

This function is performed by the so-called Steam Generation System (SGS) that commonly consists on a train of heat exchangers, arranged from the hottest salts to the coolest ones in the following way: steam superheater, evaporator and economizer, in series with the previous. These heat exchangers shall be of shell-tube or hairpin type with the water/steam circulating through the tube side and the molten salts through the shell side.

Moreover, there are ongoing projects in which the Steam Generation System is integrated in the thermocline tank by means of helical coils steam generators [16]. This could reduce the total costs of the Storage system.

The whole system shall be designed for a daily start-up and shut down.

5.1.1.4 Auxiliary Systems

Auxiliary systems are needed for the molten salt melting, drainage and tempering during transients and startups, among other minor systems.

- *Anti-Freezing System*. This system is in charge of keeping the salts over the minimum temperature, which shall be 290 °C. Different levels of protection regarding the temperature of the salts can be established, as follows:
    - The first level shall be recirculating the salts inside the heat exchangers and piping to homogenize the temperature during storage waiting hours.
    - The second protection level consists of an electrical heat tracing system distributed through the heat exchangers, drainage tank, pumps, valves and piping of the salts systems. This system is activated automatically by temperature sensors installed in the protected equipment when the set point is reached.
    - The third one is the installation of electric heaters in the bottom part of the tanks, which shall always be covered by the minimum available molten salts volume. The heaters have the aim of replacing the heat losses of the tank through the walls and ceiling.

- *Salts Fusion System*. The salts mixture described in Section 5.1.1.1 shall be supplied in solid form so they are melted before the startup of the plant. The system consists mainly of a melting furnace unit and a solid handling unit that doses the salts in the appropriate mixture composition and grain size.

- *Drainage System*. This system has the function of emptying the molten salts from all the equipment of the salts circuits and send them to the cold salts tank during maintenance. This task is usually done just by gravity driven drains, but sometimes a compressed air or nitrogen powered pneumatic transport system might be required to help the fluid be drained towards a drainage tank for its collection.

5.1.2 Configuration Analysis

The Thermal Storage System described above has to be integrated with the configuration explained in Section 4 for the water and steam conversion systems of the plant. The interfaces to be defined among the participating systems in this conceptual phase have to be suitable from the thermodynamic and constructive point of view. To achieve this, two main operating modes are defined: Loading Operating Mode and Unloading Operating Mode.

At the time of selecting which are the connection points of the Steam and Power Conversion Systems of the plant and the HTS, several approaches can be studied. This decision will be defined by the detailed heat and mass balances performed for the system, in the next deliverable (D5.2) [1]. In the following sections the configuration of the aforementioned operating modes will be explained.

5.1.2.1 Loading Operating Mode

The loading mode consists of molten salts heating up with part of the main steam produced in the SGs, and store them in the hot salts storage tank for later use. The condensed fluid would be discharged in the feedwater path towards the reactor, preliminary, right before the last preheater.

The steam-salts heat exchangers shall have three different parts: de-superheating section, condensing section and drain cooler section (see Figure 4). Due to its very high pressure (180 bar(a)), the feeding steam (green line in the Loading side of Figure 4) shall flow through the tube side of the heat exchangers in order to avoid an equipment with high design pressure and high thickness and dimensions. This equipment would work in a similar way in which the steam flows (and condenses) through the Reheaters of conventional NPPs, used to reheat the steam coming from the exhaust of the HPT towards the LPT. On the other hand, molten salts shall not circulate through the tube side of the heat exchanger as there could be problems with its solidification causing fouling in the tubes (orange and red lines in the Loading side of Figure 4).

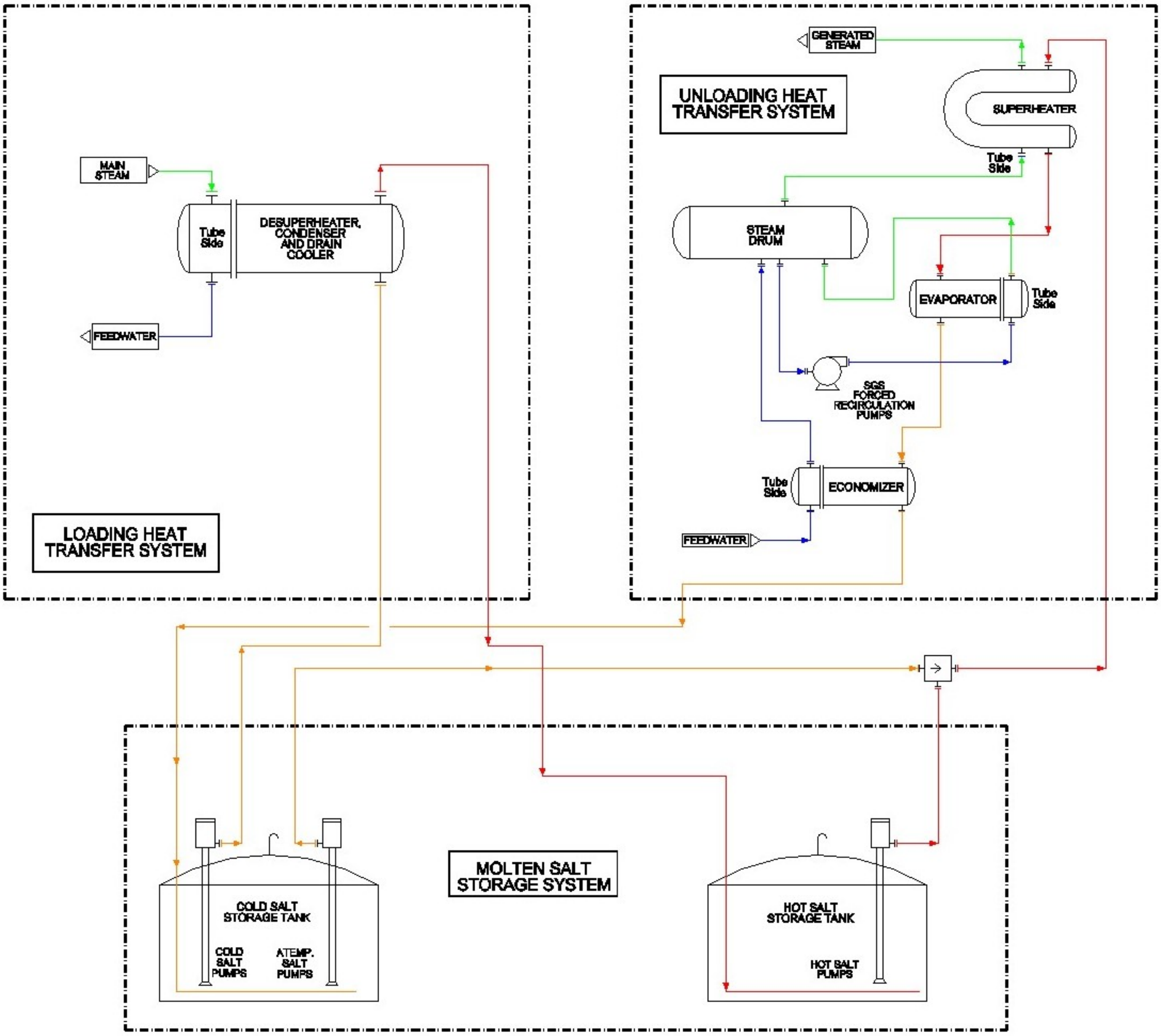

Figure 4 – Loading and Unloading Operating Mode Schematic

The limiting temperature for the cold side during Loading Mode will be the minimum operating temperature for the cold salts, which has been set to 290 °C. As this subcooled fluid is still at a high temperature and pressure, it can be returned into the feedwater system in one of the high pressure feedwater preheaters on the basis of the thermodynamic conditions of both flows. The exact point of this interface will be determined in the next deliverable of this project (D5.2).

The cold molten salts are pumped by means of several vertical pumps with variable speed installed inside the cold salts tank, from the atmospheric pressure of the cold salts storage tank to the cold side of the Loading Heat Exchangers. They are heated up to a maximum temperature of 400-420 °C, limited by the carbon steel Hot Salts Tank operating temperature, where the salts are stored back.

It has to be pointed out that there is another alternative of the previously described Loading operating mode, which consists of using electric circulating heaters to heat up the salts, fed by the electricity produced in the Steam Turbine Generator of the plant. This system is simpler and the equipment needed is already deployed in some CSP plants to preheat the salts or avoid the freezing by recirculating the salts in the cold salts storage tanks.

As it is shown in Figure 5, this equipment is similar to a conventional tube-shell heat exchanger but instead of a bunch of tubes full of circulating water, there are electric rods that are electrically activated to heat the external fluid (in this case, the molten salts).

Figure 5 – Electric Circulation Heater [17]

Nevertheless, this heating system is energetically inefficient, as energy is transformed from thermal (main steam) to electric and then back to thermal, so its implementation has to be economically analyzed to be applied.

5.1.2.2 Unloading Operating Mode

During the unloading operating mode, the hot salts (red and orange lines in the Unloading side of Figure 4) are used to generate steam (green line in the Unloading side of Figure 4) that is sent to the Low Pressure Turbine as additional steam to be expanded and generate extra electric power during times of high electricity prices. While HPT shall be designed to the reactor steam production, the LPT shall be designed for the maximum steam flow rates (including additional supply from thermal energy storage (TES) system). The hot salts are carried to the SGS, which shall be formed by an economizer, an evaporator with steam drum or a kettle, and a superheater as the existing steam generators in tower solar plants (see Figure 4). The live steam conditions cannot be achieved in this SGS if no external auxiliary heat sources are introduced.

As an assumption, it can be considered that the hot molten salt temperature when the power plant starts the unloading mode of operation will be 1 °C lower than their temperature when they were heated during the loading mode. This assumption is reasonable, as the thermal isolation materials commonly used for this kind of tanks are highly efficient, and also because it is considered that the hot salts will be used on a daily basis.

Preliminary, the conditions of the steam produced in the Unloading Heat Exchangers can be set close to the reheat steam coming from the reheaters between both turbines. With this configuration, an extra mass flow rate of steam can be expanded in the Low Pressure Turbine in order to increase the gross output of the turbine generator of the plant. The feedwater conditions at the inlet of the SGS (the blue line in the Unloading side of Figure 4) shall be over 250 °C in order to guarantee for safety reasons that the salts are always over their crystalizing temperature.

As mentioned in Section 5.1.1.3, there is an alternative for the Unloading operating system that integrates the SGS described above in a single equipment together with the thermocline storage single-tank technology.

This configuration will be fine-tuned or modified with the final heat and mass balances, to be developed in Deliverable D5.2 of the project [1].

5.1.3 Key Design Aspects

Some issues arise from the previous sections for which special attention is necessary to pay and which will require further development and research in the project future stages. Likewise, in views of preparing the next deliverable planned in the project, in which the mass and power balances of the thermal storage options proposed in this document will be developed, a series of key design aspects to be taken into account in these activities are presented below:

- *Rankine cycle with regenerative preheating adjustments.*
  The final configuration of the water-steam cycle of the plant would depend on the thermal storage configuration, so the most suitable options shall be selected in the next deliverable.

  The preliminary Balance of Plant presented herein could be modified in some aspects: the STG could be divided between the high and the low pressure ones in independent axis; moisture separator could be avoided by having saturated or slightly superheated steam at the exhaust of the HPT; the number of preheaters and the extractions feeding each of them could be modified as well.

- *Loading Operating Mode System.*
  As explained in Section 5.1.2.2, the equipment or series of equipment to perform the heating up of the molten salts by desuperheating, condensing and subcooling the main steam produced by the SGs is needed. This precise equipment is not developed in a commercial standard so it is needed to specify its requirements in order to apply realistic operating conditions to be used in the balance of plant.

  Other technological options can be investigated for performing this task, for instance the use of electric heaters by circulating molten salts.

- *Thermal storage system and SGS.*
  As shown in document, the aspect of what technology to implement in terms of salt storage has been left open. This is due to the fact that the choice of one or another technology does not condition too much the conceptual parameters of efficiency and performance of the plant, and depends to a greater extent on issues of technology development and economic aspects.

  However, it will be necessary to determine which option is chosen in order to adapt the selected plant systems and equipment to that choice. In particular, the SGS that could be integrated in the thermocline single storage tank could vary the performance in a relevant way with respect to the classical Concentrating Solar Plants Steam Generation Systems.

- *Interface operating parameters.*
  It will be necessary to analyze the interconnection points between the thermal storage system and the water-steam cycle in the next deliverable of the project, since this largely determines the final result in terms of efficiencies and performance.

The limiting operating temperatures predefined for the hot and cold salt storage tanks can be used as reference conditions, which are 400 °C and 290 °C, respectively.

Regarding the Loading operating mode, using main steam to heat up the salts seems the most reasonable option. The condensate will have a minimum temperature of 290 °C so it shall be reinjected in the last stages of the feedwater preheaters, operating at high pressures.

For the Unloading operating mode, the condensate shall enter in the SGS at a temperature higher than 250 °C, to prevent salts crystallization. The steam to be produced will depend on the hot salts operating temperature, and could be used as steam to be introduce in the LPT or as extraction steam for preheating the feedwater temperature.

- *Sizing of the Storage System.*
  A very important aspect that must be developed in future stages of the project is the sizing of the main equipment that makes up the energy storage systems, mainly with regard to the specifications of tanks, pumps, and heat exchangers. There are several variables that arise in the selection of these equipment, and affect the main performance parameters of the plant as well as its budget.

  The use of larger tanks means the plant can store a greater amount of energy in the form of volume of hot salts. This favors the incomes of the plant since it will be able to generate a greater amount of electricity during periods of time in which the market price established in the reference electrical system is higher. However, the increase in size of both the tanks and the rest of the equipment that must increase their size accordingly, is also increasing costs proportionally. These aspects have to be treated with great care in future stages of the project, specifically in the Sub-Task 5.1.2, which deals with the techno-economic analysis of the solutions analyzed in this Sub-Task [1].

5.2 Hydrogen production by electrolysis

Hydrogen gas is an energy carrier of strategic importance for European interests of the incoming decade. Numerous projects have arisen for developing the production, transport, distribution and final use of hydrogen. Unlike electricity, this light gas can be stored for a latter use. Producing hydrogen using the products of a nuclear facility (heat and/or electric forms of energy) is a good complement for dropping the net electric output of the plant while keeping the reactor at constant load.

Large quantities of hydrogen can be stored at low costs as compressed gas in underground facilities or traditional pressurized tanks.

5.2.1 Technological solution

Hydrogen can be produced by three main different methods.

The first one uses the reaction of fossil fuels with steam in a device called reformer. This method produces CO_2 emissions and has other issues related to the coupling of this process to other systems, so it will not be analyzed in detail.

The second method is based on thermochemical cycles that split water with the use of a heat source, and there are hundreds of different ways that are used in the petrochemical and fertilizers industries. Different studies analyze the efficiencies and operating conditions of several thermochemical hydrogen production processes [8]. It can be concluded that these processes require very high temperatures that cannot be achieved by the main steam of ALFRED, and also imply complex chemical reactions that have associated safety risks.

The last method is electrolysis, and it is the selected technology to be developed under the project purpose.

5.2.1.1 High Temperature Steam Electrolysis (HTSE)

The electrolysis method uses electrical energy to decompose water into hydrogen and oxygen. This process is usually performed in an individual cell in which oxygen and hydrogen are the electrodes separated by an electrolyte that acts as a membrane. There are different types of electrolysis cells for hydrogen production depending on the materials used as electrolytes and catalysts.

Other kind of classification for electrolysis process is the temperature range at which the cell works. Low Temperature Electrolysis (LTE) uses liquid water to produce hydrogen (usually at temperatures between 50 and 250 °C) and are mainly based on alkaline and proton exchange membrane water electrolysis. This method of obtaining hydrogen is well known and used, having large scale production facilities of the megawatt range and efficiencies that can reach 80% for some types.

On the contrary, high temperature electrolysis uses steam and the operating temperature range is around 700 to 900 °C. High Temperature Steam Electrolysis (HTSE) requires less electric energy input compared with electrolysis of lower temperature, as part of the energy required is supplied in form of heat at high temperatures. Moreover, the total amount of energy required, this is, the sum of the electrical energy and the thermal energy, is lower for HTSE than for LTE, as shown in Figure 6.

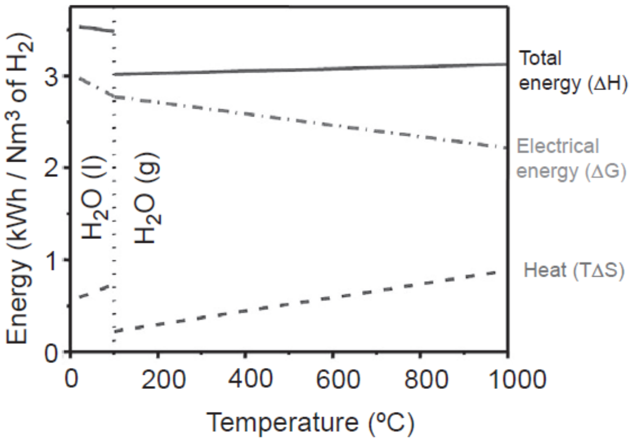

Figure 6 – Energy need for LTE and HTSE as a function of temperature [9]

At the cell level, for a single unit electrolysis cell, the electricity-to-hydrogen efficiency of the HTSE is around 96% whereas for LTE is around 60 to 70%. In case of a system level evaluation, efficiencies for HTSE are equal to 89% taking into account a loss of 8% for electrical converters and thermal auxiliaries, and around 60% for LTE [9].

In the context of ANSELMUS project, both forms of energy are available, but HTSE is the preferable hydrogen production technology to be developed in the frame of this project.

5.2.1.2 *Solid Oxide Electrolysis Cell (SOEC)*

Among the different types of HTSE cells, the so-called Solid Oxide Electrolysis Cell (SOEC) or O^{2-} ion-conducting cell is the most promising technological solution. As it is shown in Figure 7 schematic, it consists of three ceramic layers: an oxygen-conducting ceramic material acting as the electrolyte, and two porous electrodes where hydrogen and oxygen are produced, acting as the cathode and anode of the cell, respectively. A mixture of high temperature steam and a small amount of hydrogen is introduced in the cathode, and in combination with the induced electric current, the steam dissociates in hydrogen and oxygen ions, which penetrate through the electrolyte into the anode layer where they recombine forming oxygen.

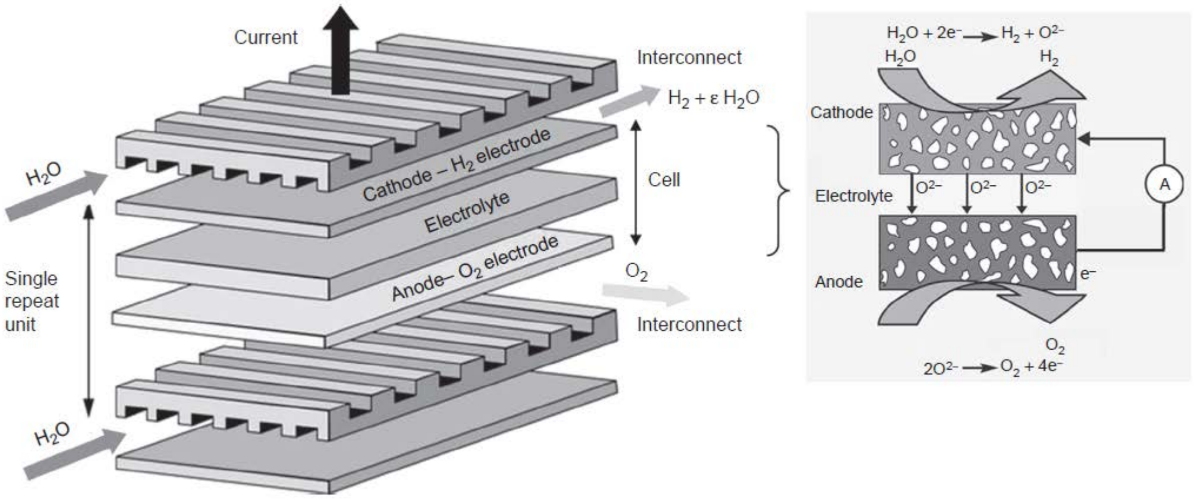

Figure 7 – Schematic representation of a SOEC stack [9]

The reference material used for the hydrogen electrode is generally a nickel/yttria-stabilized zirconia (Ni/YSZ) cermet, which provides good catalytic properties for water reduction and the ability to remain stable in a reducing environment. Similarly, the oxygen electrode requires suitable catalytic properties for the oxidation of O^{2-} ions and the ability of remaining stable in an oxidizing environment. For this purpose, Strontium-doped lanthanum manganite is considered to be the reference material.

Regarding the electrolyte, it has to exhibit adequate gas tightness, good ionic conductivity, a thermal expansion coefficient close to that of the electrodes (to limit mechanical stresses), stability in both oxidizing and reducing environments, mechanical stability in HTSE operating conditions, and finally, no chemical reactivity with the electrode materials. In most cases, the electrolyte material is Yttria Stabilized Zirconia (YSZ) [9].

The purpose of the feed gas stream of the cathode containing fraction of hydrogen (10%) is to maintain reducing conditions and avoid oxidation of the nickel in the hydrogen electrode. The steam-hydrogen mixture exits from the stack and then passes through a separator to separate hydrogen from the residual steam. Often, preheated air or steam is used as a sweep gas to remove oxygen from the stack where the sweep gas dilutes the oxygen concentration and thus decreases corrosion of the oxygen-handling component [3].

With the aim of scaling the hydrogen production, numerous cells are connected to each other forming a stack, by means of interconnecting layers that carry the electric current, and also serve to distribute the inlet and outlet fluids uniformly throughout the cells as well as acting as separators between the cathode of a cell and the anode of the consecutive one, as shown in Figure 7.

An alternative to SOECs is represented by the Solid Proton Conducting Electrolysis Cells (SPCEC), also called protonic or H^+ ion-conducting SOEC (H-SOECs). In this case, a proton conductor electrolyte is used as membrane in the cell and steam is introduced into the anode and hydrogen is electromechanically obtained from water in the form of protons which are conducted to the cathode by the electric field. Some important advantages of SPCECs with respect to SOECs are that they are able to work at lower temperatures (400 – 600 °C) and the fact that pure hydrogen can be obtained directly, whereas in SOECs a hydrogen and water mixture is produced. However, this technology is currently much less mature and requires further development and investigation, specially focused on exploring electrolyte materials [10].

5.2.2 Configuration Analysis

The Hydrogen Production System presented above has to be integrated within the configuration explained in Section 4 for the water and steam conversion systems of the plant. The interfaces to be defined among the participating systems in this conceptual phase have to be suitable from the thermodynamic and constructive point of views.

The operating temperatures of HTSE based on SOECs (700 - 900 °C) are far from the superheated steam output temperature of ALFRED reference reactor (450 °C). Therefore, intermediate processes have to be introduced in the system configuration in order to integrate the HTSE using SOECs for hydrogen production into the BOP in an efficient and feasible way.

Several studies develop the possibility of operating HTSE systems with heat sources at lower temperature without resulting in strong over-costs [12]. These studies are based on the SOEC technology explained in previous section, working at a temperature of 800 °C. The hydrogen production stacks need the injection of a high temperature superheated steam and hydrogen mixture and a sweep gas made up by high temperature compressed air. In order to obtain these high energy streams, regenerative heat exchangers and electric heaters are used before the inlet of the electrolysis cells, as shown in Figure 8 [13].

In this case study, the main heat source of the process is the superheated steam produced by ALFRED steam generators. A HTS shall be installed to remove the heat produced in the nuclear side and provide it to the water-hydrogen mixture stream. This system shall reduce operational complexity acting as a buffer system between the nuclear side and the cogeneration facility, reducing safety issues related to the thermal cycling associated to the electrolyzer operation. It is also desirable to avoid phase change in both sides of the heat exchangers, as the superheated steam has to be desuperheated, condensed and subcooled in the hot side.

The heat transfer fluid in this case shall be a high temperature, liquid-phase heat transfer fluid such as a thermal oil. Several studies propose the use of Therminol-66 due to its high reliability and its thermal stability, resisting solid formation and system fouling. The recommended operating temperature of this fluid is 345 °C and is pumpable at low temperatures. Other fluids of similar characteristics shall be selected for this function.

There are some auxiliary systems associated to the thermal oil management. These can include an anti-freezing system, due to the difficulties that there shall be related to moving the oil at low temperatures, or an ullage system to remove from the system the degradation gases produced in the thermal oil.

Figure 8 shows the configuration developed by Ansaldo Nucleare for the Hydrogen Production System using SOEC technology [3]. As it is shown, the process is fed by a “Process Heat In” stream at the inlet of the hot side of the so-called HX-102 Steam Generator, which comes from the HTS of the NPP.

The hydrogen-water mixture is preheated in several steps before entering the SOEC cell. Firstly, two low-temperature recuperator heat exchangers (HX-101 and HX-103) use the sweep gas and the hydrogen-water mixture streams to obtain back as much energy as possible after these have exited the high temperature recuperators. Then, the high-temperature recuperator (HX-106) uses the proper hydrogen-water mixture exhaust of the SOEC stack. Finally, an electrical heater (HX-107) adjusts the stream temperature to the operating set point of the electrolyzer (800 °C).

The overall hydrogen production efficiency of the plant is penalized by the electric energy to be consumed by these heaters (to be supplied by the electric generator of the plant); however, they shall only be used during transients or startups.

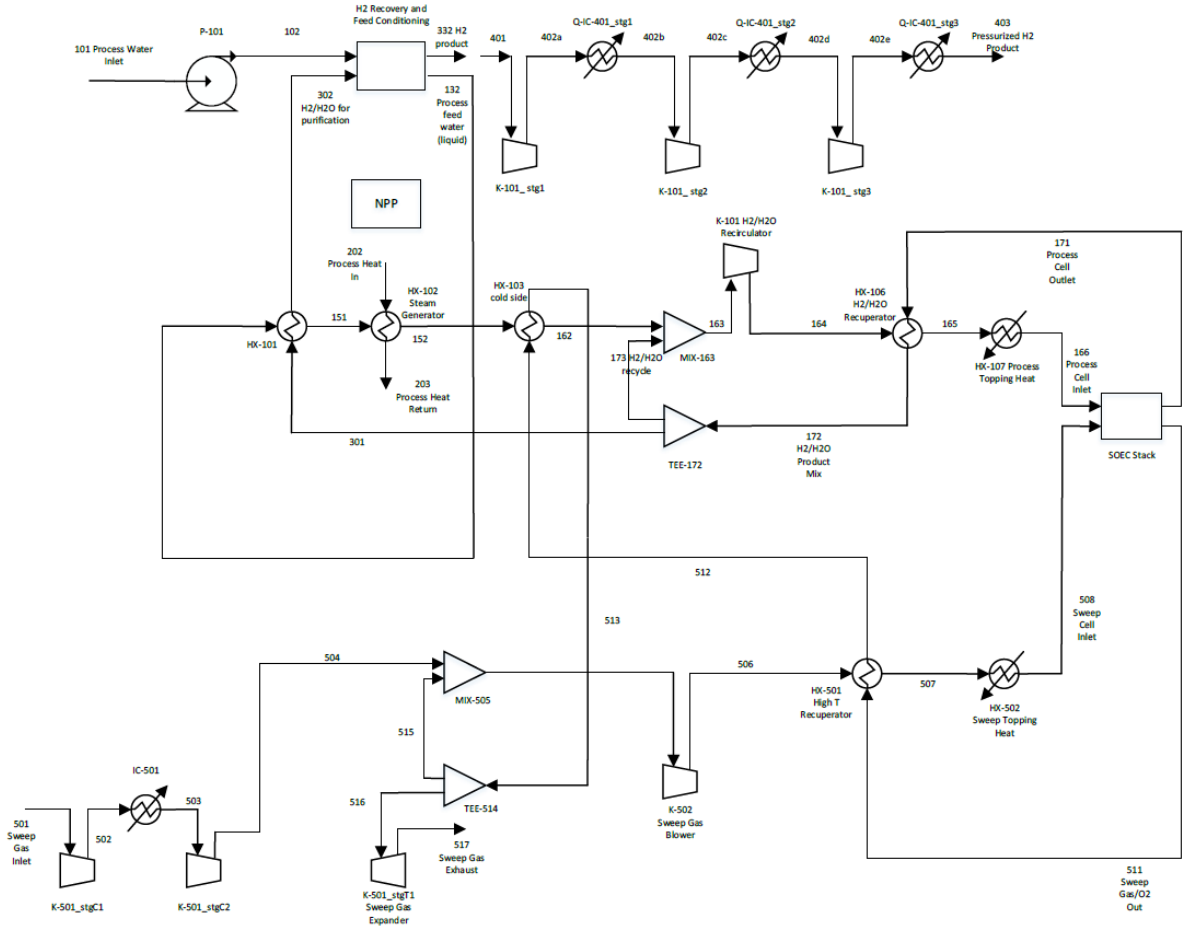

Figure 8 – Process Flow Diagram of the HTSE using SOEC [3]

The Hydrogen Recovery and Feed Conditioning System (shown at the top of Figure 8, after the process water inlet pump P-101) is in charge of two main functions. The first one is preparing the process feed water to be introduced in the electrolyzer (stream 132) by using pretreated feed water (demineralized, filtered and purified) and part of the hydrogen produced. Hydrogen is needed in the inlet of the SOEC in order to maintain a reducing environment in the cathode side of the cell, which is why certain amount of hydrogen has to be recycled. The second function is to obtain the pure hydrogen stream that forms the main product of this facility (stream 332) by several stages of compression (K-101) and cooling (Q-IC-401) to obtain the desired product pressure, temperature and purity, which shall be almost 100%.

The other main stream that feeds the electrolyzer cells is the sweep gas. This gas stream is needed to dilute and evacuate the oxygen generated in the anode side of the cells. Air is compressed in several stages with intercooling (K-501 and IC-501) up the operating pressure of the cell. The stream is afterwards preheated in the high-temperature recuperator sweep gas heat exchanger (HX-501) and in the sweep gas auxiliary heater (HX-502). The sweep gas exiting the stack is mixed with the produced oxygen in the electrolysis reaction and is channeled to the hot side of the high-temperature and low temperature heat exchangers (HX-501 and HX-103, respectively) and later is expanded in a turbo-expander (K-501) to take advantage of its remaining pressure.

Regarding the interface points of the HTS of the hydrogen facility and the Steam and Power Conversion Systems of the NPP, several configurations shall be evaluated. It has to be considered that the optimal operating temperature of the proposed thermal oil is 345 °C and that the more steam mass flow rate is expanded in the turbine, the more efficient would be the cycle. The most suitable configuration shall be selected in the following deliverable of the project (D5.2).

After the hydrogen is produced it can be stored in pressurized tanks in the facility to be sold later as a finished product. It can be used in a wide variety of industries such as oil refineries, chemical production, metal refining, food processing or electronics manufacturing, so multiple users could be potential customers for this energetic product.

5.2.3 Key Design Aspects

Some issues arise from the previous sections for which special attention it is necessary to pay and which will require further development and research in future stages of the project. Likewise, in views of preparing the next planned deliverable of the project, in which the mass and power balances of the thermal storage options proposed in this document will be developed, a series of key design aspects to be taken into account in these activities are presented below:

- *SOEC performance*
  The current state of the art for this technology clearly points out the challenges that are still facing for reaching long-term duration operation. The current lifespan for SOEC cells is around 25,000 hours [9]. The main issue is the degradation encountered during HTSE operation both during steady-state operation and cycling operation. Indeed, this technology is still in its development process in which prototypes and demonstrator facilities for high scale hydrogen production are being constructed.

- *Interface operating parameters*
  Some options are suggested for analysis in the further BOP calculations: main steam at the outlet of the NPP Steam Generators, steam from HPT exhaust, HPT steam extractions or reheated steam. The return points of the condensate leaving the HTS Heat Exchangers will depend directly on the selected supply point. Same for the definition of the heat exchangers to be installed between the NPP and the HTS of the HTSE systems.

- *Sizing of the Hydrogen Production System*
  There are many variables intervening in the complete configuration of hydrogen production by HTSE feed by the NPP. As in the case of the molten salts Storage System, the sizing of the equipment is a key factor in terms of economic and technical viability of the solution. The cost of the equipment is scaled with the desired capacity to generate hydrogen of the facility. The final use of the produced hydrogen has also to be assessed, as this will determine the economics of the plant.

5.3 Alternative thermal storage technologies

For information purposes, a screening about other forms of energy storage has been considered opportune to carry out, in this case of thermal type, which may be interesting from the techno-economic point of view.

Many of the technologies that are being developed nowadays for thermal storage systems working with nuclear applications are based on using the heat generated by the NPP in form of steam to heat up a transfer fluid which heats up a thermal storage material (special concrete, fluidized beds of sand, crashed rock, cast iron, etc. [14]). Later, the storage material transfers the heat back to the heat transfer fluid in order to heat up again water and produce back steam to be used in the balance of plant to produce extra electricity. Some of these thermal storage materials are presented below.

- *Concrete*: vertically oriented concrete plates arranged in steel modules store the sensible heat transferred by a heat transfer fluid, such as oil, which passes through small passages in between the concrete plates (Figure 9). This is a low pressure system that works with temperatures up to 600 °C.

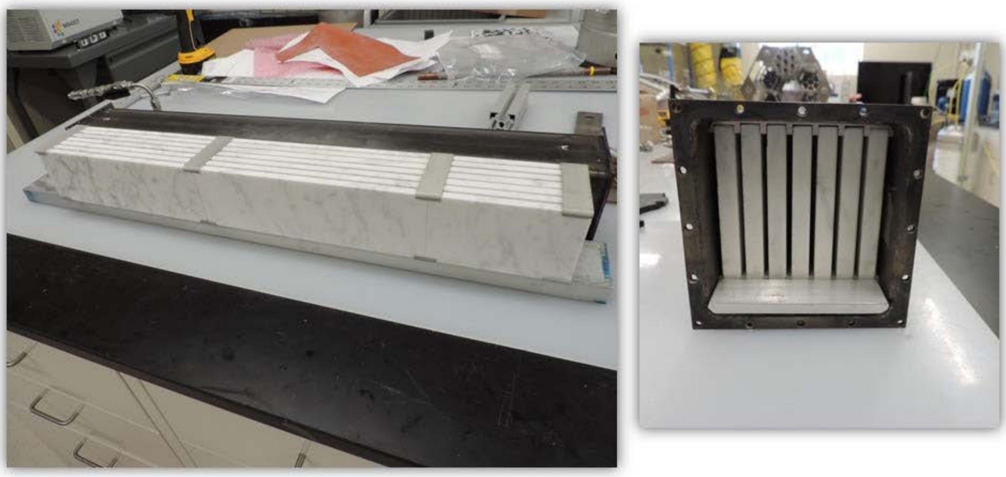

Figure 9 – Concrete thermal storage material [14]

- *Sand:* a fluidized bed made up of sand (this is, a solid particulate substance that behaves like a fluid given some conditions) is used as the thermal storage material. Different technologies are under development for using this type of material (see Figure 10 for a schematic of a commercial module for this kind of systems). Some of them heat up the sand with electric heaters during the charging phase to use them back producing superheated steam in an in-bed heat exchanger, while others can use thermal energy in form of steam as well in the input side.

These systems can reach temperatures up to 600 °C, depending on the chosen arrangement. Series and parallel approaches can be used depending on the desired operational characteristics: higher steam temperatures, higher discharge duration or power output.

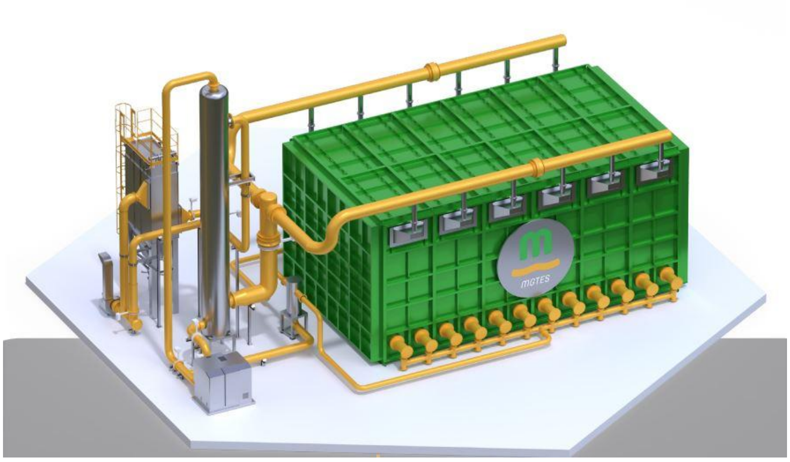

Figure 10 – Magaldi Thermal Energy Storage System [15]

- *Crushed rock:* Air is heated by means of electric heaters and/or a heat source and then is blown down into an atmospheric-pressure crushed rock heat storage volume. Temperatures can reach 750 °C [14]. When extra electricity wants to be produced, air is blown up to the steam generator heat exchangers. Air is distributed uniformly in the crushed rock and the total volume is insulated for higher efficiencies.

There are plenty of ideas for thermal energy storage that are under investigation and development. The ones shown above are just some examples, but some other materials could be cast iron with steel cladding, solid pebbles forming packed beds, permeable rocks in appropriate geological locations, etc. However, significant advances to scale up the laboratory prototypes are needed to build up demonstration plants using these technologies and see which of them offer a best economic option.

6 Conclusions

In the present report, possible configurations for ALFRED demonstrator BOP that produces superheated steam have been presented. Likewise, the evaluation of how to integrate into this secondary system an energy storage system that allows maintaining the constant load of the reactor while reducing or increasing the nominal load of electrical production discharged to the grid depending on the electricity prices set for each moment in the system, has been included.

The preliminary secondary system presented herein is based on a Rankine water-steam cycle with regenerative preheaters that delivers feedwater at 335 °C to the Steam Generators of the reactor. The main characteristics of this BOP are presented, which include a high-pressure turbine and a low-pressure one with a reheating cycle, and an additional feedwater preheater for controlling and assuring the minimum feedwater temperature requirement.

The final configuration of the BOP will be studied in a sensitivity analysis in the next deliverable, based on the calculations of energy and mass balances to be performed with the simulation software Thermoflow 30.

The first energy storage option is based on a molten salt thermal storage system that uses the main steam of the Steam Generators to accumulate the heated salts in a hot salt storage tank to be used later to produce an extra flow of steam to be expanded in the turbine. The connections points of this system with the water-steam cycle of the plant and their thermodynamic properties will be analyzed in detail in the next deliverable. An alternative of the loading mode is introduced, consisting of using the electricity produced in the STG to feed electric heaters that heat up the molten salts.

The second form of storage that is proposed uses main steam and electricity produced in the Steam Turbine Generator to generate hydrogen by means of a High Temperature Steam Electrolysis process. The selected electrolyzer is Solid Oxide Electrolysis Cell type, and uses a heat regeneration system fed with the exhaust gases of the proper cell as well as electric heaters, to raise the temperature of the steam before entering into the electrolyzing equipment. An intermediate oil circuit would also be installed between the steam and the electrolyzer system as a security buffer. The produced hydrogen can be firstly stored in pressurized tanks at the facility and later sold as an energetic product for multiple consumers.

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