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Description and techno-economic characterization of the hybrid system components

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Summary

Identifying the hybrid energy system components for the two selected configurations and their characterization. A standard template for data collection will be elaborated for the characterization of each component. Under the coordination of ANSALDO who will build a matrix of hybrid energy system components to be considered for the two typical configurations, the definition and characterisation work will be shared amongst the partners involved.

Approval

Date	By
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WP1 - Task 1.2

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Abbreviations and Acronyms

Acronym	Description
AC	Alternate Current
ACC	Accumulator
AEM	Alkaline Electrolyte Membrane
AMR	Advanced Modular Reactor
BES	Battery Energy Storage
BOP	Balance Of Plant
BWR	Boiling Water Reactor
CHP	Combined Heat and Power
CSG	Compact Steam Generator
DC	Direct Current
DH	District Heating
DHS	District Heating System
DP	Desalination Plant
EES	Electrical Energy Storage
E-SMR	European Small Modular Reactor (developed by the ELSMOR Euratom project)

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ESS	Energy Storage System
FC	Fuel Cell
FSM	Frequency Sensitive Mode
GHG	Green House Gasses
HES	Hybrid Energy System
HOB	Heat Only Boiler
HTR	High Temperature Reactor
HTSE	High Temperature Steam Electrolysis
HVDC	High-Voltage Direct Current
LAES	Liquid Air Energy Storage
LFR	Lead Fast Reactor
LOCA	Loss Of Coolant Accident
LP	Lower Plenum
LTE	Low Temperature Electrolysis
LWR	Light-Water Reactor
LW-SMR	Light-Water Small Modular Reactor
MED	Multi-Effect Distillation
MSF	Multi-Stage Flash

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NAS	Sodium-Sulphur Batteries
NPP	Nuclear Power Plant
PCS	Power Conversion System
PCM	Phase Change Material
PEM	Polymer Electrolyte Membrane
POC	Point Of Connection
PRZ	Pressurizer
PSB	Polysulfide Bromide Battery
PV	Photovoltaic
PWR	Pressurized Water Reactor
RES	Renewable Energy System
RFC	Regenerative Fuel Cell
RO	Reverse Osmosis
RPV	Reactor Pressure Vessel
SG	Steam Generator
SMR	Small Modular Reactor
SSC	Structures, System and Components
SWRO	Sea Water Reverse Osmosis

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TCS	Thermochemical Storage System
TDS	Total Dissolved Solids
TES	Thermal Energy Storage
UP	Upper Plenum
UTES	Underground Thermal Energy Storage
VHTR	Very High Temperature Reactor
VRB	Vanadium Redox Battery
VSC	Voltage-Source Converter

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Executive Summary

The TANDEM project aims at assessing nuclear safety, techno-economics and operationality of Hybrid Energy Systems (HES) integrating Light-Water Small Modular Reactors (LW-SMRs). For this purpose, the project will analyse the integration of LW-SMRs in two different Hybrid Systems configurations, focusing on different localizations and final uses: the first one aims to supply a *district heating network and a power grid*, for Northern and Central Europe regions; the second one, instead, is an *energy hub* which aims to provide power to the grid and produce valuable goods (such as hydrogen) in Southern Europe.

WP1 of the TANDEM project focuses on the "*Characterization of the studied hybrid systems*", aiming at defining the energy scenarios to be adopted in the studies, the technologies that shall be considered and implemented in the HES outlined, their techno-economic description, as well as the definition of the figures of merit (FoM) to be considered for the techno-economics and operationality assessment. This document provides information about the more suitable technologies to be involved in a HES configuration with Light-Water Small Modular Reactor. In particular, parameters like normal-operation data and transient characteristic time constants are considered. Moreover, some possible layouts of the system and its coupling with the Nuclear Power Plant, together with some economical parameters, are also considered, deriving some final considerations about the figures of merit that a certain technology should have to be coupled with a Nuclear Power Plant with Light Water Small Modular Reactors. The main goal is, indeed, giving some guidelines in choosing the best suitable technology for a certain system (namely block) of the HES.

Keywords

SMR, hybrid energy system, component description, technical parameters

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1. Introduction

In the last decade there was an increasing interest in the Small Modular Reactor technology by different designers due to some advantages with respect to larger conventional nuclear units, mainly based on some key aspects such as the faster deployment, economic efficiency and enhanced safety (IAEA, 2021). Moreover, EU Member States agree 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). The abovementioned technical report by IAEA indicates that a lot of effort has been made worldwide in the development of SMRs belonging to several technologies, from Light-Water SMRs (considering the early-deployable philosophy) to SMR based on IV generation technologies (Advanced Modular Reactors, AMRs).

In this frame, the EU TANDEM (Small Modular ReacTor for a European sAfe aNd Decarbonized Energy Mix) project "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 focussed on light-water technologies". In particular, WP1 of the TANDEM project, led by TRACTEBEL, is related to the *Characterization of the studied hybrid systems*", aiming at characterizing from a techno-economical point of view the two HES envisaged by TANDEM: i.e., in a district heating and energy hub configurations. In this framework, it is crucial to define the various technologies to be involved in the Hybrid Systems, describing each component from a technical and economical point of view, aiming to give some valuable information to be used in the modelling and simulation tasks of the project. In particular, the task the present document is referring to will be useful for Task 2.1, where " *CIRTEN-POLIMI will coordinate the identification of the modelling approach, both for the Modelica components and for the SMR models to be analysed by safety codes, following the specifications and the scenarios identified in WP1 (Task 1.2 and Task 1.4) and WP4 (Task 4.1)."*

The present document describes the work carried out in the frame of Task1.2 of TANDEM, which aimed at classifying some of the possible components/technologies selected for the two HES configurations addressed by TANDEM, giving some hints about their possible technologies, coupling configuration within the HES as well as some operational data, allowing to have a global overview of what could be their operating conditions during transient situations. The work herein described is a collection of TANDEM partners'' contributions under the coordination of Ansaldo Nucleare, to provide a description of state-of-the-art technologies. The list of possible technologies to be considered in the HES was agreed among the TANDEM partners, based also on the scenarios of interest defined within WP1. A Responsible partner, as well as the Supporter partners, were identified for each technology (or module) and the organizations collaboratively gathered data and information about the relative technology. A Standard Template, outlined by

Ansaldo Nucleare and agreed among all partners, was used for a more uniform data collection, highlighting the type of information required as well as the necessary level of detail. Progress meetings were scheduled to finetune the data collection. The energy scenarios presented during the WP1 first milestone were considered, while collecting data for some technologies (e.g., the district heating block). Thus, several technologies are detailed in dedicated sections of this document. In Table *1* all the addressed technologies (called blocks referring to the future MODELICA model) are listed.

Block	Addressed Module	Connection to the Energy Grid	Connection to Thermal Grid	Responsible Partner	Supporter(s)
NPP	E-SMR	X	X	CEA	EAI, FORTUM, TRACTEBEL
Power Conversion System	-	X		TRACTEBEL	EAI
Balance Of Plant	-	X	X	TRACTEBEL	EAI
Energy Storage	Thermal Energy Storage	X	X	ENERGORISK	EAI, TRACTEBEL, CEA, EC-JRC
	Electrical Energy Storage	X		ENERGORISK	-
Hydrogen Production	High Temperature Steam Electrolysis	X	X	CEA	EDF, ENERGORISK, TRACTEBEL, EC-JRC

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	Low Temperature Electrolysis	X		ENERGORISK	TRACTEBEL, EC-JRC
Water Desalination	Reverse Osmosis	X		EAI	TARCTEBEL, EC-JRC
	Multi-Effect Distillation	X		CEA	EC-JRC
Synthetic Fuels	Methanation	X	X	TRACTEBEL	EC-JRC
Renewables	Wind Farm	X		EAI	EC-JRC
District Heating	-	X	X	FORTUM	TRACTEBEL
Electrical Grid	-	X	X	TRACTEBEL	

Table 1 – Addressed technologies to be implemented in the HES and the type of connection to the grid, together with each responsible and supporter partner.

Concerning the photovoltaic block, it was decided that it may not be modelled as an actual module of the HES but its influence can be considered directly in the energy demand, thus using a net load where the photovoltaic contribution will be considered in a stochastic way (e.g., by applying a Monte Carlo sampling to real irradiation data of the chosen location). For this reason, regarding the renewables portion of the HES, only the wind generation is considered. The main reason why only the wind farm was considered to be directly modelled as a block of the HES relies on its inertia, which is absent in PV generators.

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2. Nuclear Power Plant

Considering a near-term deployment in Europe at timeframe 2035, the TANDEM project mainly focuses on SMR light-water technologies. Lessons learned from the Euratom ELSMOR project (towards European Licencing of Small Modular Reactors) contributes to further characterize the SMR concepts to be considered: the SMR concept chosen as use-case in TANDEM relies on the E-SMR academic concept developed by POLIMI, GRS and VTT (the owners of the E-SMR dataset) in ELSMOR. It basically shares the same design philosophy for the reactor system as the NUWARD™ concept with potential for extended applications. For the recalculated data, the new reactor and NUWARD™ may differ as there were no possible cross verifications.

Following NUWARD™ public announcements, the E-SMR could be a good example for a SMR available in 2035. This document presents the parameters used in the E-SMR dataset. Moreover, although TANDEM is specifically focused on LW-SMR and, particularly, on the E-SMR, other nuclear technologies (e.g., Advanced Modular Reactors, AMRs) could be integrated into the HES, offering added possibilities thanks to the higher temperature of the primary loop.

2.1 E-SMR General Description

The data presented in this section are the data available from the ELSMOR project at the end of December 2022. This E-SMR input deck may evolve due to ELSMOR needs during 2023.

The E-SMR input deck has mainly been built with geometrical and thermal hydraulic data coming from the MSc thesis by Cheng (2020) and the Status Report on NUWARD.

The E-SMR is a LW-SMR reaching 540 MWth/170 MWe. Like many other SMR, the E-SMR is an integral reactor, so that the impact of a LOCA is much less significant than for large conventional loop PWRs. The core is a truncated classic PWR core with 17x17 assemblies and an active height of 2m. The steam generators are compact plate heat exchanger and there are six of them in the vessel. The vessel also contains two safety steam generators for accident scenarios. Two safety condensers are located at the top of the containment to cool the safety steam generators with natural circulation and thus to cool and depressurize the primary circuit. The containment of the E-SMR has a vertical cylindrical part and two hemi-spherical parts at the top and the bottom.

The vessel dimensions are summarized in *Figure 1* and the steady states parameters of the E-SMR, which will be useful for its modelling within WP2, are presented in Table *2*. As it can be seen, the numeric value of the parameters is not reported, this is because the values coming from the ELSMOR project are still changing as the final dataset (which is not public at the moment) has not been deployed yet. Therefore, the numerical data will be provided directly in the frame of

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WP2, which may be also changed depending on the evolution/requirements that TANDEM will have throughout its prosecution.

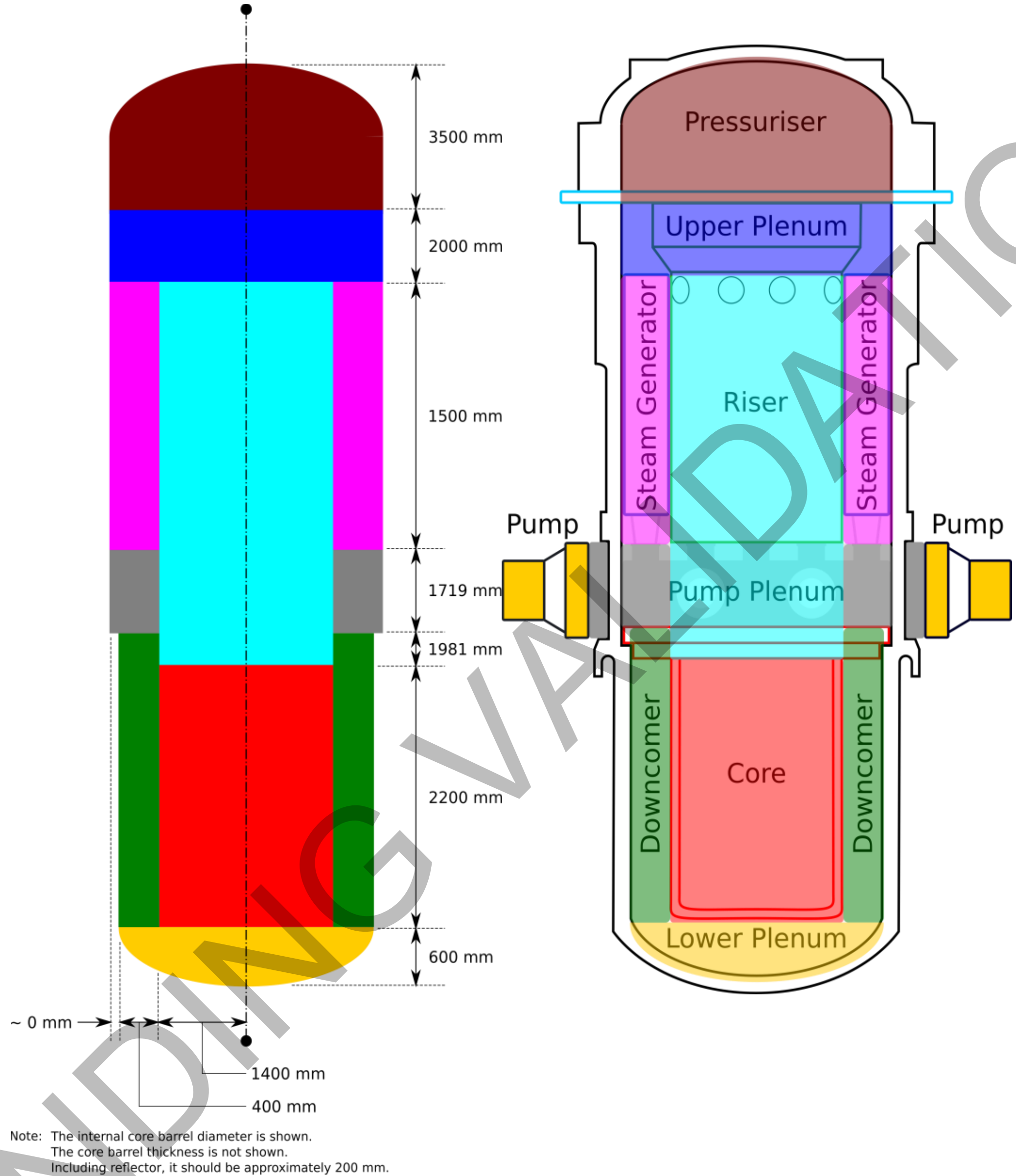

Figure 1 - E-SMR vessel design and its different heights.

The primary fluid (water) is heated in the core. It raises through the riser that also contains the control rod parking position and their internal drive mechanism. The pressurizer is integrated to the vessel, at the top of it and separated from the circulating fluid by a separation plate. The primary fluid reaches the Compact Steam generator at the outskirt of the vessel where it exchanges the heat with the secondary circuit before going through the primary pumps and going to the core through the downcomer. It has to be noted that there can be a bypass in the CSG

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region, through the Safety-CSG that shouldn't be active during normal operation but that still have hydraulics diameter allowing the fluid to circulate. The secondary side is at a much lower pressure compared to actual large conventional PWR to ensure that there is no liquid water and an overheating at the exit of the secondary fluid as the CSG are once-through exchangers.

Description	Value	Unit
Core Thermal Power		MWth
Electrical Output		MWe
Nominal Coolant Flow Rate (Primary)		kg/s
Nominal Coolant Flow Rate (Secondary)		kg/s
Core Inlet Temperature		°C
Core Outlet Temperature		°C
Mean Core Temperature		°C
CSG feedwater inlet temperature		°C
CSG steam outlet temperature		°C
Primary Pressure (in UP center)		bar
Secondary Pressure (CSG outlet)		bar
CSG primary side pressure drops		kPa
CSG secondary side pressure drops		kPa
PRZ collapsed water level		m
Primary coolant volume		m^3
Primary coolant inventory		kg
Secondary Coolant Inventory (maximum)		kg
Containment suppression pool initial water level		m
Containment suppression pool initial water volume		m^3

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RPV total drymass		t
RPV drymass		t
Core drymass		t
Core barrel drymass		t
Water wall coolant volume		m^3
Containment free volume		m^3
Containment free volume (with total RPV+ACCs volume)		m^3
Free containment volume with total blockage		m^3
Primary coolant density on the cold side		kg/m^3
Primary coolant density at mean core temp		kg/m^3
Primary coolant density on the hot side		kg/m^3
Design Conditions coolant mass		kg
LP coolant mass		kg
Cold side coolant mass		kg
Riser coolant mass		kg
UP coolant mass		kg
PRZ coolant mass		kg
Hot side coolant mass		kg
SG annular plenum coolant mass		kg
SG primary side coolant mass (6 CSGs)		kg
Core coolant mass (Average Channel + bypass)		kg
Total RPV (calculated from geometry data and densities)		kg

Table 2 – Main parameters useful for E-SMR modelling.

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The main safety systems of the E-SMR are two safety condensers linked to the two CSGs. These passive heat exchangers are located at the top of the containment so that natural circulation is ensured for the primary secondary and tertiary circuit. The ultimate heat sink is the water wall (i.e., the cooling pool) around the containment. The metallic containment is immerged in the water wall and is used to evacuate the decay heat in a Loss Of Coolant Accident (LOCA) scenario. To maintain a liquid water level in the vessel, two accumulators will inject water.

2.2 Prospects

The ELSMOR project has built a consistent dataset for transient analysis. This E-SMR dataset is still evolving and new data may be transferred to the TANDEM project for specific simulations. This section, therefore, summaries the steady state data used for the E-SMR and a more complete dataset is available on the E-SMR excel file shared with TANDEM.

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3. Balance of Plant and Power Conversion

For the E-SMR used in TANDEM, the BOP will consist of a closed water-steam cycle with turbines for electricity production and with means of heat exchange for heat applications.

The power conversion module, which is integrated in the BOP module, will convert the mechanical power from the steam on the turbine to electrical power. The generator of the turbine provides electricity to the external and internal electrical grid.

3.1 Technology Selection

Balance Of Plant (BOP) has different definitions in different organisations. In the framework of TANDEM, the BOP module encompasses all structures, systems and components (SSC) used to connect the SMR with the hybrid energy system. Because of its nearby link, it was also decided to include the power conversion, converting the mechanical power from the steam on the turbine to electrical power, in the module.

Depending on the SMR technology / design, the secondary fluid might be another fluid than water (e.g. molten salt). However, for the E-SMR (based on NUWARD design) used in TANDEM, the BOP will consist of a water-steam system.

The steam in the E-SMR is produced in 6 compact plate heat exchangers (CSG) in superheated steam conditions.

Electricity will be produced with turbines connected to a generator. This technology is commonly used in Nuclear Power Plants (NPPs) and conventional fossil power plants. *Figure 2* shows a generic PWR with BOP with the main common components. Depending on the power of the plant and maximum steam temperature high pressure turbine, intermediate pressure turbine and/or low-pressure turbines are used. For the applicable power and steam temperature of E-SMR, it is chosen to use only a high pressure and low-pressure turbine. Between the high pressure and low-pressure turbine, there are a moisture separator and reheater(s) (see again *Figure 2*).

In large NPPs (PWRs and BWRs), turbines for saturated steam are used, while in conventional fossil power plants turbines with superheated steam are commonly used. This superheated steam is also the case for E-SMR.

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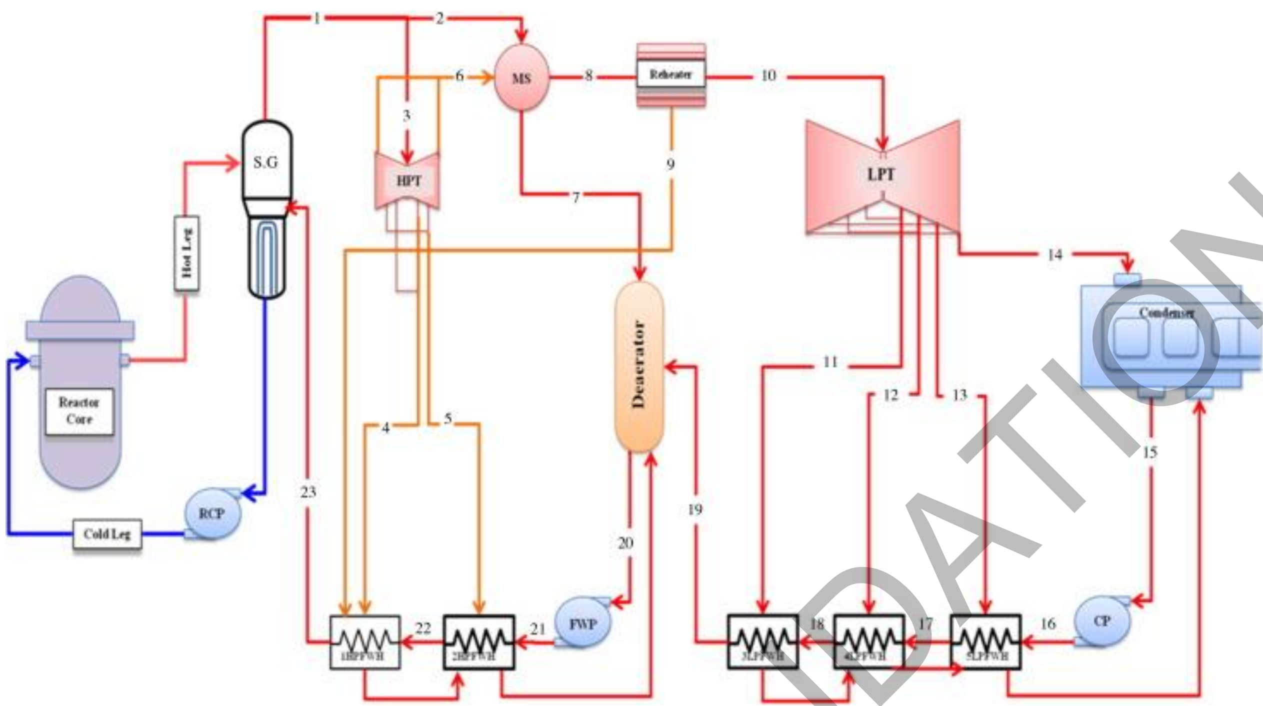

Figure 2 - Generic PWR with BOP with main components (Ibrahim and Attia, 2015).

A condenser is used to condensate the steam downstream of the turbines. This condenser is cooled by a tertiary circuit, which may be cooled by a natural convection wet cooling tower, forced convection wet cooling towers, or (natural of forced) air cooled cooling towers. For simplicity, the tertiary circuit will not be simulated, and a directly air-cooled condenser is chosen.

To provide feedwater at the correct conditions (pressure, temperature, flowrate) to the heat exchangers of the SMR, condensate pumps, feedwater pumps, and preheaters are used (see again *Figure 2*). These preheaters (and the reheaters between the turbines) are heated by steam extracted upstream and between the turbines and by steam coming from turbine steam extractions. To control the feedwater conditions, a control logic is used.

Heat is demanded by several other modules from the hybrid energy system, especially those that are thermally connected to the NPP, i.e., the hydrogen production plant, district heating system and desalination plant. Since the conditioned secondary fluid should stay isolated in the secondary circuit (risk of light radioactive leaks between primary and secondary loop), the heat from the secondary steam is exchanged with the other modules via heat exchangers. The steam upstream, between the turbines, and coming from turbine steam extractions may be used for this heat exchange. The appropriate steam temperature(s) for the application is used. For safety and operational reasons, a steam turbine bypass to the condenser, a steam dump to the atmosphere, and overpressure safety valves are normally provided in the main steam system. For TANDEM, the choice of the modelling of these components depends on the transients to be

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modelled. It is expected that a turbine bypass for power modulation and island operation would at least be required (as shown on the Model flow diagram, *Figure 5*). A control logic should be implemented to control the power generation of BOP in relation to power demand and NPP power.

Other BOP systems, such as systems for the secondary chemistry, auxiliary, and emergency feedwater systems, will not be further considered for the current level of detail of TANDEM.

For power conversion, the turbine-generator will convert the mechanical power from the steam on the turbine to electrical power and provide electricity at a commonly used voltage level (typically about 20 kV). The connection to the external grid (typically at about 400 kV) is made with a transformer and an electrical switch (see *Figure 3*), which when opened could lead to islanding mode of the local grid. The internal grid of the plant (with safety and non-safety loads) might be considered depending of the required level of detail.

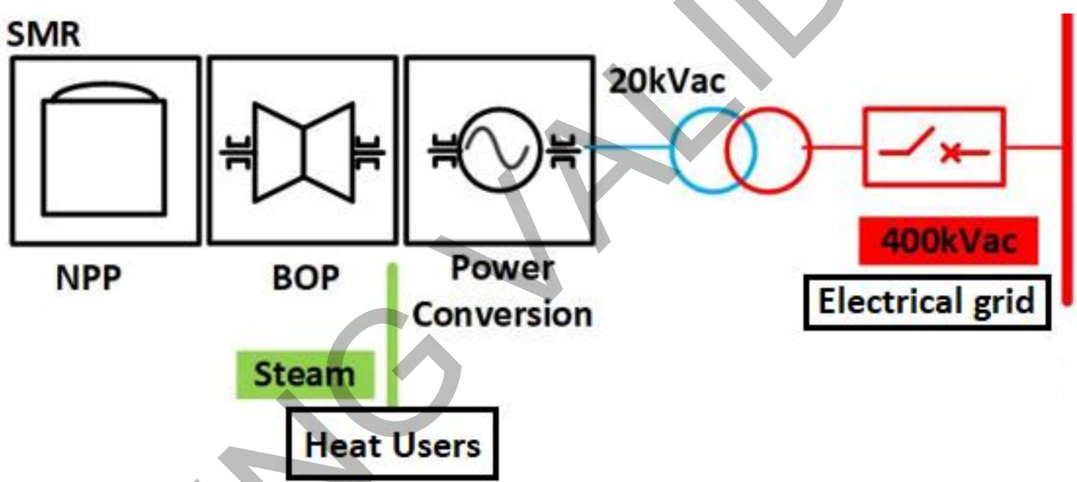

Figure 3 - BOP and Power Conversion connected to SMR, Heat Users and Electrical grid (created by TRACTEBEL in the scope of the TANDEM project).

3.2 Component coupling with HES

Several modules of the HES will be coupled to the BOP and power conversion module. Several modules that use the heat and electricity from the BOP + Power Conversion block are listed here. The goal of the BOP is to be able to handle a variety of users effectively while limiting complexity.

Feedwater and steam connection with NPP:

For TANDEM, it is considered that steam generators (CSG) are within the perimeter of the NPP module. Depending on the required complexity for the transients that should be modelled, the connection between NPP and BOP is 1) only made with the heat flux from NPP to BOP (if no effects from transients in BOP towards NPP should be modelled) or 2) the BOP module provides a total feedwater flow (at determined pressure, temperature and flowrate) to the NPP module and receives a total (superheated) steam flow (at determined pressure, temperature and flowrate) from the NPP module. Via the control of the steam generator outlet conditions, the flowrate towards the NPP steam generator (depending on the NPP power) is controlled.

Modules that are connected for electricity:

- Electrical grid. The module is coupled via the transformer and electrical switch with the turbine generator (and the plant internal grid). It is proposed that two electrical switches are implemented in HES at the connection: one in the BOP and power conversion module for the connection of the turbine generator and one in the electrical grid module. From the Electrical grid module, the electrical demand is communicated to the BOP module (for possible power modulation).

- NPP. The NPP receives electricity for electrical components from the plant internal grid and therefore from the turbine generator when it is producing electricity. The connection will depend on the level of detail and might be limited to a power supply from the generator (0D, lump sum, subtract house load from electrical production) or a more detailed approach with an internal grid with separation of loads between safety and non-safety loads.

Modules that are connected for heat (see *Figure 4*):

- Energy Storage – Thermal (TES). Heat is exchanged between BOP and TES module during charging (adding heat from BOP to TES) and discharging (heat from TES to BOP) operations. For heat, steam from upstream and between the turbines, and coming from turbine steam extractions may be used. For the TES design in TANDEM, steam from the NPP heat exchangers upstream of the high-pressure turbine will be used for charging. The condensate after heat exchange with the TES heat exchanger will be sent to the condenser due to the transient nature of the energy storage and for simplicity, although it might be energetically more interesting to send the condensate to a feedwater reheater. For TES discharge operations, condensate from the condenser will be heated and evaporated to conditions appropriate for the steam inlet of the low-pressure turbine and will be sent to the moisture separator between high-pressure and low-pressure turbine.
  It is considered that the TES heat exchangers for charging and discharging operations are within the perimeter of the TES module. The BOP module provides charging steam at determined conditions (pressure, temperature and flowrate) to the TES charging heat

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exchanger and receives condensate at determined conditions (pressure, temperature and the same mass flowrate). The BOP module provides the discharging condensate at determined conditions (pressure, temperature and mass flowrate) to the TES discharging heat exchanger and receives steam (and possibly condensate) at determined conditions (pressure, temperature and the same mass flowrate). Depending on the energy demand (electricity and/or heat) from other modules, BOP will control flowrates towards the TES heat exchangers.

- High temperature hydrogen production (HTSE – High Temperature Steam Electrolysis). Heat is exchanged between BOP and HTSE module for high temperature hydrogen production. The electricity for the electrolysis is provided by the Electrical grid module. Similar to the TES charging operations, steam from the NPP heat exchangers upstream of the high-pressure turbine will be used and (for simplicity) the condensate is then sent back to the condenser. Similarly, to the TES heat exchangers, it is considered that the HTSE heat exchanger is within the perimeter of the HTSE module. The BOP module provides steam at determined conditions (pressure, temperature and flowrate) to the HTSE heat exchanger and receives condensate at determined conditions (pressure, temperature and the same mass flowrate). The HTSE module communicates on the heat (steam) demand to the BOP module.

- District Heating (DH). Heat is exchanged between BOP and DH module. Since DH only needs heat at limited temperature (considered between 100°C and 150°C), steam from between high and low pressure turbines and/or from turbine steam extractions from the low-pressure turbine may be used. The condensate is then sent back to the condenser. Similarly, to the TES and HTSE heat exchangers, it is considered that the DH heat exchanger is within the perimeter of the DH module. The BOP module provides steam at determined conditions (pressure, temperature and flowrate) to the DH heat exchanger and receives condensate at determined conditions (pressure, temperature and the same mass flowrate). The DH module communicates on the heat (steam) demand to the BOP module.

- Other applications (for example Water Desalination): some of the Water Desalination modules (e.g., Distillation) needs heat from the BOP module for their processes. In this case, steam from upstream and between the turbines and/or from turbine steam extractions may be used for heat. Similarly to other heat extractions above, the condensate would return to the condenser. The heat exchanger with the Water Desalination process would be in the perimeter of the Water Desalination module. The Water Desalination module would communicate on the heat (steam) demand to the BOP

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module. The electricity for the water desalination is provided by the Electrical grid module.

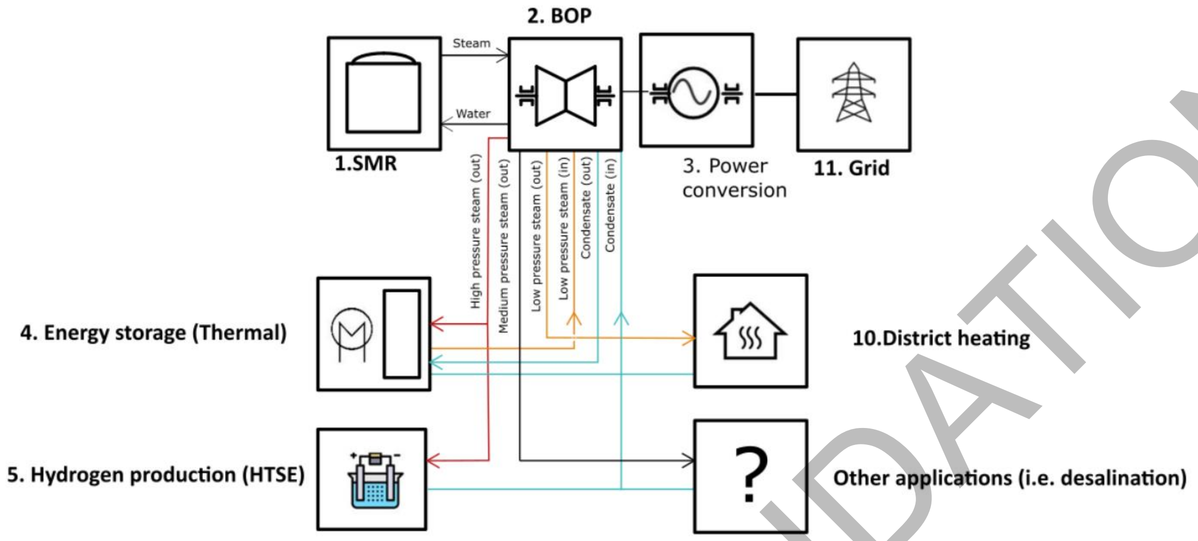

Figure 4 - Coupling of BOP with other modules of HES (the steam and condensates at different pressures are coloured differently) (created by TRACTEBEL in the scope of the TANDEM project).

3.3 Main system architecture and operating data

3.3.1 General system architecture

The BOP and power conversion module consist of several components and control loops. These are listed here (not in detail) and shown in the Model Flow Diagram (see *Figure 5*).

Main components:

- High pressure turbines with steam extractions;
- Low pressure turbines with steam extractions;
- Moisture separator and reheater(s) (MSR) between high pressure and low-pressure turbines;
- Condenser: directly air cooled;
- Condensate pump and feedwater pump;
- Feedwater preheaters;

- Feedwater and steam connection to NPP heat exchangers;
- Connections for steam and condensate between extractions and heat exchangers with other modules, reheaters, preheaters;
- Turbine generator;
- (Transformer and) Electrical switch with the Electrical grid;
- Connections for power supply for NPP (possibly lump sum).

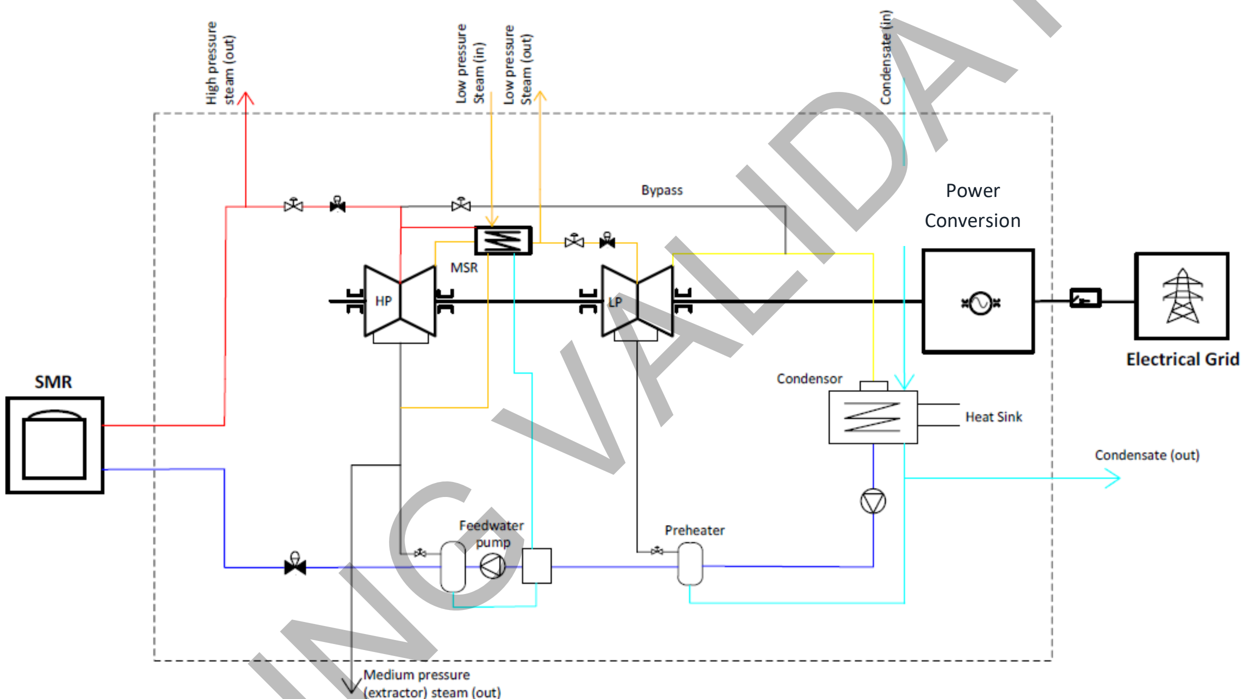

Figure 5 - Model flow diagram (created by TRACTEBEL in the scope of the TANDEM project).

Main control loops:

- Feedwater (NPP heat exchangers) inlet and outlet conditions control (flowrate, temperature, pressure);
- Flowrate control towards heat exchangers with other modules;
- Electricity production control and turbine bypass control;
- (Ramp up speed of turbine for a further level of detail).

3.3.2 Main operating data, main components of the system and relative data

Main operating data and unknowns are here listed. Main data of NPP are listed in Table *3*. Main data related to turbine, power conversion and electrical grid are in Table *4*. Main data related to condenser, reheaters, preheaters, condensate pump and feedwater pump can be found in Table *5*. Main data related to heat users, instead, are listed in Table *6*. As discussed in the previous section, the values of some parameters have not been deployed yet, hence they may change going on with the project.

As it can be seen from the tables reported in this section, some of the data have not been defined yet, hence they will be provided directly in the framework of WP2 to all partners involved in the modelling phase.

Description	Value	Unit
Thermal Power from E-SMR through CSG	540	MWth
Approximate net electrical output to grid	170	MWe
Approximate nominal secondary coolant flow rate		kg/s
CSG feedwater inlet temperature		°C
CSG steam outlet temperature		°C
Secondary Pressure (CSG outlet)		bar
CSG secondary side pressure drops		kPa

Table 3 - Main steady state data for BOP and power conversion module related to NPP.

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Description	Value	Unit
Maximum (gross) electrical power production	To be defined (related to TES and requirements)	MWe
Nominal turbine speed	1500	rpm
Minimum (turbine) steam load	load for internal loads (islanding)	
Voltage level of generator	20	kV
Voltage level of electrical grid	400	kV
Nominal internal load	To be defined	MWe

Table 4 - Main steady state data for BOP and power conversion module related to turbine, power conversion and electrical grid.

Description	Value	Unit
Nominal condenser pressure	~0.1	bar abs
Condenser outlet temperature	Depending on atmospheric temperature	
Nominal condensate pump outlet pressure	About 15	bar abs
Nominal feedwater pump outlet pressure	About 50	bar abs
Number of feedwater preheaters	To be defined	
Number of reheaters	To be defined	
Number of extraction places from high pressure turbine	To be defined	
Number of extraction places from low pressure turbine	To be defined	

Table 5 - Main data related to condenser, reheaters, preheaters, condensate pump and feedwater pump.

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Description	Value	Unit
Maximum TES charging power / steam flowrate	To be defined	
Maximum TES discharging power / condensate flowrate	To be defined	
TES charge heat exchanger steam inlet conditions	CSG steam outlet (see above)	
TES discharge heat exchanger condensate inlet conditions	Condensate from condensate pump (see above)	
Maximum HTSE power / steam demand	To be defined	
HTSE heat exchanger steam inlet conditions	CSG steam outlet (see above)	
Maximum DH power / steam demand	To be defined	
DH heat exchanger steam inlet conditions	Depending on chosen extraction place / temperature	
Maximum Water Desalination power / steam demand?	To be defined	
Water Desalination heat exchanger steam inlet conditions?	Depending on chosen extraction place / temperature	

Table 6 - Main steady state data for BOP and power conversion module related to heat user.

3.4 Compatibility with other SMR technologies

In this section, the Balance Of Plant and the Power Conversion System blocks (here considered within the same module as explained above) were described from a technical point of view, considering the light-water technology of Small Modular Reactor being the one addressed by the TANDEM project. Nevertheless, several technologies of SMR have been addressed so far to perform cogeneration within, for instance, several EU projects (see, e.g., EUROPAIRS or GEMINI+, which consider the HTR technology).

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For its purposes, the TANDEM project aims to model the Hybrid Energy System within WP2 by developing an open source library written in the MODELICA language. The model that will be developed, however, should be conform to welcome also other technologies of SMR (e.g., advanced reactors with higher live steam temperature, namely Advanced Modular Reactors AMR,) in order to create a tool with a global capability of application which could be, moreover, further optimized in future projects.

To reach this goal, the module with major interest is the Balance Of Plant being the one directly connected with the nuclear reactor. However, there are no big differences between the balance of plant of a light-water SMR and that of an AMR. Considering, e.g., a Lead-Fast Reactor (LFR), the schematic layout of the balance of plant is reported in *Figure 6*.

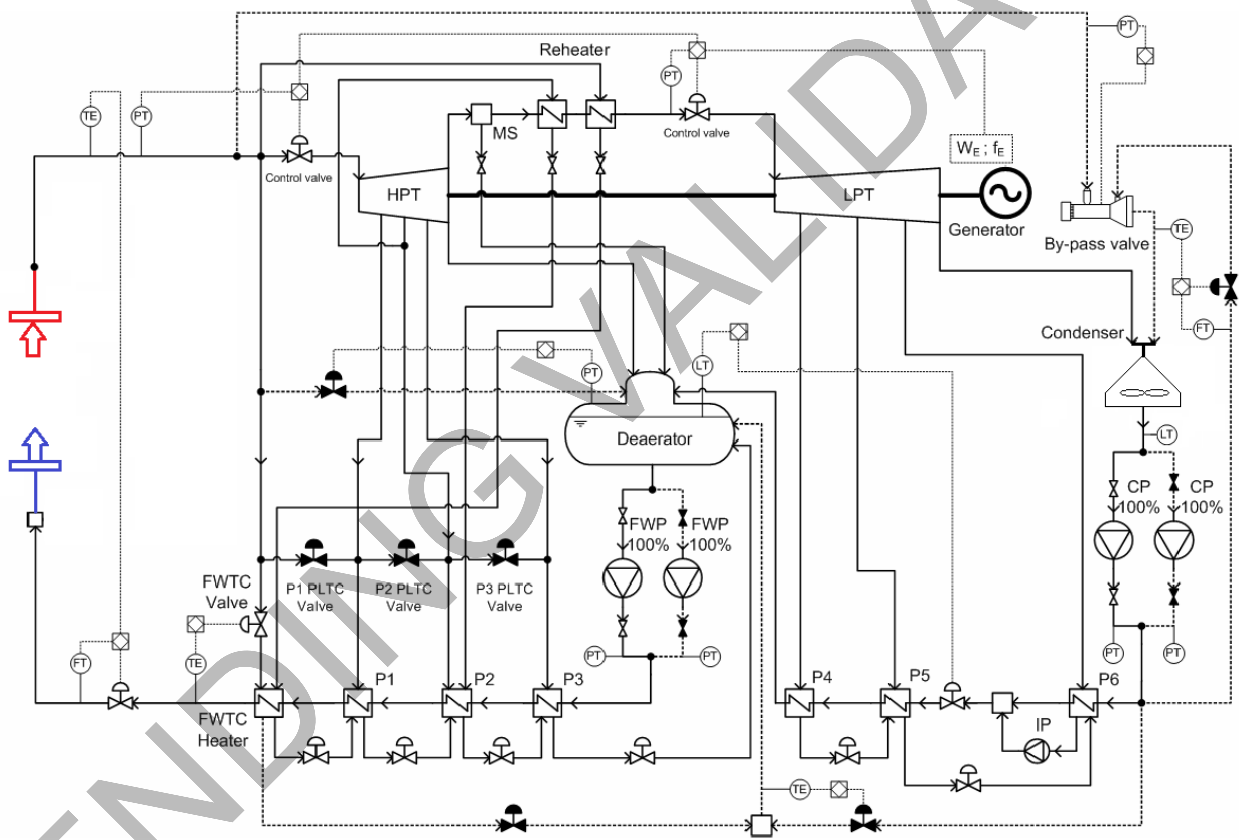

Figure 6 - BOP envisaged for a lead-fast reactor (Palmero et al., 2022).

As it can be seen from *Figure 6*, the general architecture of the BOP which is supplied by an AMR is pretty similar with the one envisaged for the E-SMR (i.e., LW-SMR) to be modelled in TANDEM and shown in *Figure 2*. Moreover, there are some similarities also considering the possible thermal energy storage. As described in the dedicated section, indeed, the energy storage which could be used for a HTR has molten salts as working fluid, which architecture is very similar to

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that suggested for TANDEM with thermal oil (i.e., a two-tank system, see *Figure 14* and *Figure 18*) as it is explained in the dedicated section. For the sake of completeness, Table *7* reports some parameters of the steam cycle foreseen for the addressed LFR.

Nominal Condition Parameters	Value
Thermal Power (MW)	300
Lead Core Inlet Temperature (°C)	400
Lead Core Outlet Temperature (°C)	520
Secondary steam mass flow rate (kg/s)	192.6
Feed water inlet Temperature (°C)	335
Steam Outlet Temperature (°C)	450
Steam Generator outlet pressure (bar,a)	180

Table 7 - Some of the main parameters of the primary and secondary fluid foreseen for a LFR plant (Palmero et al., 2022).

Therefore, the modelling of the BOP and the relative thermal energy storage for TANDEM could be easily coupled with other technologies of Small Modular Reactors with higher temperature by simply changing the boundary conditions and the working fluids of the thermal energy storages, thus keeping the architecture unchanged.

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4. Energy Storages

Energy storages represents a crucial component to be implemented in a grid with high penetration of intermittent sources to damp the load variations. Moreover, some energy storages technologies also allow to control, e.g., the grid frequency and voltage (i.e., electrical energy storages), whereas others permit to increase the efficiency of the steam cycle of a Nuclear Power Plant (i.e., thermal energy storages). In *Figure 7* a global overview of electrical energy storage technologies is presented.

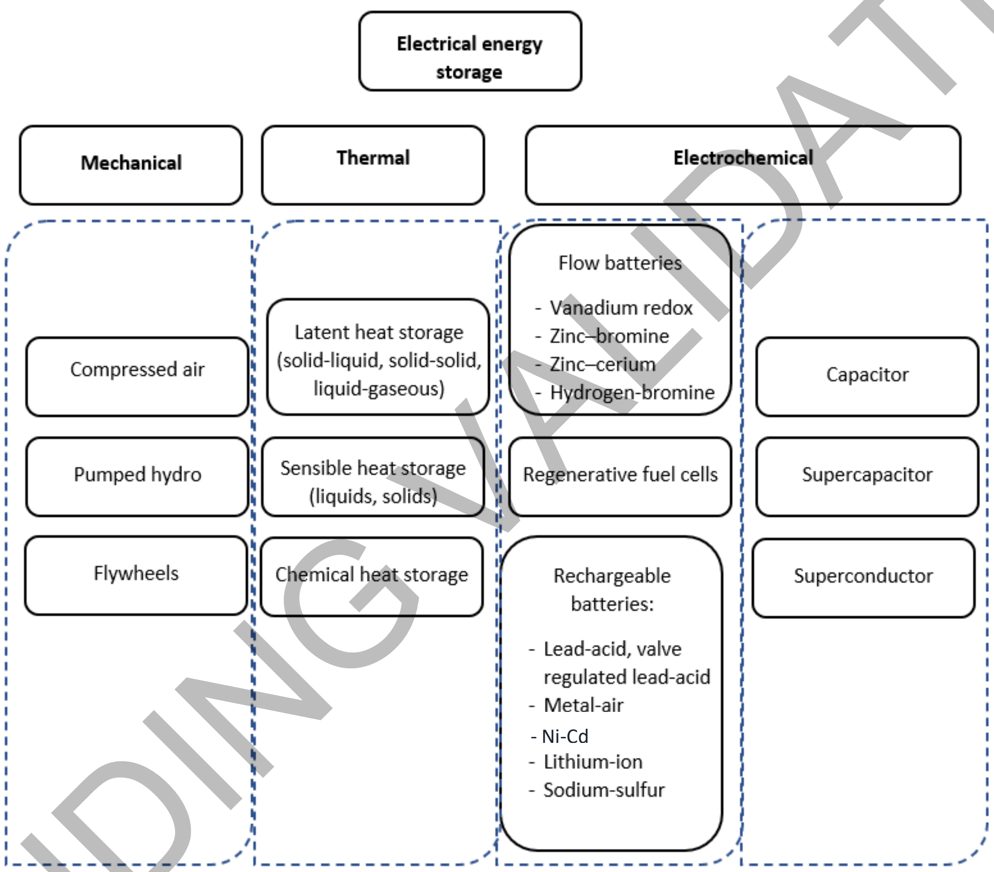

Figure 7 - Classification of electrical energy storage technologies (created by ENERGORISK in the scope of the TANDEM project).

For the purposes of the TANDEM project, only thermal and electrical energy storages were considered to be investigated. Concerning electrical energy storages, batteries were chosen to be considered because of their well-known compatibility with Renewable Energy Sources. On the other hand, thermal energy storages were chosen to be addressed since they could have the capability of letting the nuclear source working at its nominal capacity while reaching enough flexibility to deal with variations of the thermal and electricity loads. Moreover, thermal energy storages are also important in view of the district heating application of a LW-SMR, guaranteeing the requested flexibility to meet the thermal demand.

Another important factor that helped in making the choice between all the available technologies is their economic viability, technology maturity level and capability of being implemented in the system in a reasonable easy way (e.g., pumped hydro is not easy to be implemented due to several constraints, among which the need of having an available and suitable water source).

4.1 Electrical Energy Storage

There is a wide variety of electrical energy storage technologies, each with different attributes and intended for different applications. Choosing the ideal storage technology depends on a number of factors, e.g. amount of energy or power that needs to be stored, the time for which this stored energy must be stored or released, siting requirements, etc.

Battery energy storage technologies are judged to be predominant for cases when continuous energy supply is of greatest importance. Today, application of battery technologies in grid-connected systems, besides their broad use in RES or for similar purposes, includes frequency regulation, and fast-start backup power source for nuclear power plant to ensure the stability of the country's energy network (TVO, 2022). Having new developments in battery technologies, increasing application of such technology at NPPs including SMRs is anticipated in near future.

4.1.1 Technology Selection

The storage of electrical energy is done by transforming electrical energy into another form (mechanical, chemical, thermal, electrical or electrochemical). Classification of electrical energy storage (EES) technologies is presented again on *Figure 7*. There are two groups of electrical energy storage: rechargeable and non-rechargeable. Non-rechargeable EES further is not considered.

ESSs are useful in every section of an electrical power system, for large (GW), medium (MW), or micro (kW) scale applications, depending on the function and location. At generation, they are employed for transmission and distribution - energy arbitrage, balance and reserve; for smart grid systems; for frequency regulation and investment deferral at transmission level; for voltage control, investment deferral, grid capacity support at distribution level; and for peak shaving, time-of-use cost management, etc. at the customer-side. They are also a necessary component, which are expected to thrive in the future for widespread deployment of distributed generation technologies (Akiniele and Rayudu, 2014).

Mapping of EES depending on power and energy relationship is shown on *Figure 8* and *Figure 9*

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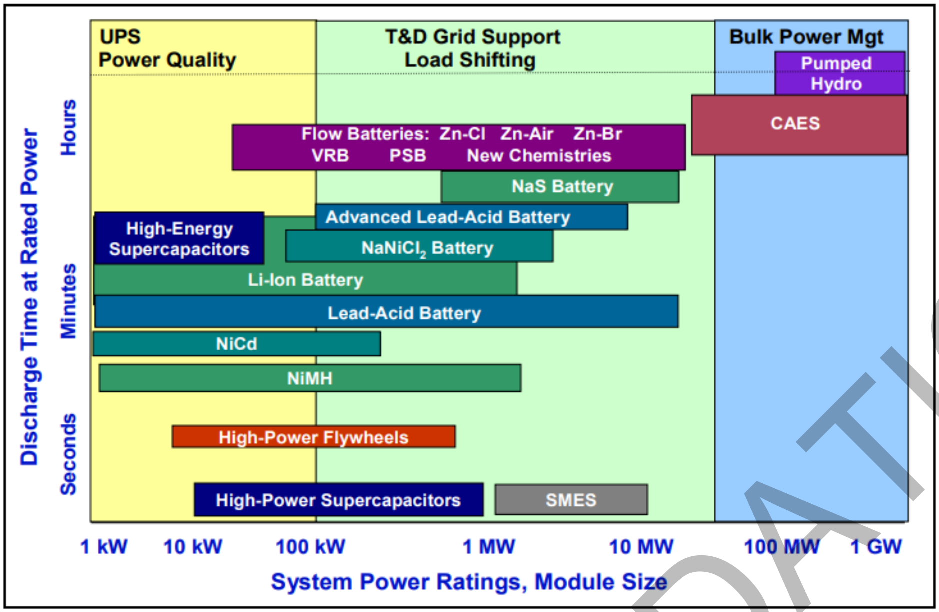

Figure 8 – EES rating (Akhil et al., 2013)

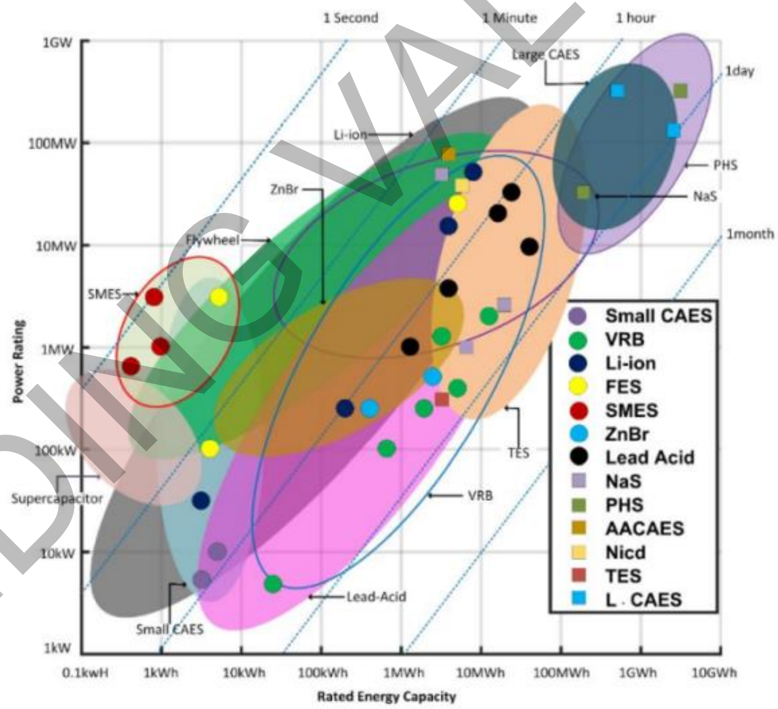

Figure 9 – EES power rating vs energy capacity (Hossain et al., 2020).

According to *Figure 8* and *Figure 9*, chemical and electrochemical EES are capable of discharge times in minutes/several hours, with correspondingly high sizes that reach several dozen megawatts, up to 100 MW. Regarding application, battery energy storage (BES) and capacitors

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are generally used for lower storage applications. For mid capacity applications (i.e., from 100 kW up to more than 10 MW, see again *Figure 8*), generally flow batteries, lead-acid batteries and sodium–sulfur (NaS) batteries are used. Since SMRs are positioned as mid power range, capacitor and super capacitors are not further considered.

All conventional rechargeable BES and flow batteries store the electrical energy in the form of chemical energy coming from electrochemical reaction. The principal difference between BES and flow batteries is that BES do store internally their own fuel (in anode) and oxidant (in cathode), while flow batteries receive a constant supply of these two chemicals from an outside source, where it is stored. Batteries are generally considered to represent a high-energy-density, low-power-density technology.

4.1.2 Flow Batteries

This technology essentially consists of two electrolyte reservoirs from which the electrolytes are circulated through an electrochemical cell comprising a cathode, an anode and a membrane separator. The energy density of such systems is entirely dependent on the volume of the electrolyte being stored. Power density in flow-battery systems is essentially dependent on the rates of the electrode reactions occurring at the anode and cathode respectively.

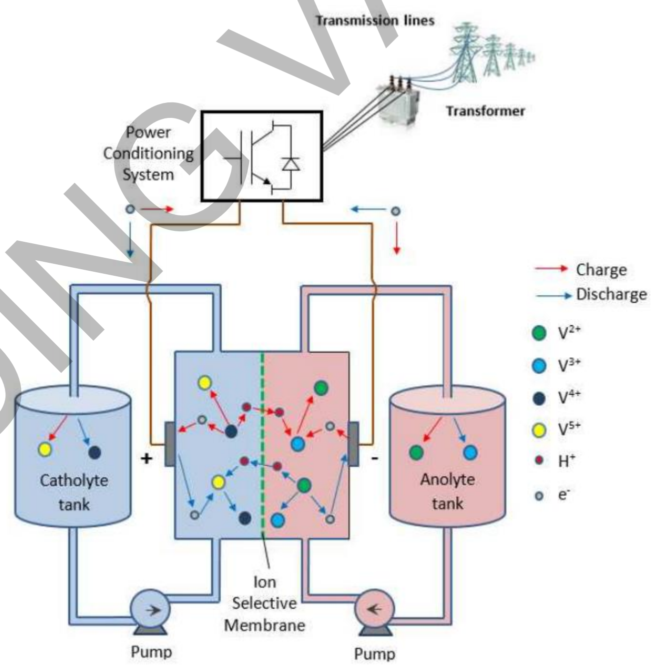

Figure 10 – Schematic diagram of flow battery energy system vanadium redox example, (Nikolaidis and Poullikkas, 2017).

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Flow batteries typically require additional equipment, such as pump sensors and control units. They may also provide variable and generally low energy density, but they present major advantages in comparison with standard batteries as they have long cycle life, quick response times, can be fully discharged and can offer unlimited capacity through increasing their storage tank size. Schematic diagram of flow battery energy system is presented in *Figure 10*.

Vanadium redox battery (VRB) is a type of flow battery, and the most mature of all flow battery systems available. In flow batteries, energy is stored as charged ions in two separate tanks of electrolytes, one of which stores electrolyte for positive electrode reaction while the other stores electrolyte for negative electrode reaction. Vanadium redox systems are unique in that they use one common electrolyte, which provides potential opportunities for increased cycle life. When electricity is needed, the electrolyte flows to a redox cell with electrodes, and current is generated. The electrochemical reaction can be reversed by applying an overpotential, as with conventional batteries, allowing the system to be repeatedly discharged and recharged. Like other flow batteries, many variations of power capacity and energy storage are possible depending on the size of the electrolyte tanks.

Polysulfide Bromide battery (PSB) is a type of flow battery involving a reversible electrochemical reaction between two salt-solution electrolytes: sodium bromide and sodium polysulfide. PSB electrolytes are brought close together in the battery cells where they are separated by a polymer membrane that only allows positive sodium ions to go through, producing about 1.5 volts across the membrane. Cells are electrically connected in series and parallel to obtain the desired voltage and current levels. The net efficiency of this battery is about 75%. This battery works at room temperature. It has been verified in the laboratory and demonstrated at multi-kW scale (120 MWh, 15 MW e) in the UK and USA (Joseph and Shahidehpour, 2006).

Zinc-bromine (ZnBr) is a type of redox flow battery that uses zinc and bromine in solution to store energy as charged ions in tanks of electrolytes. As in vanadium redox systems, the zinc-bromine battery is charged and discharged in a reversible process as the electrolytes are pumped through a reactor vessel. However, zinc bromine falls into the hybrid flow batteries category. Hybrid flow batteries are distinguished from conventional redox flow batteries by the fact that at least one redox couple species is not fully soluble and may be either a metal or a gas (Kazacos et al., 2011). In ZnBr both of the electrolyte loops employ an electrolyte of zinc-bromine. In the charge state, metallic zinc is plated as a thin film on one side of the carbon-plastic composite electrode, while bromine oil sinks to the bottom of the electrolytic tank at the other side. The two compartments are separated by a microporous polyolefin membrane. The disadvantages of this system are the lower efficiency (75%), cycling capability (2000- 3500 cycles) and metal corrosion (Luo et al., 2015). Although many ZnBr devices have been built and tested, their use in utility-scale EES applications is in the early stage of demonstration.

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Iron-chromium (Fe-Cr) redox flow battery systems is another type of flow battery still in the R&D stage but are rapidly advancing. The low-cost structure of these systems also makes them worth evaluating for grid-storage solutions. Fe-Cr flow battery systems can be used for time shift on either the utility or customer side of the meter, as well as for frequency regulation services (Akhil et al., 2013).

Zinc-air batteries are a metal-air electrochemical cell technology. Metal-air batteries use an electropositive metal, such as zinc, aluminium, magnesium, or lithium, in an electrochemical couple with oxygen from the air to generate electricity. Because such batteries only require one electrode within the product, they can potentially have very high energy densities. In addition, the metals used or proposed in most metal-air designs are relatively low cost. This has made metal-air batteries potentially attractive for electric vehicle and power electronics applications in the past, as well as raising hopes for a low-cost stationary storage system for grid services. Zinc-air batteries take oxygen from the surrounding air to generate electric current. The oxygen serves as an electrode, while the battery construction includes an electrolyte and a zinc electrode that channels air inside the battery. The Zinc-air battery produces current when the air electrode is discharged with the help of catalysts that produce hydroxyl ions in the liquid electrolyte. The zinc electrode is then oxidized and releases electrons to form an electric current. When the battery is recharged, the process is reversed, and oxygen is released into the air electrode. Despite the many advantages, metal-air batteries also pose several historical disadvantages. The batteries are susceptible to changes in ambient air conditions, including humidity and airborne contaminants. The air electrode – a sophisticated technology that requires a three-way catalytic interface between the gaseous oxygen, the liquid electrolyte, and the solid current collector – has been difficult and expensive to make. However, the technology is far more stable and less dangerous than other battery technologies (Akhil et al., 2013).

4.1.3 Regenerative Fuel Cells

Fuel cells (FC) are electrochemical conversion devices that consume hydrogen and oxygen to produce water and electricity (Lemofouet and Rufer, 2006). Regenerative fuel cells (RFC) are devices that combine the function of the fuel cell and the electrolyser into one device. The hydrogen is stored as gaseous fuel for future use to generate electricity. In principle all FCs can work as regenerative one, but they are typically optimized to perform only one function. Combining the two functions reduces the system size for applications that require both energy storage (production of hydrogen) and energy production (production of electricity). The major advantage of fuel cells is their ability to convert chemical energy directly to electricity, without involving any intermediate energy-intensive steps and noisy moving parts. To date, the developed and commonly used several groups of fuel cells: alkaline, proton exchange membrane, solid oxide, phosphoric acid and molten carbonate. Current research aims to use polymer

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electrolyte membrane FCs with hydrogen or methanol as the main fuel. The issue is to design an efficient system in both hydrogen and electricity production. Current FCs designs are less efficient in hydrogen production than other methods such as conventional electrolysis. RFC have been proposed for aerospace applications that are not as cost sensitive and require the highest possible energy density. Like conventional FCs, regenerative cells experienced life degradation in dynamic applications. Therefore, these devices are often coupled with electrochemical double-layer capacitors or other ESS to smooth the changes that the regenerative fuel cell suffers (Vazquez et al., 2011).

By Nikolaidis and Poullikkas (2018), regenerative fuel cell (Figure *11*) provides the highest specific energy and excellent cycle capability. Hence, it can be considered as long-term EES technology despite the low roundtrip efficiency (20–50%) and high capital cost which is inversely proportional to its maturity. In addition, some limitations affecting the self-discharge performance of these devices relate the hydrogen storage and more R&D is needed for the appropriate materials development.

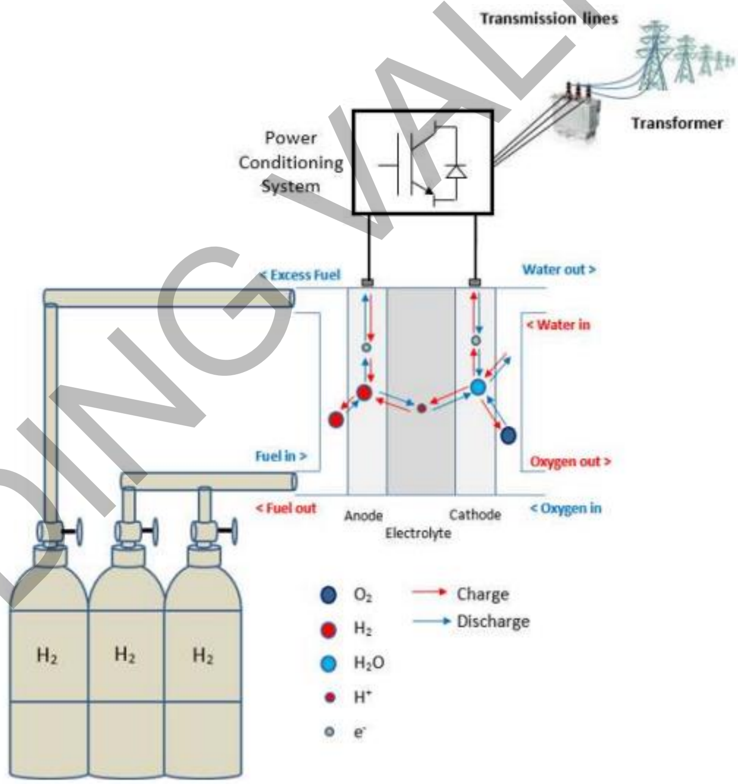

Figure 11 – Schematic diagram of regenerative fuel cells energy storage system (example for proton exchange membrane FC) (Nikolaidis and Poullikkas,2017).

4.1.4 Batteries

Batteries consist of cells each comprising two electrodes immersed in an electrolyte and they can store and provide energy by electrochemical reversible reactions. Generally, during these reactions, the anode or negative electrode is oxidized, providing electrons, while the cathode or positive electrode is reduced, accepting electrons through an external circuit connected to the cell terminals (Hadjipaschalis et al., 2009). During the discharge phase, electrochemical reaction takes place and the metal in anode dissolves into the electrolyte as anions, leaving behind electrons in the anode. These electrons travel from the anode to cathode through the external circuit; therefore, current is produced due to the flow of electrons. During the charging phase, the electrons travel in the opposite direction, i.e., from cathode to anode. The voltage produced by a single battery cell is not enough to meet the requirements. Therefore, multiple battery cells are connected in series to produce the desired output voltage. Operation of BES is illustrated on *Figure 12*.

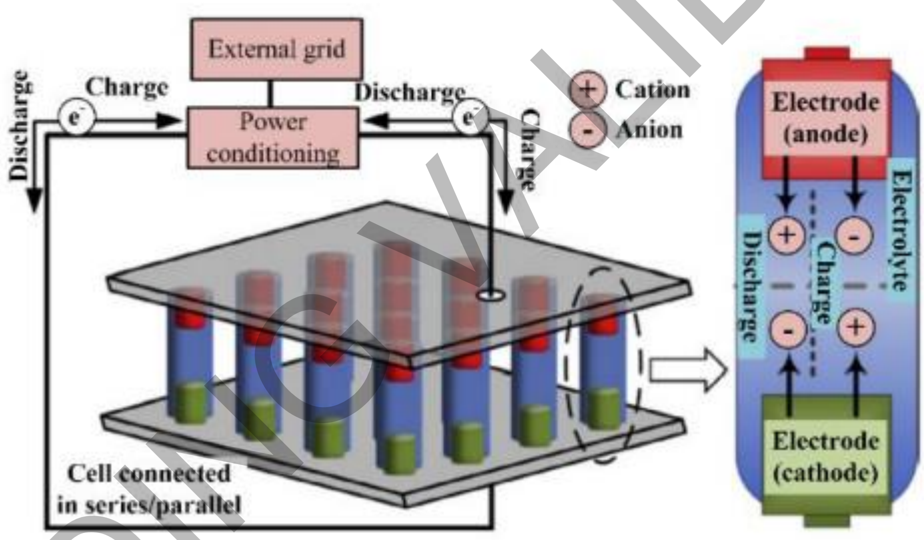

Figure 12 - Schematic diagram of BES operation (Luo et al., 2015).

Lead-acid is the most commercially mature rechargeable battery technology in the world so far. Lead acid battery cell consists of spongy lead as the negative active material, lead dioxide as the positive active material, immersed in diluted sulfuric acid electrolyte, with lead as the current collector. Lead acid batteries are still prevalent in cost sensitive applications where the low energy density and limited cycle life is not an issue and where ruggedness and abuse tolerance are required. Lead acid batteries are used in a variety of applications, including automotive, marine, telecommunications, and UPS systems. However, there have been few utility applications for such batteries due to their relatively heavy weight, large bulk, cycle-life limitations and perceived reliability issues (stemming from maintenance requirements). It should

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be noted that lead acid batteries are widely applied at NPPs as part of uninterruptible power supply for safety-important systems.

Work to improve lead-acid battery technology and materials continues. Innovation in materials is improving cycle life and durability, and several advanced lead-acid technologies are being developed are in the pre-commercial and early deployment phase (EPRI, 2010). These systems are being developed for peak shaving, frequency regulation, wind integration, photovoltaic smoothing and automotive applications. Some advanced lead batteries have "supercapacitor-like" features that give them fast response similar to flywheels and supercapacitors.

Nickel-cadmium batteries. Nickel cadmium batteries along with lead acid batteries are considered to be the most matured and popular battery technologies. Nickel-cadmium batteries comprise nickel oxide for cathode and potassium hydroxide for electrolyte. Similar to lead-acid, nickel-cadmium spent batteries create environmental concerns because of cadmium and nickel toxicity, and consequently are largely being displaced.

Metal–air batteries. These batteries are a type of fuel cell which employs metal (Ca, Mg, Fe, Al, Li and Zn) as the fuel and air as the oxidizing agent. They are environmentally friendly and have a potential to offer a cost-effective storage option in the future. However, the major challenge with metal–air batteries are that they have a low cycle efficiency.

Lithium-ion batteries. In Lithium-ion batteries the lithium ions move between the anode and cathode to produce a current flow. The main advantages of this battery technology are high energy-to-weight ratios, no memory effect and a low self-discharge. Main applications include solar systems, portable equipment, laptops, cameras, mobile telephones and portable tools. Due to its high energy density, Li-ion is proving to be the most promising battery technology for plug-in hybrid and electric vehicle applications. However, the price of Li-ion batteries is still high for many applications. It should be noted that Lithium-ion batteries are tend to be applied for NPPs. Recent example includes construction of BESS with Lithium-ion technology for Olkiluoto Unit 3, Finland (TVO, 2022).

Sodium-sulphur batteries (NAS) consist of molten sulfur at the positive electrode and molten sodium at the negative electrode separated by a solid beta alumina ceramic electrolyte. NaS batteries exhibit high power and energy density (over four times that of the lead-acid battery), high columbic efficiency, good temperature stability, long cycle life, low cost and good safety. These batteries can be used for load levelling, emergency power supply or uninterruptible power supply applications, being suitable to a number of markets, including industrial applications, commercial owners and wind power generating systems (Vazquez et al., 2011).

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4.1.5 Comparison of Technologies

General comparison of different types of BES based on data selected from Hossain et al. (2020), Luo et al. (2015), Nadeem et al. (2019), Akinyele and Rayudu (2014), Nikolaidis and Poullikkas (2017) is presented in Table 8.

Parameter	Lead acid	Lithium -ion	NaS	NiCd	Vanadium redox	ZnBr	Polysulphide bromine	Metal air	RFC
Energy Density (kWh/m3)	25-90	94-500	150-345	15-150	10-33	5-70	10-60	150–3000	25-770
Power Density (kW/m3)	10-400	56-800	1.3-50	38-141	2.5-33	3-8.5	1.3-4.2	500-10000	1-300
Specific Energy (Wh/kg)	25-50	75-200	100-240	45-80	10-30	30-80	15-30		200-1200
Specific Power (W/kg)	75-300	150-2000	90-230	150-300	166	100	-		5-50
Rated Energy Capacity (MWh)	0.001-40	0.004-10	0.4-244.8	6.75	≤60	0.05-4	Up to 120		0.06
Power Rating (MW)	0-40	0-100	≤34	0-40	0.03-50	0.05-10	0.004-15	0-0.01	0.312
Daily Self-Discharge (%)	>0.3	>1	almost zero	>0.6	Very small	Small	Almost zero	Very small	0.06-3
Lifetime (Years)	5-15	14-16	10-20	15-20	10-20	5-10	10-15	>1	5-15

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Parameter	Lead acid	Lithium -ion	NaS	NiCd	Vanadium redox	ZnBr	Polysulphide bromine	Metal air	RFC
Cycling Times (Cycles)	600-2000	200-1800	2500-4500	2000-3500	12000	1500-2000	-	1000-3000	20000
Discharge Efficiency (%)	85	85	85	85	75-82	60-70	-		90
Cycle Efficiency (%)	63-90	75-97	75-90	60-83	65-85	65-80	60-75	≤50	20-50
Response Time	Milli-seconds	Milli-seconds	Milli-seconds	Milli-seconds	>1/4 cycle	>1/4 cycle	20 milli-seconds		seconds
Suitable Storage Duration	Minutes–days; short to medium term	Minutes–days; short to medium term	Minutes–days; short to medium term	Minutes–days; short and long term	Hours-month; long term	Hours-month; long term	Hours-month; long term	Hours-month;	Hours-month;
Discharge Time at Rated Power	Seconds–hours	minutes–hours	Seconds–hours	Seconds–hours	Seconds–hours	Seconds–hours	Seconds–hours	Seconds–hours	Seconds–hours
Power Capital Cost ($/kW)	200-600	900-4000	350-3000	500-1500	600-1500	200-2500	700-2500	100-250	
Energy Capital Cost ($/kW)	50-400	600-3800	300-500	400-2400	150-1000	150-1000	150-1000	60-160	15
O&M Cost ($/kW/year)	50	-	80	20	70	-	-	-	13
Maturity	Mature	Commercial	Commercial	Mature	Developing	Demo	Developing	Demo	Developing

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Table 8 - Technical parameters of different BES.

Each technology has advantages and disadvantages which are summarized in Table 9, which information are taken from (Tumino, 2020) and ADB, 2018).

BES	Advantage	Disadvantage
Lead-acid	Matured technology Low cost per watt-hour Low maintenance requirement Good performance at low and high temperature	Non- environment friendly Slow charge Must be stored in charged condition to prevent sulphating
Lithium-ion	High energy density Cycle or round-trip efficiency is a key element in evaluating EES options in power system applications. Lithium-ion batteries has very high efficiency No memory effect Low self-discharge Long cycle life, maintenance free	Requires protection circuit to prevent thermal runaway if stressed, requires fire protection Degrades at high temperature and when stored at high voltage No rapid charge possible at freezing temperatures High cost
NAS	Low-cost potential: Inexpensive raw materials and sealed, no-maintenance configuration High cycle life; liquid electrodes Good energy and power density: Low-density active materials, high cell voltage	Need to be operated above 300°C Highly reactive nature of metallic sodium (part of the material used in construction), which is combustible when exposed to water Extra cost of constructing the enclosing structure to prevent leakage

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	Flexible operation: Cells functional over a wide range of conditions (rate, depth of discharge, temperature) High energy efficiency: 100% coulombic-efficient, reasonable resistance Insensitivity to ambient conditions: sealed, high temperature systems; State-of-charge identification: voltage rise and top-of-charge and end-of-discharge	Stringent operation and maintenance requirements
Nickel cadmium	Matured technology Low maintenance requirement Economically priced Good low temperature performance Long shelf life, can be stored in discharge state	Toxicity of cadmium requires a complex recycling procedure Lower energy density compared to newer technologies High self-discharge Low cell voltage requires many cells in series to achieve high voltage
Flow batteries **(Vanadium redox, Z-r, PSB)**	High power and energy capacity Fast recharge by replacing exhaust electrolyte Long-term storage duration Long life enabled by easy electrolyte replacement Full discharge capability	Complexity: require pumps, sensors, flow and power management, and secondary containment vessels

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	Use of non-toxic materials Low temperature operation	
Metal-air	Low cost	Non-matured technology
Regenerative fuel cells	Long-term storage duration	Non-matured technology

Table 9 - BES pros and cons.

Suitability of BES and selection of the best technology depends on their specific application requirements (power quality, energy management, emergency back-up power, ramping and load following, peak shaving, voltage regulation and control etc.). For example, for utility or renewable energy integration, energy storage capacity, power output and life cycle are key performance criteria, while for transportation applications portability, scalability and energy and power density are key performance criteria (Vazquez et al., 2011). Lead-acid and Lithium-ion batteries are suitable and highly promising for the most of what was considered by (Hossain et al.,2020) applications (23 applications in total), except of seasonal energy storage, while NAS batteries are highly promising for several applications. Vanadium redox, NaS and large-scale (lead–acid, Lithium-ion, Ni–Cd) technologies, are applied for energy management purposes, because of their long discharge timescales. Lithium-ion is likely to replace Ni–Cd in the future, due to toxicity of cadmium and its complicated recycling process (Akinyele and Rayudu, 2014).

Considering above-mentioned data, the following BES can be recommended for modelling:

- Lithium-ion
- Lead-acid
- VRB
- NaS

4.1.6 Component coupling with HES

For the TANDEM project purposes, battery energy storage system (BESS) can be modelled as a unit or at simplified configuration as it shown in *Figure 13*, without detailed modelling of architecture of the BESS components.

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Possible modelling options include modelling of one BESS box with required capacity, depending on SMR power (e.g., 50 MW) or several units of 1 MW each.

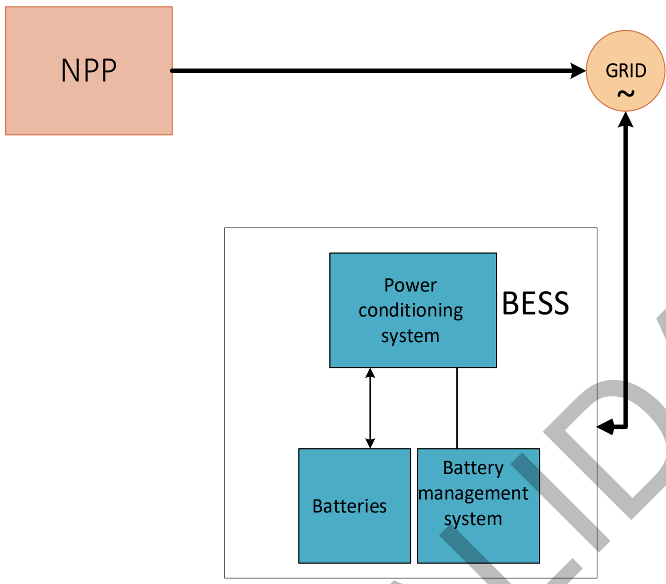

Figure 13 - BES coupled with the SMR (created by ENERGORISK in the scope of the TANDEM project).

4.1.7 Main system architecture and operating data

A BESS is composed of different levels both logical and physical. Each specific physical component requires a dedicated control system. A complete BESS system consists of power conditioning system, battery system, electrolyte tanks and pumps (only for flow battery, VRB), as well as electrolyte materials. The battery components vary depending on type, but the power conditioning system (or power conversion system), PCS, and balance of plant are similar.

The battery system is composed by the several battery packs and multiple batteries inter-connected to reach the target value of current and voltage. It also includes the battery management system (BMS) that controls the proper operation of each cell in order to let the system work within a voltage, current, and temperature that is not dangerous for the system itself, but good operation of the batteries. This also calibrates and equalizes the state of charge among the cells. The battery system is connected to PCS - inverters, in order to convert the power to AC. PCS include also auxiliary services needed for the proper monitoring. For PCS requires cooling under high load conditions. The next level is for monitoring and control of the system and of the energy flow (energy management system). The general monitoring and control are usually included in the SCADA system (Supervisory Control And Data Acquisition system), while the

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energy management system has the specific purpose of monitoring the power flow according to the specific applications. Lastly, there is the connection with the medium-voltage/low-voltage transformer and according to the size of the system, the high-voltage/medium-voltage transformer in dedicated substation. Main operating data for BESS is presented in Table *10*. The value of charging/discharging efficiency were taken from literature (see, e.g., Valøeny and Shoesmith, 2009, and Power-Sonic Corporation, 2018).

Parameter	Lead acid	Lithium-ion	NAS	Vanadium redox
Energy Density (kWh/m^3)	25-90	94-500	150-345	10-33
Power Density (kW/m^3)	10-400	56-800	1.3-50	2.5-33
Specific Energy (Wh/kg)	25-50	75-200	100-240	10-30
Specific Power (W/kg)	75-300	150-2000	90-230	166
Rated Energy Capacity (MWh)	0.001-40	0.004-10	0.4-244.8	≤60
Power Rating (MW)	0-40	0-100	10-34	0.03-50
Daily Self-Discharge (%)	0.1-0.4	0.15-0.3	0.05-20	Very small
Operating temperature (°C)	-30 to +50	-20 to +60	300-350	10-40
Nominal cell voltage (V)	2.0-2.35	3.6-4.2	2.1	1.4-1.5
Response Time	Milli-seconds	Milli-seconds	Milli-seconds	Milli-seconds

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Parameter	Lead acid	Lithium-ion	NAS	Vanadium redox
Charge/discharge time	1-8 hours	1-3 hours	6-8 hours	5-10 hours
Charge/discharge Efficiency (%)	50-95	80-90	70-85	75-80
Capital cost, $/kW, for 100 MW BESS, (Mongird et al., 2020)	4.091	3.565	3.168	3.845
Operational cost, $/kW, for 100 MW BESS (Mongird et al., 2020)	12.67	9.3	9.2	11.31

Table 10 – Main parameters for each addressed technology of batteries.

According to several sources (including International Energy Agency, Argonne National Laboratory, etc.) the most promising battery technology at 2030-2040 timeline is the next generation of Lithium batteries - alternative Li-ion technology with lithium sulphur/air, where Lithium-metal is used as anode and sulphur or oxygen/air as cathode. Nevertheless, although this technology has been introduced at early 2000, it is still under academic research.

However, besides Lithium-ion and alternative Li-ion batteries, flow batteries (e.g. vanadium redox) could emerge as a breakthrough technology for grid-scale storage (since they do not show degradation of performance for long period and are capable to be sized according to energy storage needs).

Regarding non-matured technologies, instead, it is difficult to predict which concept will be well matured at 2035 for grid-scale storage purposes. It can only be stated, indeed, that there are several research works just started on next generation batteries or discussed idea, e.g.: nanobolt Lithium Tungsten batteries; rechargeable Zinc-Manganese oxide battery; Gold nanowire gel electrolyte batteries, etc.

During the charging process of VRB, the following chemical reactions occur at the negative and positive electrode respectively:

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Negative: $V^{3+} + e^- \rightarrow V^{2+}, \quad E^0 = -0{,}26\ V$

Positive: $VO^{2+} + H_2O \rightarrow VO_2^+ + 2H^+ + e^-, \quad E^0 = +1.00\ V$

Lithium-ion batteries

$$C + nLi + ne^- \leftrightarrow Li_nC$$

$$LiXXO_2 \leftrightarrow Li_{1-n}XXO_2 + Li^+ + ne^-$$

NaS batteries

The charge and discharge process can be described by the chemical equation:

$$2Na + 4S \leftrightarrow Na_2S_4$$

In the discharge process, the two elements combine to form sodium polysulfides but in the charging process, the sodium ion is released back through the electrolyte. The discharge process produces roughly 2 V.

Lead-acid batteries

Discharge is:

$$PbO_2 + 2H_2SO_4 + Pb \rightarrow 2PbSO_4 + 2H_2O$$

The discharge process produces about 2 V. The reaction is reversed during charging.

As the battery charging process is nonlinear, different methods have been developed to effectively control battery charging. Control methods commonly used in battery charging are: constant current (CC), constant voltage (CV), two-step charging - constant-current followed by constant-voltage (CC-CV), pulse charging, reflex charging or negative pulse charging, trickle charge or taper-current, and float charge.

The most used control method for battery charging and discharging is CC-CV. CC is applied at the initial charging stage until the battery voltage reaches an overcharged stage or a predefined voltage. At a second stage, the charging method switches to CV to maintain the battery voltage, so that it avoids overvoltage. Previous research has shown that the CC–CV charging method is the most efficient for battery charging, regardless of the battery type, and also that it is the most used control method (see, e.g., Banguero et al., 2018). Detailed description of CC-CV charging

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process and equations can be found from the work by (Liu et al.,2017) for Lithium-ion batteries; (Akter et al.,2019, and Chen et al.,2011) for vanadium redox batteries.

4.2 Thermal Energy Storage

Thermal energy storage technologies accumulate and release energy by heating, cooling, melting, or solidifying a storage medium so that the stored energy can later be used for various applications by simply reversing the process. When coupled with NPP, TES technologies could store any excess energy not being used for power production. This energy could later be used to generate heat or electrical power when needed (e.g. for load following, energy arbitrage). This would enable NPPs to operate in base-load, without necessity for load following to match the demands of the market. It would lead to increase efficiency of NPP and to reduce any mismatches between energy supply and demand.

It should be noted that Generation IV reactors provide higher temperatures to the power cycle relative to LWR, which is beneficial for thermal storage because at higher temperatures, less storage material is required to deliver a desired amount of thermal power.

4.2.1 Technology Selection

Thermal energy can be stored in the form of latent heat, sensible heat, and reversible thermochemical reactions. TES has been in use for a long time for energy redistribution and energy efficiency on short or long-term basis (Kalaiselvam and Parameshwaran, 2014). In TES, energy is hoarded by cooling or heating a medium, which can be used to cool or heat other objects, or even for generating power.

TES can also be classified by other factors:

- operational temperature: low-temperature and high-temperature,
- location: surface and underground.

According to the recent studies (the list of literature is not exhaustive), there are the following TES technologies were considered or evaluated in conjunction with nuclear power plant including LWR and Generation IV SMRs:

- Sensible heat storage. Energy stored as temperature difference in solid or liquid media:
    - Liquid based sensible heat storage
        - Two-tank systems (Saeed et al., 2022; Mikkelson et al., 2019; Frick et al., 2018);

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        - Thermocline systems, packed bed thermal storage (Saeed et al., 2022; Mikkelson et al., 2019; Frick et al., 2020);
        - Hot and cold-water systems, steam accumulators (Saeed et al., 2022; Mikkelson et al., 2019; Johnson et al., 2019);
    - Solid based sensible heat storage (Johnson et al., 2019)
        - Firebricks (Mikkelson et al., 2019 ; Saeed et al., 2022);
        - Concrete (Mikkelson et al., 2019 ; Saeed et al., 2022);
        - Ceramics, graphite, and alloys (Saeed et al., 2022);
    - Underground storage (Saeed et al., 2022; Johnson et al., 2019);
    - Geothermal heat storage (Mikkelson et al., 2019).

- Latent heat storage (Al Kindi et al., 2022; Ali et al., 2022). Energy stored using phase-change materials:

    - Molten salt (Saeed et al., 2022; Mikkelson et al., 2019; Johnson et al., 2019; Soto et al., 2022; Borissova and Popov, 2020);
    - Liquid air, cryogenic air energy storage (Johnson et al., 2019; Park et al., 2022; Li et al., 2014).

- Thermochemical energy storage (Saeed et al., 2022; Mikkelson et al., 2019; Johnson et al., 2019). Energy stored in chemical bonds.

4.2.2 Sensible Heat Storages

In sensible heat storage the energy is stored in the change of temperatures of storage material that experience a change in internal energy, without changing its phase. At a system level, sensible TES consists of a storage medium, a container and inlet/outlet devices. Tanks must both retain the storage material and prevent losses of thermal energy. Sensible heat storage can be made by solid media or liquid media. Solid media are usually used in packed beds, requiring a fluid to exchange heat. The heat transfer fluid absorbs the thermal energy from the heat source and transfers it to the storage medium. It can also do basically the same thing in reverse: namely, absorb heat from the storage medium and deposit it to a heat user. TES designs can involve one or more heat transfer fluids, depending on the nature of both the heat source and the power block consuming the heat. In some cases, the heat transport fluid can also be used as the storage medium itself (Saeed et al., 2022).

Besides the density and the specific heat of the storage material, other important properties are operational temperatures, thermal conductivity and diffusivity, vapor pressure, compatibility among materials stability, heat loss coefficient as a function of the surface areas to volume ratio, and cost (Buonomo et al., 2020).

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Two-tank system

The two-tank system (see *Figure 14*) is the most common form of sensible heat storage technology for applications that require hours of storage capacity.

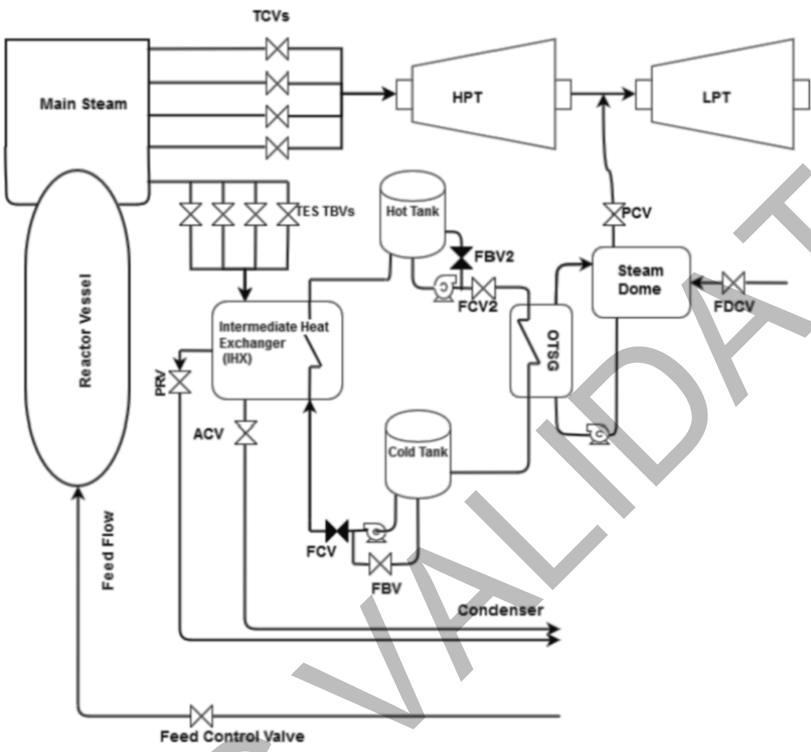

Figure 14 - Schematic demonstrating coupling between a nuclear reactor and a two-tank TES system (Frick et al.,2018).

In this case, referring again to *Figure 14*, it must be highlighted that the thermal output of the Thermal Energy Storage heat exchanger may be used to supply other thermal users more than the steam turbines.

This technology was deployed on a large scale in concentrated solar power plants in which, depending on the operating temperature, the heat transfer fluid and the storage medium can be thermal oils or molten salts. In some applications for which both fluid types are used, the thermal oils usually operate as the heat transfer fluid—transferring heat from the generator to the storage system—and the molten salts serving as the heat storage medium. Operation of this TES technology involves the use of two large tanks, each capable of storing the entire mass of the storage medium; a heat source to charge the TES system; and a power block to discharge it.

Within the two-tank TES designs, a further classification can be made based on whether the heat storage medium is heated directly by the heat source, or indirectly via a heat transfer fluid. During

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the charging cycle in the indirect setup, the storage medium is first pumped from the cold tank and through an intermediate heat exchanger that couples the system with the heat source, then transferred to the hot tank for storage. During the discharge cycle, the system operates in reverse: depositing its heat to a fluid that is then sent to the power block. The power block uses the heated fluid to produce steam that is then expanded in a turbine to generate electricity. The direct design differs from the indirect setup only during the charging cycle, since the storage medium is directly heated by the heat source prior to being transferred to the cold tank (Saeed et al., 2022).

There are several thermal oils that are commercially available: Dowtherm (mixture of alkyl benzenes) and Therminol (modified terphenyl). These oils have upper limit on operating temperatures below 400°C. These heat storage systems are compatible with LW-SMRs with peak temperatures less than 300° C. For temperatures above 400 °C, molten salts are the only viable option for sensible heat storage using the two-tank setup, for high temperature SMRs. In most molten salt energy storage systems, the molten salt is maintained as a liquid throughout the energy storage process.

Hot and Cold water

Hot and cold water is characterized as large tanks of hot or chilled water stored above ground and cycled typically on a daily basis. The water is held at temperatures either right above the freezing temperature of water or right below the boiling temperature. Pressurized storage tanks can hold water at even higher temperatures. Even still, the storage output temperature of this technology is limited. Chillers can use either waste heat or low-demand time electricity to produce a local reservoir of cold water. Hot water is produced via heat exchangers and stored below saturation temperature in order to avoid pressure concerns. Hot/cold water TES storage tanks are probably the most prominent form of thermal energy storage. These energy storage systems are used primarily to shift the energy demand for the heating and cooling of residential and commercial buildings to off-peak periods to reduce costs, hence it can be considered as the thermal energy storage architecture for the district heating scenario as well.

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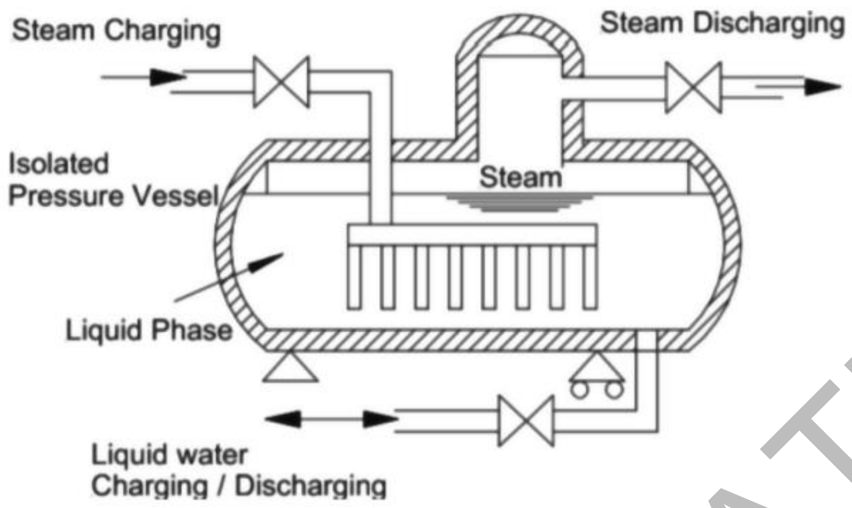

Figure 15 - Schematic of a sliding pressure steam accumulator (Laing et al., 2011).

Steam accumulators (see *Figure 15*) are another form of hot water energy storage in which steam produced by NPP is stored directly as a pressurized saturated water in a sliding pressure Ruths type vessel (Mikkelson et al., 2019). During charging, steam is injected in the bottom of the tank system via diffusers. The system mixes into a saturated system, pressurized by the steam volume in the upper section. During discharge, a valve is opened allowing for steam to escape. The ensuing vacuum in the top of the vessel lowers the pressure, causing some liquid to flash to steam. Thus, during discharge the pressure out of SAs decreases.

Steam accumulators store energy at around 20–30 kWh/m^3. Although steam accumulators have rapid discharge capabilities with round-trip efficiencies of 60–80%, they only produce saturated steam at sliding pressures. This is detrimental because the efficiency of the power cycle decreases as more steam is released from the steam accumulator. Furthermore, steam accumulators are pressure vessels, thus they have physical constraints dictated by the operating pressure. To overcome this, the discharged steam can be superheated using electrical topping heat prior to delivering it to the power block (Saeed et al., 2022).

Thermocline System

Thermocline system is based on replacing the two-tank system with a single tank. Within the thermocline tank, the hottest fraction of the storage medium floats naturally (driven by density difference) over the coldest fraction, being separated by a thermocline zone. The thermocline can include either only fluid or it can incorporate a packed bed system where a low-cost filler material (e.g., granite, quartzite) is placed in the tank to store heat and reduce the amount of high-cost thermal fluid.

Thermocline system takes advantage of buoyancy and low internal heat transfer characteristics to store hot and cold liquid in a single tank separated by a thin but steep thermal gradient layer. This thermocline would move up and down in the tank during discharging and charging.

One immediate advantage of a single tank configuration is a reduced quantity of storage materials and thus reduced tank size and cost. However, in comparison with the two-tank TES system, lower thermal efficiencies are obtained due to heat transfer interference (diffusion) between the two temperature zones.

Water is currently used in thermocline systems, and research is being done for other materials (molten-salt, thermal oil). For example, recently floating barriers (insulating membranes) were developed to intermediate density between the two layers in order to reduce the amount of heat transfer diffusion and maintain thermal stratification. In such technology, thermal oils and molten salts can serve as the heat transfer and storage media. Thermocline systems that employ thermal oils are suitable for reactors operating at low to medium temperatures (~300–450 ◦C), whereas those that employ molten salts would afford higher storage and discharge temperature capabilities (Saeed et al., 2022). Specific mixing, material considerations, and thermocline reduction are all areas of concern in these systems (Mikkelson et al., 2019).

When compared to two-tank systems, the maximum energy withdrawal (round-trip efficiency) of thermocline systems is significantly lower for discharging energy at temperatures above 550 ◦C: around 65% for single-tank thermocline and > 99% for two-tank systems that feature a similar size and heat transfer fluid (Angelini et al., 2014).

Solid-based sensible heat storage

Water has a very high heat capacity, and as a result, water has a high energy storage density. However, as a form of sensible thermal energy storage, water also has limitations. Since the boiling and freezing temperatures for water are relatively close compared to other materials, such as concrete, water can only be heated to a certain temperature without causing it to boil, and it can only be cooled so much before it begins to freeze. Freezing or boiling water can have drawbacks because water is often transported as a liquid through pipes and stored in tanks or, in the case of underground TES, underground caverns and aquifers. Solid media energy storage systems offer a form of sensible thermal energy storage for high-temperature (Johnson et al., 2019). Schematic of concrete-based TES is illustrated on *Figure 16*.

The following materials are used: firebrick, concrete, crushed rock, ceramics, graphite, and alloys. These materials are inexpensive, environmentally friendly, and easy to handle. The energy density of solid materials is generally much lower than liquid storage media though.

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Concrete energy storage uses specialized concrete overlaid onto tubing lattices to transfer heat from a Heat Transfer Fluid (HTF) into the surrounding concrete. A cold HTF is used to recover heat from the concrete. Concrete is normally used as an insulator, and so material and design considerations must account for a slower rate of heat flow through the storage medium itself during charging and discharging. Firebrick thermal energy storage (FIRES) uses electrical resistance heated ceramic bricks to store very low or negatively priced electricity to resell at higher priced times via air heated by the firebrick. If possible, the firebrick system will optimally operate at a 1000 ^{0}C temperature from 850-1850 ^{0}C. Firebrick discharge will either be used for direct thermal energy or to produce electricity via a Brayton cycle.

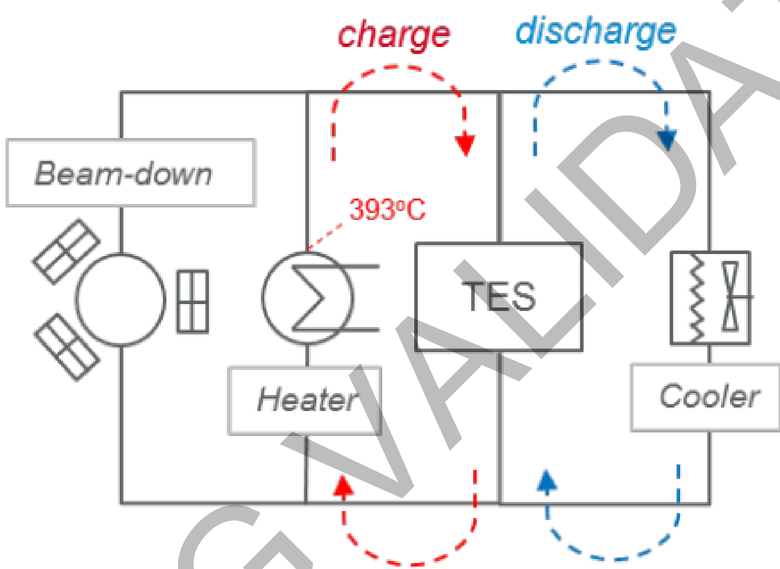

Figure 16 – Schematic of concrete-based TES (Hoivik et al., 2017).

Underground storage

In underground TES (UTES) heat is stored by pumping heat into underground locations at large depths from surface such as boreholes (30–100 m), aquifers (20–200 m), and caverns (30–60 m). Current experience with underground TES is focused in seasonal storage for domestic heating and cooling, and for air conditioning applications. The storage uses hot and cold water that is exchanged between hot and cold stores, using the environment as the primary heat storage medium.

Borehole TES consist of drilled wells with coaxial tubes or U-bend thermal loops that form an array of cold/hot storage media. On the other hand, aquifer thermal storage systems are based on two separate wells. In summer, water from the cold aquifer is pumped outward, used for cooling, then transferred to the warm aquifer. In winter, this process is conducted in reverse,

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with water from the warm aquifer being used for heating purposes prior to being returned to the cold aquifer (Saeed et al., 2022).

Geothermal energy storage is similar to underground TES, except that the storage is much deeper in the ground and the primary storage medium is steam and water. By creating an aquifer-like structure at depths where the hydrostatic pressure will not cause fracturing, it is possible to store water or steam deep in the earth at relatively high temperatures and pressures. Example depths of at least 2km allows for saturation temperatures around 250 ^{0}C (Mikkelson et al., 2019). Examples of UTES are shown on *Figure 17*.

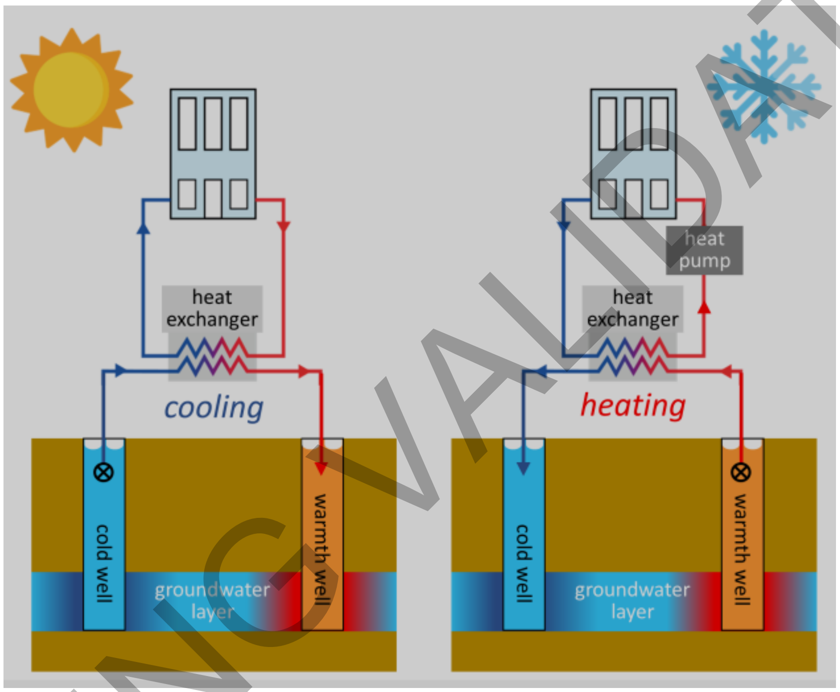

Figure 17 – Schematic of aquifer-based TES (WAGE, 2022).

Integrating this technology with a nuclear reactor is possible as long as the reservoir pressure exceeds the steam pressure. This would require a depth of at least 1,200 m to maintain sufficient saturation pressure and to keep the liquid water at 250 ^{0}C. These conditions would allow direct steam removal from a turbine bypass stream to charge the TES system. Discharge of such a system would ideally produce saturated steam, which can be used directly in a power block or for other industrial heat applications. To prevent impurities from entering the power generation system, an intermediate heat exchanger is often needed to facilitate the heat transfer. As in the case of hot/cold TES, underground storage is expected to perform relatively poorly compared (Saeed et al., 2022).

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4.2.3 Latent Heat Storages

In latent heat storage media, the energy is stored nearly isothermally in storage material as the latent heat of phase change, as heat of fusion (solid–liquid transition) or heat of vaporization (liquid–vapour transition). Phase Change Materials (PCM) are typically separated into three categories: organic, inorganic, and eutectics (Saeed, 2018). In theory, any phase change material can be used for thermal energy storage, but only a few have been proved as effective. Latent TES consist of a storage tank (or vessel) in which heat exchangers are fully immersed in a stationary energy storage material. Because latent heat TES technology involves a solid-to-liquid phase change—or vice versa—their design and operation are more complex than sensible heat storage technology. A dedicated heat exchanger is needed to support heat transfer between the heat transfer fluid and the stationary storage medium in the tank. Storage systems utilizing PCM can be reduced in size compared to single-phase sensible heating systems. Heat transfer design and media selection are more difficult, and experience with low temperature salts has shown that the performance of the materials can degrade after moderate number of freeze melt cycles. Phase change materials allow large amounts of energy to be stored in relatively small volumes, resulting in some of the lowest storage media costs of any storage concepts (Buonomo et al., 2020).

Although sensible thermal energy storage can be effective and relatively inexpensive, latent thermal energy storage technologies offer superior energy densities and target-oriented discharge temperatures.

Molten Salts

Molten salts are a phase change material that is commonly used for thermal energy storage. Molten salts are solid at room temperature and atmospheric pressure but change to a liquid when thermal energy is transferred to the storage medium.

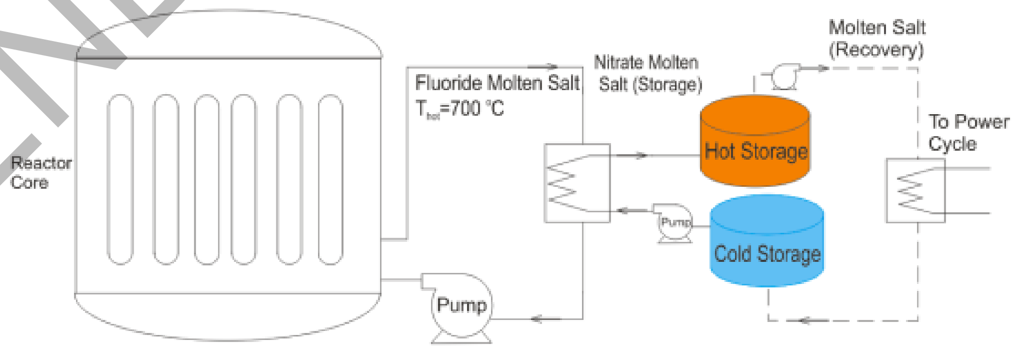

Figure 18 – Schematic of molten salt TES (Edwards et al., 2016).

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Molten salts are typically made up of 60% sodium nitrate and 40% potassium nitrate, and the salts melt at approximately 220°C (Johnson et al., 2019).

Currently, low-temperature latent heat storage systems are already commercialized and have been commissioned in various residential, commercial, and industrial facilities for heating and cooling peak load shifting (Saeed et al., 2022).

Latent heat storage systems (see *Figure 18*) consist of a storage tank (or vessel) in which heat exchangers are fully immersed in a stationary energy storage material. Because latent heat TES technology involves a solid-to-liquid phase change—or vice versa—their design and operation are more complex than sensible heat storage technology. A dedicated heat exchanger is needed to support heat transfer between the heat transfer fluid and the stationary storage medium in the tank.

While latent heat storage systems that operate at these temperatures are fully developed and now commercially available, latent heat storage systems for higher temperatures NPP may cause additional challenges for developers. At the material science level, several molten salts have already been studied and are very well documented in the literature. At the system engineering level, despite its readiness for room-temperature applications and other types of industrial systems, latent heat storage systems for high-temperature applications remain at the laboratory scale for validation in relevant environments (Saeed et al., 2022).

Liquid Air

Liquid air (or cryogenic) TES technologies are gaining traction as an efficient and cost-effective energy storage method due to their large scale and long duration as well as their compatibility with existing infrastructure. Liquid air TES systems (see *Figure 19*) store energy using a method very similar to compressed air energy storage systems. However, instead of storing compressed air in a large cavern, the volume of the gas is reduced further by refrigerating the air and liquefying it. The liquid air is then stored in an insulated, low-pressure tank above ground, eliminating the geographic requirements associated with compressed air energy storage systems. In liquid air TES natural gas is typically burned to drive the expansion process. However, the advanced adiabatic and isothermal compression methods that are being developed for compressed air energy storage systems are applicable to liquid air TES systems as well.

Liquid Air TES (LAES) systems are particularly attractive as a method of thermal energy storage due to their high expansion ratio from liquid to gaseous air and the high-power density of liquid air compared to compressed air. These systems operate more effectively at a larger scale, where the economics, self-discharge rate, and efficiency all improve. Therefore, the technical

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characteristics of this technology are best suited for long duration storage applications (Mikkelson et al., 2019).

Cryogenic air energy storage is a large-scale energy storage technology which uses cryogen (liquid air/nitrogen) as a storage medium and also a working fluid for energy storage and release processes. During off-peak hours, when electricity is cheapest and demand for electricity is lowest (typically during nights and weekends), liquid air/nitrogen is produced in an air liquefaction and separation plant and stored in cryogenic tanks close to the atmospheric pressure. During peak hours, the cryogenic liquid is heated up by using the environmental heat and then superheated using other heat sources (if available). Boiling of the cryogenic liquid will form a high-pressure gas to drive an expander (e.g., a turbine) to produce electricity.

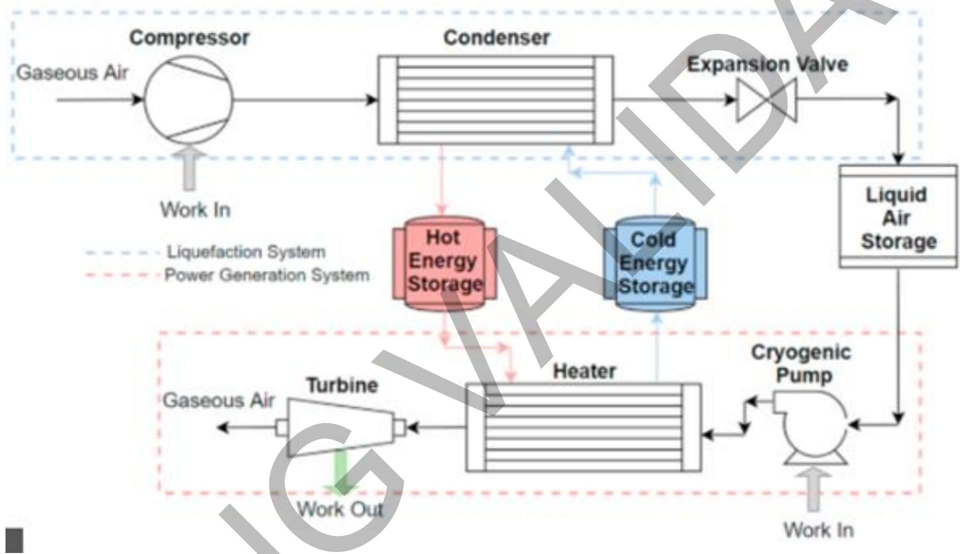

Figure 19 – Schematic of cryogenic air TES (O'Callaghan and Donnellan, 2021).

Cryogenic air TES has an expected life span of 20–40 years, and an efficiency of 40–50% (Akinyele and Rayudu, 2014).

One of main advantages of the cryogenic air TES technology is its highly efficient heat-to-power conversion in energy extraction process using cryogen itself as the working fluid. Due to the constrained working pressure and temperature in steam generators, the thermal efficiency of pressurized water NPPs is only around 30–32%, which is much lower than that of fossil fuel fired power plants. The integration of NPPs and CES technology could increase the thermal efficiency of nuclear heat utilization at peak hours and as a result the net power output. The round-trip efficiency of the energy storage could also be improved significantly (Li et al., 2014).

4.2.4 Thermochemical Energy Storages

Thermochemical storage systems (TCS) have emerged as a potential energy storage solution recently due to the technology's superior energy density and absence of energy leakage throughout the technology's storage duration. These systems store energy in endothermic chemical reactions, and the energy can be retrieved at any time by facilitating the reverse, exothermic reaction. The storage output temperature is dependent on the properties of the thermochemical that was used as the storage medium.

Typically, thermochemical storage refers to two main processes, thermochemical reactions and sorption processes. Thermal adsorption reactions can be used to store heat or cold in the bonding of a substance to another solid or liquid. A common sorption process used in these systems is the adsorption of water vapor to silica gel or zeolites.

Energy charge/discharge steps in a $Ca(OH)_2/CaO$-based thermochemical cell are as follows. Decomposition of $Ca(OH)_2$ into CaO is the dehydration process or energy storage step in which the water vapor is released from the hydroxide. The reaction is endothermic, with a positive reaction enthalpy. The reverse hydration reaction, in which CaO reacts with water vapor, is exothermic, with a negative reaction enthalpy, and functions as the energy discharge step. Current challenges regarding thermochemical storage technologies include the high cost of such systems and the technical complexity involved in their use. One advantage they offer over latent or sensible heat storage is higher energy storage density. However, the poor cyclability of reactions prevents such technologies from quickly moving from the theoretical design or laboratory experiment stages to commercialization. Another challenge is the unavoidable complexity of the reactor design in order for the thermochemical energy storage process to work (Saeed et al., 2022). Although the energy densities of thermochemicals are greatly superior to other energy storage technologies, thermochemicals are currently economically infeasible (Johnson et al., 2019).

4.2.5 Comparison of technologies

General performance metric for different TES is presented in Table *12* based on (Johnson et al.,2019, Saeed et al.,2022, and Mikkelson et al.,2019). Advantages and disadvantages for different thermal energy storage technologies are presented in Table *11*.

Suitability of TES and selection of the best technology depends on their specific application requirements (power quality, energy management, emergency back-up power, ramping and load following, peak shaving, voltage regulation and control etc.). Compatibility between TES technology and application is shown in Table *12*.

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	Sensible heat storage	Latent heat storage	Thermochemical energy storage
Energy Density	~200 – 500 kJ/kg (for ~200 – 400 °C temperature differential)	~100 – 200 kJ/kg for nitrate salts; ~200 – 500 kJ/kg for metals; ~1000 kJ/kg for fluoride salts	~300 – 6,000 kJ/kg
Advantages	Demonstrated large energy capacity (~GWh) Inexpensive media Solid media does not freeze and can achieve >1000°C	Good for isothermal or low delta temperature applications Highly efficient heat-to-power conversion (liquid air) Can provide large energy density with combined sensible and latent heat storage	Large energy densities Small heat losses Potential for long term storage Compact storage system
Challenges	Requires insulation to mitigate heat losses Lower energy density requires larger volumes Thermal oils are of greater environmental concern than molten salts, due to post-use leakage and deposition.	Potential for corrosion For larger delta temperature, may need cascaded systems (adds costs and complexity) Emissions produced during operation (for liquid air) Challenges with PCMs include relatively high costs and narrow operating temperature ranges. Using PCMs to provide energy to a heat engine will typically require a cascaded system with multiple PCMs with different melting points. The use of molten silicon at high temperatures provides challenges with materials containment and heat loss. Phase-change systems must still be well insulated to prevent heat loss and subsequent phase change	Higher complexity Higher capital costs May require storage of gaseous products

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Maturity	High	Low	Low
Cost	~$1/kg for molten salts and ceramic particles ~$0.1/kg for rock and sands ~$1/MJ – $10/MJ (system capital cost)	$4/kg – $300/kg ~$10/MJ – $100/MJ (system capital cost)	$10/MJ – $100/MJ (system capital cost)

Table 11 - TES pros and cons.

	Two-tank	Hot/cold water	Thermo-cline	Solid sensible	Under-ground	Molten salt latent	Liquid air	Thermo-chemical
Storage Output Temperature , °C	~300 (thermal oil) 290-565 (molten salt)	95–98 or 120–130 (pressurized)	<350 (thermal oil) 300-545 (molten salt)	350 (concrete)	< 250	-40-400 (Depending on the type of molten salt)	<400	20-200
Energy Capacity, MWh		10-2000		>1100 (concrete)	3900	350	20-1000	
Average Total Energy Storage Capacity, kWh/m3	68 (thermal oil) 113 (molten salt)	20-30 (steam accumulators)	68 (thermal oil) 113 (molten salt)	65 (concrete) 90 (firebrick)	46-58 (water at ΔT 40 ^{0}C)	170-420		150-1100

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	Two-tank	Hot/cold water	Thermo-cline	Solid sensible	Under-ground	Molten salt latent	Liquid air	Thermo-chemical
Round Trip Efficiency, %	75-80	50-90 60-80 (steam accumulators)	45-65	50-90	50-90	40-93	55-80	80-99
Ramp time	10 min - 1 hour (molten salt)	Up to 1 hour	10 min - 1 hour	Few minutes	Several hours-several days	10 min - 1 hour	minutes	Very slow
Discharge time		Minutes to hours		1 day (concrete)	TES are designed to cycle on a seasonal basis and cannot charge/discharge on demand, or even on a daily basis		Several hours	Several hours
Maturity	High	High	Low	Low/demo	High	High-low for LWR	Low/ Demo	Demo
Applicability for LWR	Yes (thermal oil, low	Yes, Integration with NPP is	Yes (thermal oil)	Yes	Yes, but have geographical sensitivity	Yes, only for low	Yes	Yes, but there are some

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	Two-tank	Hot/cold water	Thermo-cline	Solid sensible	Under-ground	Molten salt latent	Liquid air	Thermo-chemical
	temperature molten salt)	limited to stored cold water employed by buildings for cooling applications using an electric chiller, or hot water that serves as a heat source by being drawn out of a low-pressure turbine	No (molten salt)			temperature molten salt		uncertainties associated with thermochemical systems
Energy arbitrage	compatible	compatible	compatible	compatible	incompatible	compatible	compatible	compatible
Frequency regulation	incompatible	incompatible	incompatible	incompatible	incompatible	incompatible	incompatible	incompatible
Load following	somewhat compatible	incompatible	somewhat compatible	incompatible	incompatible	somewhat compatible	compatible	incompatible

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	Two-tank	Hot/cold water	Thermo-cline	Solid sensible	Under-ground	Molten salt latent	Liquid air	Thermo-chemical
Voltage support	incompatible	incompatible	incompatible	incompatible	incompatible	incompatible	incompatible	incompatible
Spinning reserves	compatible	incompatible	compatible	incompatible	incompatible	compatible	compatible	incompatible
Non-spinning and supp reserves	compatible	compatible	compatible	compatible	incompatible	compatible	compatible	somewhat compatible
Black start	incompatible	incompatible	incompatible	incompatible	incompatible	incompatible	compatible	incompatible
VSR integration	compatible	compatible	compatible	compatible	incompatible	compatible	compatible	compatible
Seasonal storage	incompatible	compatible	incompatible	incompatible	compatible	incompatible	compatible	compatible
Process heat applications	compatible	compatible	compatible	compatible	compatible	compatible	somewhat compatible	incompatible

Table 12 - Summary of TES

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According to recent studies on evaluation of TES technologies that could be potentially coupled with advanced NPPs, the highest ranking was judged to the following (ranked by order of preference) technologies:

- Two tank system with molten salt, molten salt latent heat storage, solid based sensible heat storage (Saeed et al., 2022);
- Two tank system with low temperature molten salt, two tank system with thermal oil, steam accumulator system, solid based sensible heat storage (concrete) (Mikkelson et al., 2019);
- Hot/cold water, underground TES, solid based sensible heat storage, liquid air (Johnson et al., 2019).

Considering above-mentioned data (maturity, possible applications, energy storage capacity, etc.) the following TES can be recommended for modelling: molten salt, two tank system with thermal oil or hot/cold water.

As a base case for TANDEM project, considering E-SMR parameters on steam temperature, two tank system with thermal oil is proposed.

4.2.6 Component coupling with HES

Principal scheme of TES coupling with SMR is presented at *Figure 20*. For the TANDEM project purposes, TES can be modelled as a unit or at simplified configuration as it shown in *Figure 22*, without detailed modelling of all components of TES.

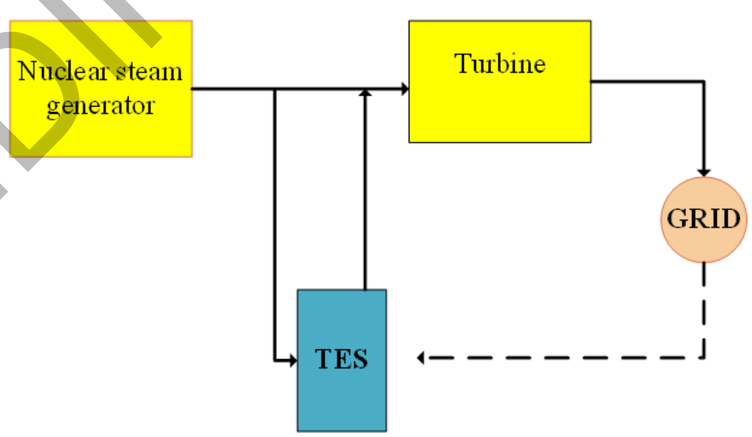

Figure 20 – TES coupled with the SMR (created by ENERGORISK in the scope of the TANDEM project).

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The integration of TES with LW-SMR uses a turbine bypass valve, moving steam at its highest energy point after the reactor steam generators. After TES, steam reintroduction into the nuclear power conversion process would depend on turbine design and available temperature and pressure coming out of the TES. It is commonly discussed to reintroduce this peaking steam before the low-pressure part of the turbine (see Figure *21*, a for option 1). Another possible option 2 is to direct steam to a separate low-pressure turbine. Due to presence of additional turbine (with auxiliary equipment) option 2 is less economically competitive than option 1.

Besides producing electricity using steam from TES, SMR can use TES to directly provide heat to various processes. For example, two-tank TES can be used for district heating. Typically, hot water tank (as explained in Section 4.2.2 - Hot and cold water.) heat storage is applied for that purpose. Essentially, the principle of hot/cold water TES operation is similar to two-tank system, the difference is using water as storage medium instead of thermal oil/molten salt. For district heating, the system would utilize heat that might otherwise be wasted, or steam discharge out of the low-pressure part of nuclear turbine.

It should be noted that two-tank TES can be also coupled with advanced modular reactors. In case of high-temperature reactors molten salts as storage medium can be recommended.

4.2.7 Main system architecture and operating data

The performance of a TES depends on the connection point to the steam side of turbine. TES charge can be done by providing high pressure steam at connection point before high pressure cylinders of turbine, or by low pressure steam after high pressure cylinders of turbine, or by combination of high-pressure and low-pressure charging for two TES stations.

TES discharge can be done using capacities of main turbine (primary steam Rankine cycle) or using dedicated turbine for TES (secondary steam Rankine cycle).

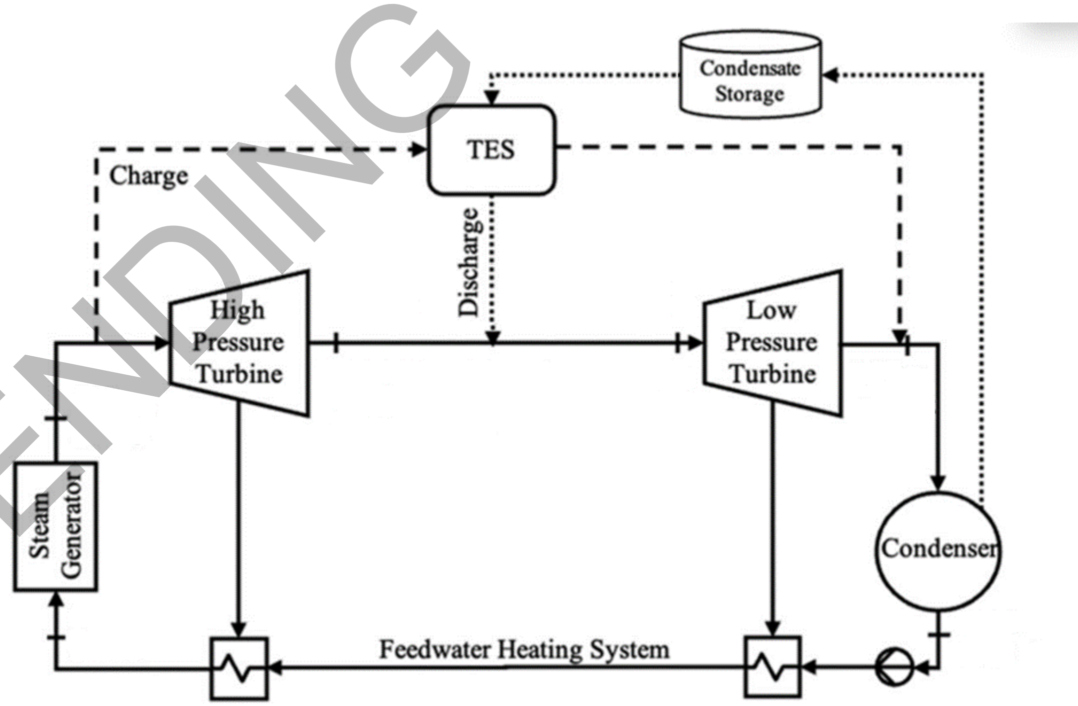
As starting (simplified) point for modelling at MODELICA, the first option - primary steam Rankine cycle by high pressure charging - is recommended, see *Figure 21* (a). TES unit at *Figure 21* consist of several principal parts: hot tank, cold tank, pumps and heat exchangers (see *Figure 22*).

Main operating data for TES is presented in Table *13*.

Parameter	Thermal oil (therminol 66)
Density (kg/m^3) at 260 °C	840

Parameter	Thermal oil (therminol 66)
Specific heat (kJ/kg-K) at 260 °C	2.42
Thermal conductivity (W/m-K) at 260 °C	0.0993
Operating temperature (°C)	-2.7 ÷ +343,3
Viscosity (mPa-s)	0.529
Boiling point (°C)	358
Heat Storage (Wh/m^3 ◦C)	1039
Levelized cost of storage (€/kWh) (Cascetta et al., 2021)	0.447

Table 13 – TES data.



(a)

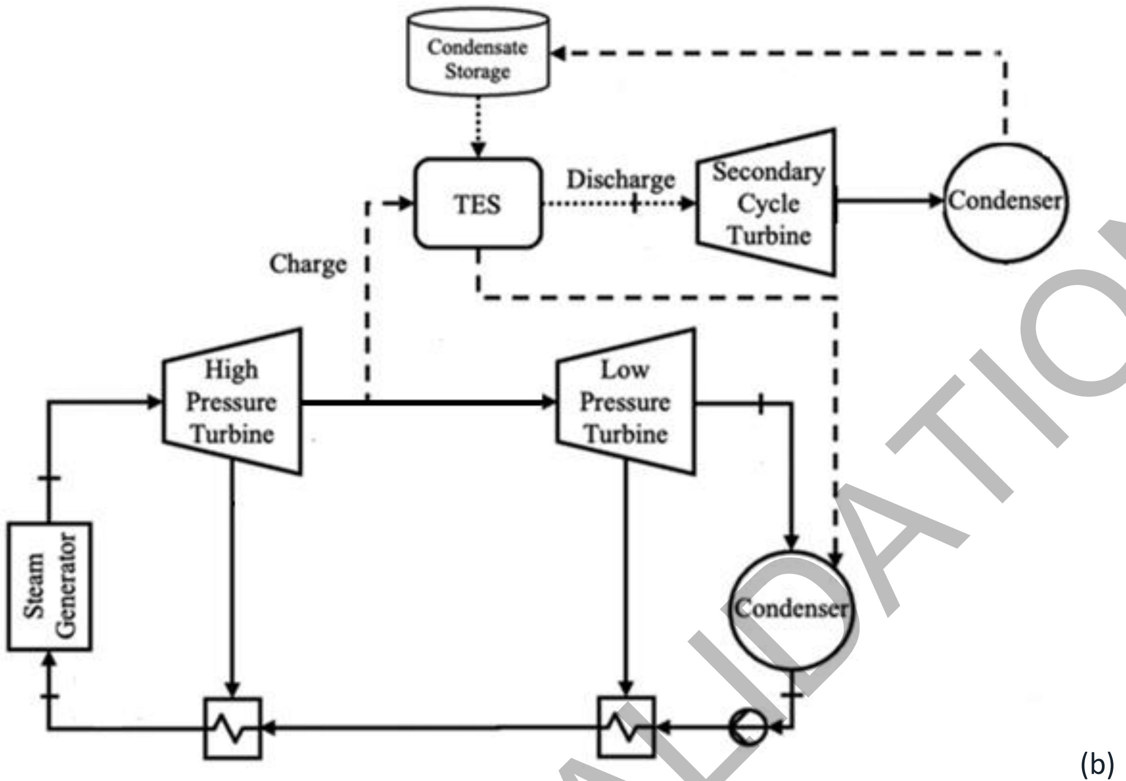


Figure 21 - TES connection to turbine cycle (created by ENERGORISK in the scope of the TANDEM project).

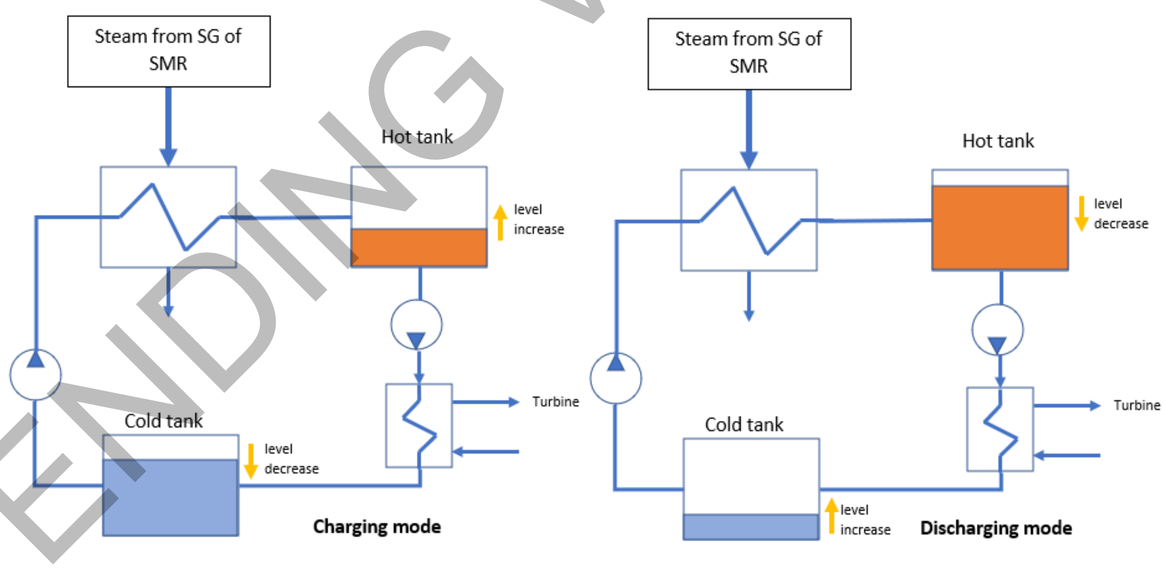


Figure 22 - TES simplified architecture with charge and discharge mode (created by ENERGORISK in the scope of the TANDEM project).

The pump located after cold tank operates at full power at any time, in order to extract always the same nominal power from nuclear core that operates at base load. Conversely, the pump located after hot tank is characterized by a variable power, resulting in a variable mass flow rate

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in the heat exchanger and thus in a variable power transmitted to the turbine. During TES charge mode (heat storage), hot tank pump provides lower mass flow rate than the cold tank pump, or even stopped to decrease charge time to full tank. In fact, a minimum mass flow rate is required depending on the steam supply mode from SMR. If there is uncontrolled steam supply with constant rate, then a certain flow rate from the hot tank pump is needed, e.g., to provide heat sink and to prevent the hot tank overflow. In opposite case, when we can decease steam supply (using control valve or steam dump valve) to TES, pumps can be stopped. In case a minimum flow rate is foreseen, the storage medium (thermal oil) level at hot tank increased, while the level decreased at cold tank. During TES discharge mode (heat release), hot tank pump provides higher mass flow rate than the cold tank pump. Thus, the storage medium level at hot tank decreased, while the level increased at cold tank.

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5. Hydrogen Production

Although hydrogen is colourless gas, there is colour classification of hydrogen depending on hydrogen extraction processes. Hydrogen produced by using nuclear energy is often called as pink hydrogen.

Conventional production of hydrogen predominantly uses steam-methane-reforming. However, its advantage has been severely decreased due to increase of hydrocarbons (methane) cost as well due to need to sequester co-produced CO_2. Operating at very high capacity factors, nuclear energy is well positioned to produce zero-carbon hydrogen as a new energy carrier with a wide range of applications. This is strengthening the economic reasons for producing pink hydrogen.

There are several pilot projects ongoing worldwide to prove the technical feasibility and economic benefits of pink hydrogen production, which could facilitate future opportunities for large-scale commercialization. For example, construction and installation of a low-temperature electrolysis systems at the Nine Mile Point NPP, Davis-Besse NPP and Palo Verde NPP at USA is ongoing, first pink hydrogen in USA is expected by 2023, see e.g., (NINE,2022). Research and design activities to develop hydrogen production system that uses small modular reactors are also ongoing in several countries. Using small modular reactors could help balance and stabilize power grids dominated by renewable energies by producing hydrogen. Hydrogen could be used as an end-product at times when energy demand is high and renewable energy production is low, or as a stored energy source to be processed through a reversible solid oxide fuel cell for electricity generation (WNN, 2022).

Hydrogen production technologies include several processes: steam reforming of natural gas, catalytic decomposition of natural gas, partial oxidation of heavy oil, coal gasification, water electrolysis, thermochemical cycles, and photo-chemical, electrochemical and biological processes. The first four processes are based on fossil fuels, while water electrolysis and thermochemical cycles can be used for pink hydrogen production. Nuclear power can be used in the following main processes (WNA, 2021):

- Cold electrolysis of water, using off-peak capacity (needs 50-55 kWh/kg H_2),
- Low-temperature electrolysis, using heat and electricity from nuclear reactors,
- High-temperature steam electrolysis, using heat and electricity from nuclear reactors.,
- High-temperature thermochemical production using nuclear heat, which temperature input (around 800 °C) is higher than the what is made available by a LW-SMR.

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In addition, nuclear heat can assist the process which provides most of the world's hydrogen today:

- Use of nuclear heat to assist steam reforming of natural gas (methane).

Regarding LWR (and LW-SMR), low-temperature and high-temperature electrolyses are options compatible with the reactor technology. Low temperature electrolysis uses electricity exclusively to split water into hydrogen and oxygen. The current low-temperature electrolysis technologies include:

- alkaline,
- proton exchange membrane (PEM),
- anion exchange membrane (AEM).

5.1 High Temperature Steam Electrolysis

This section quickly presents the High Temperature Steam Electrolysis (HTSE) technology and, in the framework of the coupling with a SMR within a Hybrid Energy System (HES), formalizes its:

- scope, global architecture and Inputs & Outputs,
- data for operating conditions and specifications for the system level at the HTSE scope boundaries,

to be used for its modelling in the WP2. First, it must be mentioned that the HTSE modelling may evolve along the project, following hypothesis modifications and exchanges between all the WPs. For this reason, in this section only general information are provided, whereas further data useful for the HTSE modelling will be directly provided within WP2.

The High-Temperature Steam Electrolysis technology 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 steam produced by the LW-SMR (i.e., though thermally coupling the HTSE system with the NPP through the Balance Of Plant).

Moreover, it must be mentioned that this technology is relevant for both the short-term (target 2035) and long-term (2050 and beyond) since, based on its maturity level, it is expected to further evolve and improve in terms of efficiency and effectiveness. However, this technology has a

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relatively low maturity compared to Alkaline or PEM, especially at system level (and its interactions with the core technology), thus hypothesis have to be taken, which could be modified along the technology development.

5.1.1 Technology Description

HTSE is intended to participate to the energy decarbonization by massive hydrogen production, and at a better energy efficiency than low temperature water electrolysis technologies.

The better energy efficiency comes from the energy gain with gas phases (i.e., water vapour):

- At low temperature: ΔH° = 285.84 kJ/mol,
- At high temperature: ΔH° = ~250 kJ/mol.

In this reaction, the reaction enthalpy

$$\Delta H = \Delta G + T\Delta S$$

is almost constant, equal to almost 250 kJ/mol at 650-850°C, which is the high temperature range to be considered for HTSE (ΔG decreases with T, and TΔS increases with T).

The main technology that is taken as reference for the HTSE system is the Solid Oxide cell as the electrolyzer core technology. This type of technology, indeed, is already used in some industrial markets.

Nevertheless, the HTSE technology has lower maturity than low temperature water temperature electrolysis technologies as stated previously. At the moment, there are several research institutions that are investing in the HTSE technology (e.g., INL, Karlsruhe Institute of technology, CEA, etc.) and also some industries like Sunfire, SolidPower and GENVIA.

In literature, some references can be considered which cover the HTSE technology coupled with nuclear power plants, e.g., the work by Frick et al. (2019) which assess the coupling of a HTSE with an NPP using the LW-SMR technology (NuScale Power SMR).

In the frame of EU projects, another project assessing the same technology and its coupling with nuclear applications is the NPHyCo project (see the NPHyCo official website). NPHyCo is an EU research project dedicated to the production of hydrogen from nuclear power. The latter initiative will focus on the potential for developing large scale, low-carbon, hydrogen production facilities linked to nuclear power plants. It will start by assessing the feasibility of producing hydrogen near an existing nuclear power plant as well as the added value of such project.

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Furthermore, it will look at potential locations where a pilot project could be implemented. Another project that could be taken as reference is GEMINI4.0 project (see the GEMINI4.0 website), which deals with HTR and hydrogen production coupling.

Solid Oxide Electrolyser

In a Solid Oxide Cell electrolyzer (SOEC), water is electrochemically reduced at the cathode (producing dihydrogen) and oxygen is produced at the anode (Figure *23*).

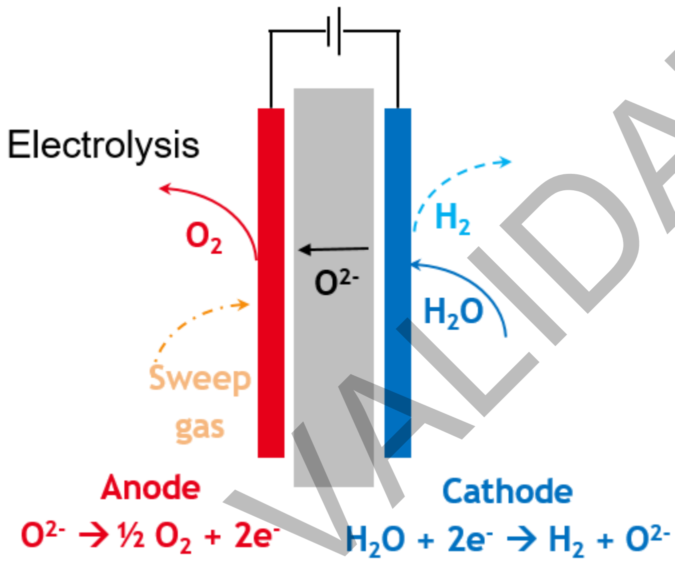

Figure 23 - SOC electrolysis reactions at anode and cathode (created by CEA in the scope of the TANDEM project).

Figure 24 presents the general scheme of a high temperature electrolyzer producing hydrogen from steam. In this specific case of HTSE, the current collecting and fuel/air flows distribution are ensured by using additional elements called interconnects.

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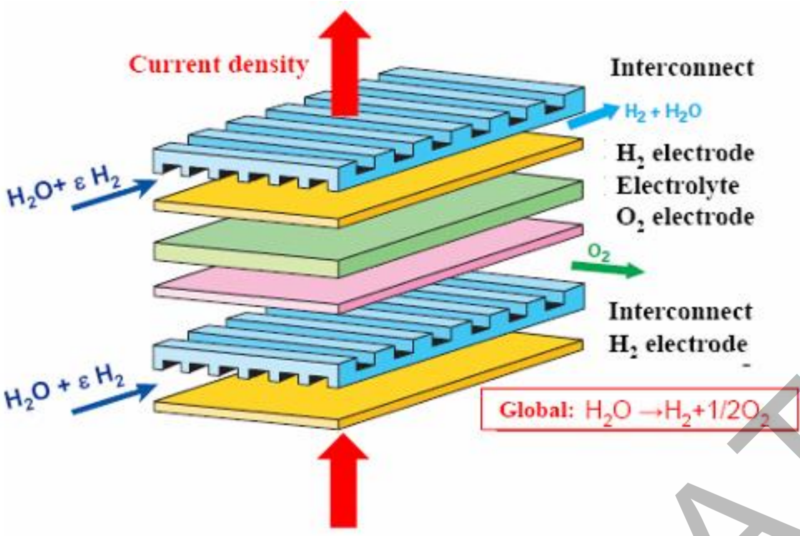

Figure 24 - General scheme of a high temperature electrolyzer (from University Of Cambridge website).

HTSE is realized with Solid Oxid cells (SOC) electrolyte, generally made of ceramics.

The SOC is an electrochemical converter (with a reversible operating capability):

- Electrolyzer mode: combined inputs of electrical energy and heat, to produce H_2 and O_2;
- Fuel Cell mode: H_2 and air are used, to produce electricity (and heat).

The ceramics used in Solid Oxide Cells do not become significantly electrically and ionically active until they reach high temperatures (several hundred Celsius degrees, with the temperature level depending on used materials and targeted performance). Steam is oxidizing for the Ni material of the fuel side, used as an electrical conductor. Thus, in order to remain in a reducing atmosphere, a minimum concentration of hydrogen shall be present at the stack fuel-side entrance. The hydrogen concentration at the stacks' inputs level may come from the hydrogen production itself, for instance thanks to a recirculation loop. In the electrolysis mode, SOEC cells are targeted to operate as in thermo-neutral mode, at the thermo-neutral voltage, which is a pure thermodynamics voltage (i.e., it does not depend on the cell technology and materials). *Figure 25* shows the Voltage-Current operating curve of a SOEC, which generally depends on different parameters (e.g., cell temperature, inlet steam flow rate, hydrogen concentration in inlet flow rate, etc.).

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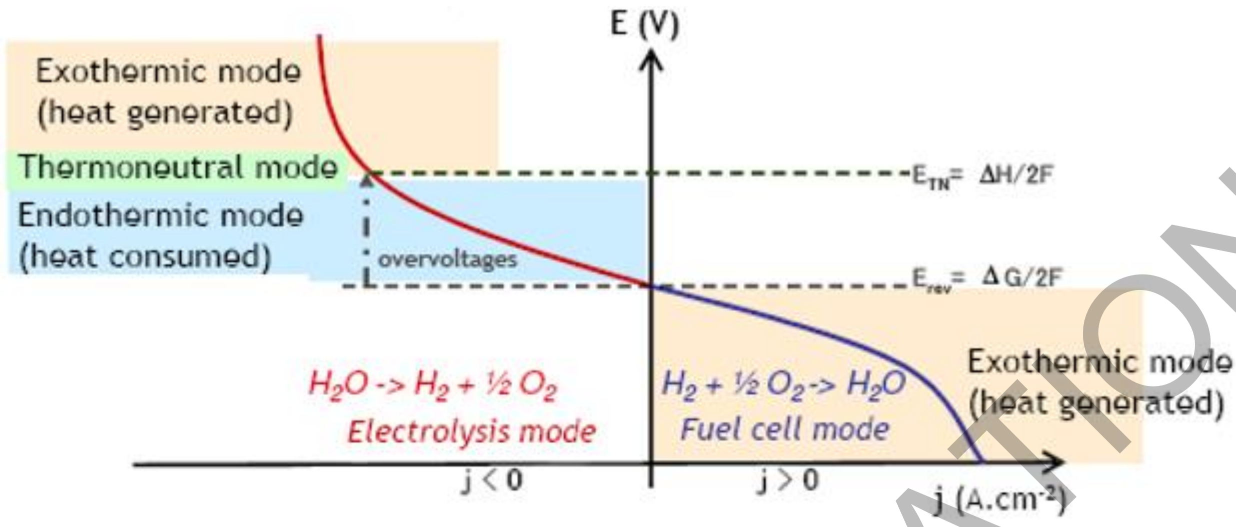

Figure 25 – Current-Voltage cell performance curve (created by CEA in the scope of the TANDEM project).

Figure 26 presents the global architecture of the HTSE subsystem scope, with their inputs/outputs from/to the other parts of the system (SMR + HES +BOP). The confinement where the SOEC stacks are inserted is called "Hot Box".

Dashed lines and text in *italics* represent optional parts (Air in circuit, and thus air heat exchanger and electrical heater, fuel recirculation loop) as it is explained in the next section.

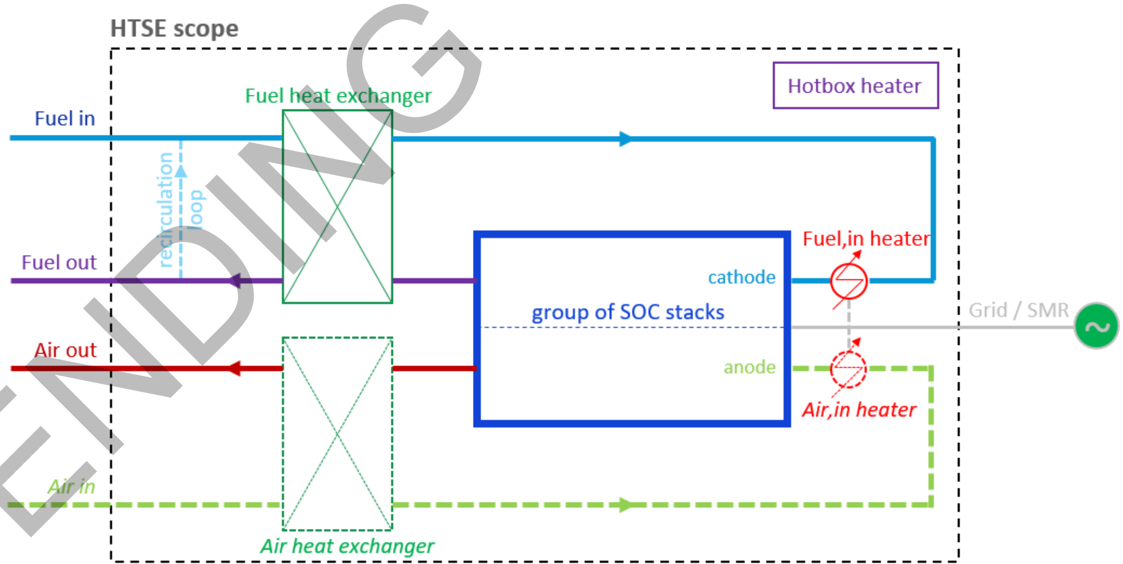

Figure 26 - Example of HTSE architecture scheme that might be addressed (created by CEA in the scope of the TANDEM project).

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5.1.2 Component coupling with the HES

HTSE technology can be considered a very useful way to have a massive production of hydrogen at a better energy efficiency than low-temperature technologies. For the modelling purposes, directly considered by WP2, it is suggested to have a 1D modelling in order to calculate flow conditions along the gas circuit (between HTSE components).

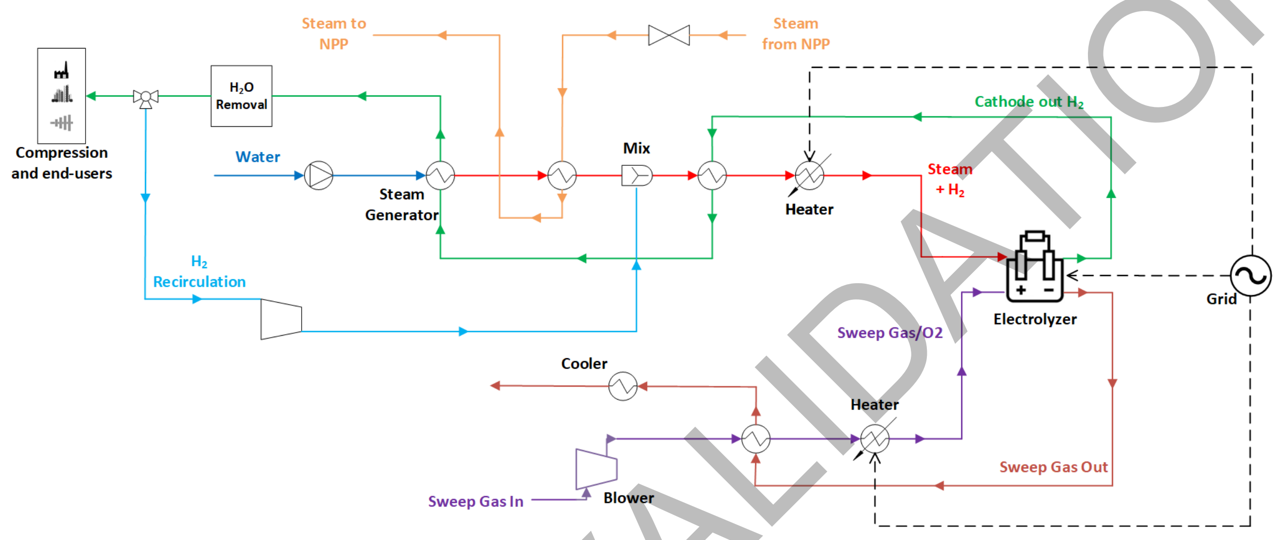

Figure 27 - General layout of a High Temperature Steam Electrolysis plant coupled with an NPP (created by ANN in the scope of the TANDEM project).

The HTSE system can be coupled with the NPP following the general scheme presented *in Figure 27*. As it can be seen from reported sketch, the thermal coupling with the NPP could be made through a heat exchanger supplied with the steam coming from the BOP which will help in the production of the feedstock steam to be sent to the Solide Oxide Electrolyzer, starting from raw water input.

Moreover, the HTSE system has a connection to the electrical grid as well, since some electrical energy is needed to perform temperature topping of the feedstock streams via electricity and, as well-known, to directly supply the SOEC which needs electricity to split the water molecules.

Obviously, some differences may be foreseen with respect to the architecture shown in *Figure 27*:

- Considering the inlet streams of water steam and hydrogen, the hydrogen concentration is provided via a recirculation loop. However, the recirculation loop could be avoided as well, though in this case a hydrogen storage must be foreseen from which hydrogen is sent in the SOEC stacks together with the steam. The two solutions must be carefully assessed as both of them may depend on the final uses of hydrogen as well as on safety aspects. The optional fuel recirculation loop involves dedicated compressor, valve and pipes. In this case, another heat exchanger is also possibly added to cool down the hydrogen flow before the compressor. Additionally, also other components for the hydrogen treatment (purification, drying by cooling, etc.) and compression (up to a given pressure level, with water condensates evacuation if required).

- Concerning the sweep gas inlet, instead, it is optional. The chemical reaction of the SOEC, indeed, does not require oxygen as a reactant (see again Figure *23*). However, oxygen is required if the electrolyser is considered to be reversible (i.e., it can work both as electrolyser and as a fuel cell). In the latter case, the sweep gas inlet must be foreseen.

5.1.3 Main operating data

Supposing that all stacks operate at the same operating point, the Faraday's law links the hydrogen production molar flowrate to the current crossing the stacks:

$$Q_{H_2}[mol/s] = \frac{N_{cell} \cdot I_{stack}}{2F}$$

With:

- N_{cell}: total cells number (of the whole system)
- I_{stack}: stack current [A]
- F : Faraday constant = 96485 C/mol

The dissociated water steam molar flowrate equals the hydrogen production molar flowrate because of the stoichiometry reaction indicated in Figure *23*. Then, the produced hydrogen (or dissociated water steam) molar flowrate can be easily transformed as mass flowrates, using the H_2 and H_2O molar masses [kg/mol].

Finally, the required water steam flowrate is also linked to the Steam Utilization (SU), also called Steam Conversion, SC, defined as:

$$SU = \frac{Q_{H_2}}{Q_{steam,in}}$$

where $Q_{steam,in}$ and Q_{H_2} are, respectively, the water steam molar flowrate and the produced hydrogen molar flow rate both in mol/s. For what was mentioned above, the Steam Utilization can be also defined as:

$$SU = \frac{Q_{H_2O,diss}}{Q_{steam,in}}$$

Being $Q_{H_2O,diss}$ the dissociated water steam molar flow rate. Usually, SU is in the range 40 - 60%. Table *14* lists the main Operating Conditions of a Solid Oxide Electrolyzer Stack.

Condition	Current design	Projected ~2035 design
Cell Temperature [°C]	min ~650 – max ~850	
Operating Pressure [bar abs] (at stack inlet)	1.1 – 1.2	5 – 10
Cell nominal current Density [A/cm^2]	0.5 – 1	2
Minimum **H_2** concentration at the stack fuel-side entrance [%vol]	10	possibly < 10
Cell surface [cm^2]	200	200 (to be confirmed)
Cell voltage [V] stabilized functioning at the thermo-neutral voltage	~1.29	
SC (Steam Conversion rate) [%] defined as: (Q_ **H_2O**_out - Q_ **H_20**_in) / Q_ **H_20**_in	60 – 70	>80
Pressure difference "Air - Fuel" [mbar] considered at the stack outlet	~30	Not Applicable
Steam quality (deionized specification)	To be defined	To be defined

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Energy consumption [kWh/kg_ H_2] / [kWh / Nm³] (at thermo-neutral voltage)	~35 / ~390
Degradation and Lifetime	treated in the next section

Table 14 - Main Operating Conditions of a Solid Oxide Electrolyzer Stack.

From a preliminary point of view, in order to model the HTSE, the following consideration shall be considered:

- Inlet fuel stream (i.e., water steam and hydrogen):
    - Minimum temperature (in order to prevent condensation in pipes): 130°C;
    - The water steam and hydrogen flowrates depend on:
        - The maximum reactor power percentage planned to be used to produce hydrogen;
        - The conditions of the steam bled from the BOP and used to heat up the feedstock steam to be sent to the SOEC;
        - The HTSE architecture definition and operating conditions concerning the hydrogen production flowrate, which in turns depends on these variables:
            - Cell current density [A/cm^2] x cell surface [cm^2] x cells number,
            - Steam Utilization SU,
            - recirculation loop and its functioning point if present (H_2 re-injected upstream the stacks),
            - Note that it should depend on the maximum reactor power percentage foreseen to be used to produce hydrogen.

- Inlet air stream:
    - No specific criterion on the air temperature at the inlet of the HTSE scope (see again *Figure 26*), except for stacks thermo-mechanical resistance. Of course, inlet air to the SOEC stacks must be as close as possible to the operating temperature of the SOEC itself;
    - The air flowrate is mostly linked to the water steam flowrate, and process components pressure losses, in order to respect the pressure difference "Air - Fuel" criterion indicated in Table *14*;

- Grid electrical connections:

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- DC for stacks power delivery (consistently to the H_2 production flowrate), with a considered efficiency AC/DC converter (e.g. 95%);
- AC for gas heaters to maintain Fuel and Air gas temperature around the SOEC operating value;
- AC for HTSE other components (compressors, blowers, pumping systems, etc.).
- Another connection must be foreseen for the “Hotbox heater” depicted in *Figure 26* in order to keep the temperature of the SOEC stack close to the operating point during stand-by phases (i.e., to compensate only the thermal losses).

5.1.4 Degradation

Stack degradation is the on-going subject of massive investigation by all actors involved in the technology. There are many different degradation mechanisms, among which are:

- cell microstructure evolutions,
- unwanted oxidation,
- chemical growth of insulation layers,
- poisoning.

The consequences of degradation range from decreased electrical performances, decreased maximum current and/or steam conversion, seal and/or cell breakage, etc.

In electrolysis mode, SOEC stacks are preferably operated at the thermo-neutral voltage (~1.29 V at ~800°C), which is a stable equilibrium and permits easier thermal management. In order to stay at the thermo-neutral voltage, due to degradation, stack temperature needs to be increased as qualitatively shown in *Figure 28*.

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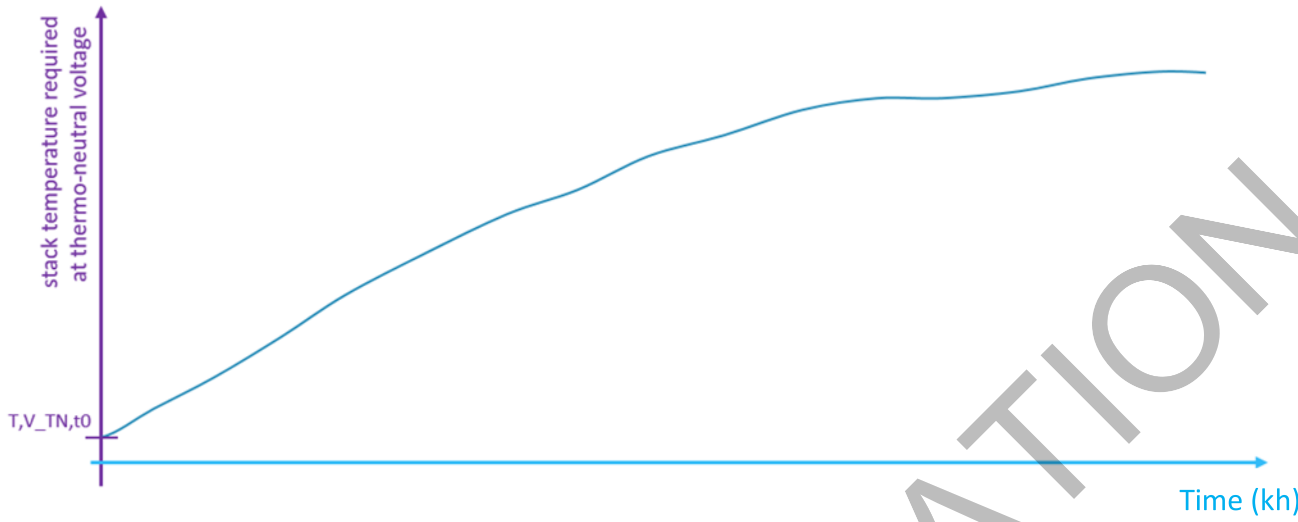

Figure 28 - Thermo-neutral temperature evolution as a function of time (created by CEA in the scope of the TANDEM project).

Apart from the optimal operating temperature that permits to have the thermo-neutral voltage in the SOEC stacks, they can be operated up to a given defined maximum temperature (which depends of the used material, and the cell/stack/module designs). For instance, the maximum temperature for elcogen cells used in CEA stacks is 800°C.

To conclude, degradation implies to operate stack according to this usage profile:

Considering a new SOEC stack, the operating temperature must be increased with time in order to continuously operate at the thermo-neutral voltage. The increase in temperature will stop when the maximum stack temperature will be achieved. After reaching the maximum temperature, the current density needs to be decreased in order to keep constant the voltage equal to the thermo-neutral value.

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5.2 Low Temperature Electrolysis

5.2.1 Alkaline Electrolysis

Alkaline electrolyser utilizes a pair of electrodes (the cathode and anode) submerged in an aqueous alkaline solution, usually containing either potassium hydroxide or sodium hydroxide. The electrodes are commonly separated by a porous diaphragm that allows hydroxide ions to migrate but prevents the hydrogen that is produced at the cathode from mixing with oxygen that is produced at the anode, see Figure *30*. Alkaline electrolysers are suited for stationary applications and are available at operating pressures up to 25 bar. Commercial alkaline electrolysers operate at 100°–150°C. Alkaline electrolysis is a mature technology, with a significant operating record in industrial applications, that allows remote operation. Process diagram of alkaline electrolysis is presented at Figure *29*.

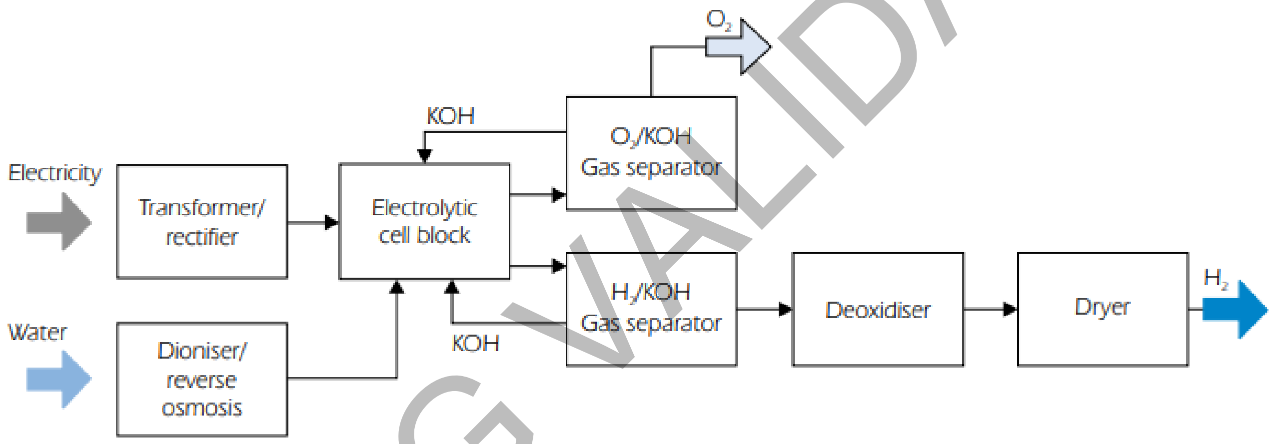

Figure 29 - Process diagram of alkaline electrolysis (IEA, 2006).

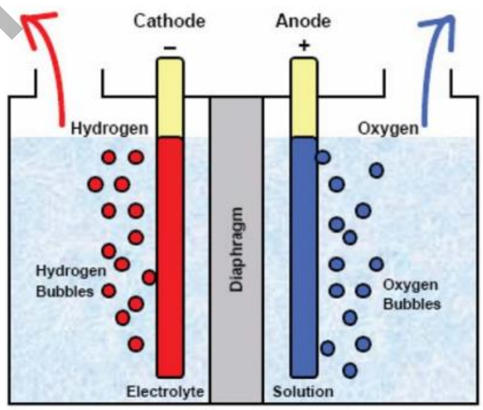

Figure 30 – Principle of alkaline electrolysis (IAEA, 2013).

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As noted by (Hongmei and Baolian,2018), the insoluble carbonate clogs the porous catalytic layer, hindering the transfer of products and reactants and greatly reducing the performance of the electrolyser. Furthermore, it is difficult to quickly initiate or shut down an alkaline electrolyser, and it is also difficult to adjust the rate of hydrogen production quickly. This is because the pressures at the anode and cathode of the electrolyser must be kept constant to prevent the infiltration of hydrogen and oxygen gases through the porous asbestos diaphragm, as the mixing of these gases will result in an explosion. So, alkaline electrolysers are not easily compatible with energy sources with rapid fluctuations in power output.

5.2.2 Polymer Electrolyte Membrane

PEM electrolysis (see Figure *31*), also referred to as proton exchange membrane electrolysis, is a newer technology that is related to PEM fuel cells. A PEM electrolyser is literally a PEM fuel cell operating in reverse mode (NAE, 2004). PEM electrolysers require no liquid electrolyte, which simplifies the design significantly. The electrolyte is an acidic polymer membrane that allows protons to cross between the electrodes and prevents mixing of the produced hydrogen and oxygen. This membrane design allows for hydrogen production at up to 20 MPa (thus avoiding or reducing energy intensive compression of the gas). The membrane typically includes a catalyst such as platinum or a platinum group metal to catalyse water splitting, making it a higher cost option than alkaline electrolysers.

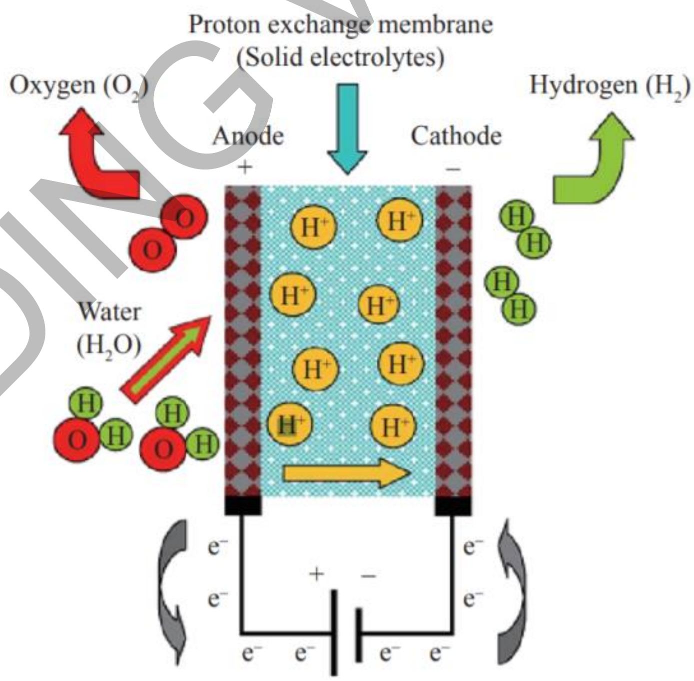

Figure 31 – Principle of PEM electrolysis (Hongmei and Baolian, 2018).

The main drawback of this technology is the limited lifetime of the membranes. The major advantages of PEM over alkaline electrolysers are the higher turndown ratio, the increased safety due to the absence of KOH electrolytes, a more compact design due to higher densities, and higher operating pressures (IEA, 2006).

In a report by IAEA (IAEA, 2022) it can be read that "*PEM electrolysers have higher current densities, allowing them to adapt to rapid changes in power that could be caused by a tightly coupled nuclear–renewable HES that is following grid signals. Rapid fluctuations in loads or generation (such as those that might be caused by wind or PV solar generation) can create variability on the grid that requires quick responses from load following entities. Since the only energy supply to LTE systems is electricity, electricity is the integration point. Within a tightly coupled nuclear–renewable energy system, the electricity could be generated from either renewable or nuclear energy, or both. PEM electrolysers can provide frequency control and voltage regulation because of their ability to ramp very quickly).*"

PEM electrolysers can further be fully shut off very rapidly and can be put through very rapid cold starts; thus, they do not require a continuous electricity source. In addition, because electrolysers are modular, the manufacturing process can be scaled. Such scaling is unlikely for thermochemical processes.

At an average electricity requirement of 50 kWh/kg hydrogen produced, electrical capacity of 100 MW could produce 48 000 kg/day. The larger electrolyser systems (>1 MW/stack) use alkaline technologies, but PEM electrolyser systems of 1 MW(e) and higher – 1.25 MW are now also being marketed (Schmidt et al., 2017), including use of nuclear energy (NINE, 2022; Kim et al., 2022).

5.2.3 Anion Exchange Membrane

As an alternative to water electrolysis, the AEM method combines the merits of alkaline and PEM electrolysis into a single cell. The reaction is composed of two half-cell reactions. Water is passed through the anode and two electrons are added to produce hydrogen and hydroxyl ions. Thus, the hydroxyl ions diffuse to the anode portion of the AEM through positive attraction, whereas electrons move through the external circuit to the anode portion. In the anode chamber, the hydroxyl ions are recombined with oxygen and water through the loss of electrons. By forming bubbles on the anode's surface, oxygen is released. During both half-cell reactions, the electrode surfaces must be actively catalysed in order to generate and release the corresponding gases.

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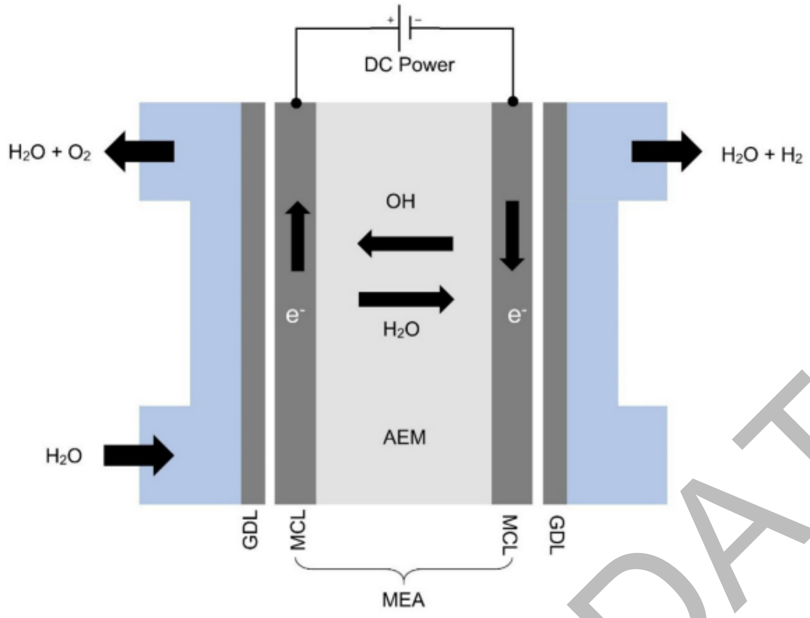

Figure 32 – Principle of AEM electrolysis (Agyekum et al., 2022).

Figure *32* shows the work principle of the AEM. It takes 1.23 V of theoretical thermodynamic cell voltage to split water into hydrogen and oxygen at 25 C. For efficient hydrogen production, however, the cell voltage must be higher than 1.23 V. Electrolyte and electrolyser components must have additional voltage in order to overcome the ohmic and kinetic resistances (Chand and Paladino,2023).

5.2.4 Comparison of Technologies

General performance metric for different LTE is presented in Table *15*, based on (Pozio et al.,2021, Li et al., 2022, Wang et al.,2022, and Schmidt et al.,2017).

	Alkaline	**PEM**	**AEM**
Electrolyte	20-30% KOH	Acid membrane	Alkaline membrane
Charge carrier	OH	H^+	OH^-
Catalyst	Ni, Co, Fe	Pt, Ir, Ru	Ni, Co, Fe

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	Alkaline	PEM	AEM
Temperature, °C **(typical parameters)**	65-100 (70-90)	20-200 (90)	50-70
Pressure H_2, bar	25-30	30-80	30
Current density, mA cm^{-2} (typical parameters)	200-500 (400)	800-2500 (2000)	200-500
Durability, h	90.000	20.000	N/A
Purity of H_2, vol%	99.3-99.9	99.9999	99.99
Efficiency, %	62-82	67-82	81-92
Hydrogen production, Nm^3 h^{-1}	1-760	0.265-30	0.25-1
Energy consumption, kWh Nm^{-3}	4.5-5.5	4.2-6.6	5.2-4.8
Power, kW	2.8-3534	1.8-174	1.3-4.8
Cell voltage, V	1.8-2.4	1.8-2.2	1.6-2.0
Cell area, m^2	Up to 4	0.13	0.03
Response time	Minutes	seconds	
Hydrogen production system cost, €/kg	1300-800	2000-1200	N/A

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	Alkaline	PEM	AEM
Technology status	Mature	Mature	Developing
Advantage	Not depend upon a noble metal catalyst for the hydrogen production Easily handled due to the relatively low temperatures	Fast response and start-up, high purity of H_2, PEM electrolysis offers safety due to the absence of caustic electrolyte. Possibility of using high pressure on the cathode side, while the anode can be operated at atmospheric pressure	Combination of merits of Alkaline and PEM electrolyses
Disadvantage	Corrosive electrolyte, gas crossover, low current densities	High cost of PEM and noble metals, acidic corrosion environment, limited durability	Low OH- conductivity and efficiency, limited durability and small stack scale

Table 15 – Technical data of LTE.

Considering the abovementioned data (maturity, technical parameters on efficiency/ hydrogen purity, possible coupling nuclear-renewables-hydrogen, advantages), PEM technology can be recommended for modelling.

It should be noted that PEM technology was recently evaluated by the Horizon 2020 project, NEPTUNE "Next Generation PEM Electrolyser under New Extremes". The NEPTUNE project developed a set of breakthrough solutions at materials, stack and system levels to increase hydrogen pressure to 100 bar and current density to 4 A/cm^2 for the base load, while keeping the nominal energy consumption <50 kWh/kg H_2. The project scope also included techno-economic analysis and an exploitation plan to bring the innovations to market.

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5.2.5 Component Coupling with HES

Principal scheme of LTE coupling with SMR is presented in *Figure 33*.

For the TANDEM project purposes, LTE can be modelled as a unit or at configuration as it shown on *Figure 34*.

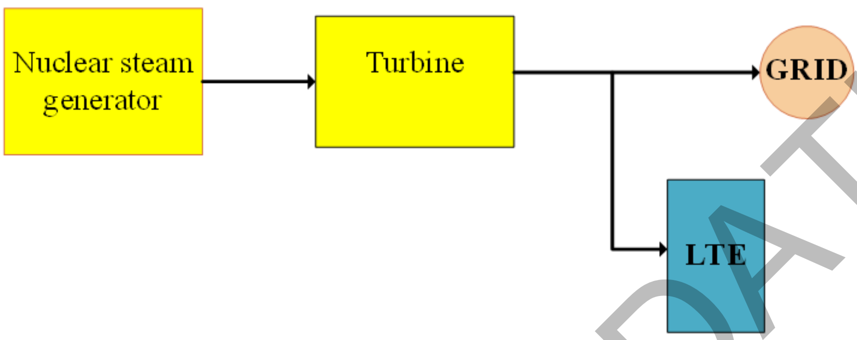

Figure 33 – LTE coupled with the SMR (created by ENERGORISK in the scope of the TANDEM project).

5.2.6 Main System Architecture and Operating Data

Architecture PEM electrolysis system is shown at *Figure 34*.

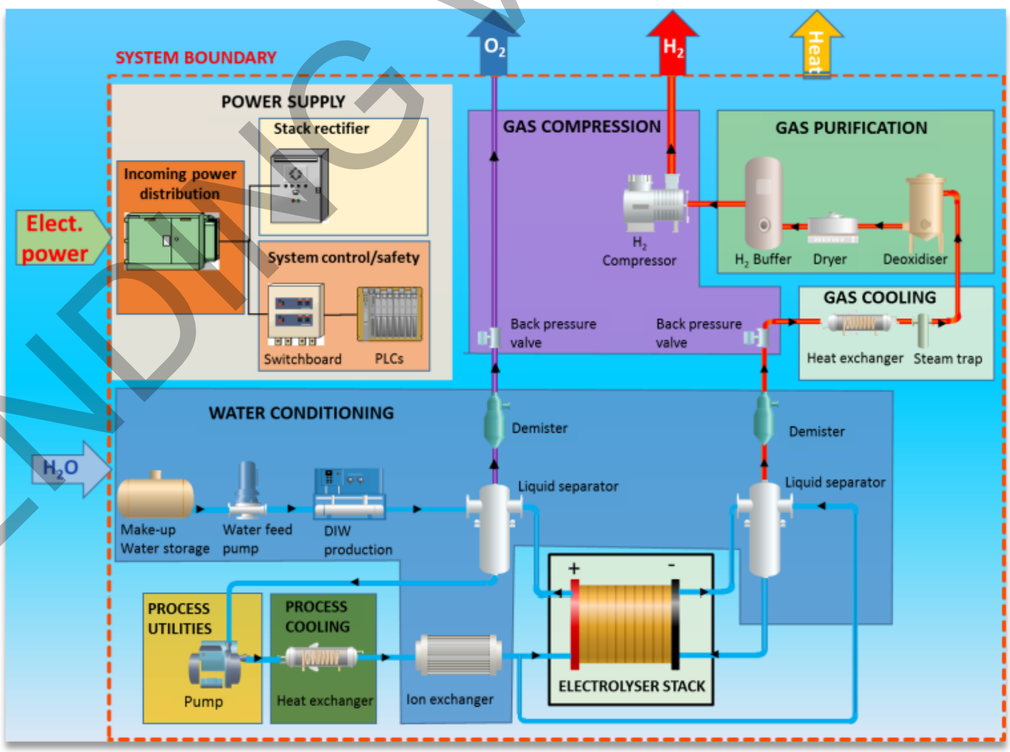

Figure 34 - PEM architecture (Tsotridis and Pilenga, 2018).

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The typical components of a PEM electrolysis system are the following (Tsotridis and Pilenga, 2018):

- Power supply, which includes: incoming power distribution, which consists of the grid connection and transformer to adjust the electricity from the energy source to the operational requirements; rectifier for stack operation; system control board for other auxiliary components of the electrolysis system, including an automatic control system to operate the system according to the manufacturer's specifications. It includes safety sensors, process parameter measuring devices, piping and valves, programmable logic controller (PLC), data input/output (data I/O), personal computer (PC);

- Water conditioning for the necessary treatment of the water supplied and recovered, composed of the following: make-up water tank; water feed pump; de-ionized water production unit; anodic circulation loop consisting of several components (water purification unit — mostly an ion-exchange resin bed — used to keep the water quality at the desired level, to minimize the risk of chemical contamination of the stack; oxygen/water separator vessel used for a first separation of residual liquid water in the gas outlet stream; demisters used for further removal of small liquid-water droplets from the gas outlet stream); cathodic circulation loop consisting at least of a hydrogen/water separator vessel and subsequent demister, and sometimes an additional circulation pump for defined thermal management of the cathode side;

- Electrolyser stack, which is the core of the system where water is electrochemically converted into hydrogen and oxygen by means of a DC current. It comprises one or more PEM stack(s) connected either in series or parallel mode;

- Process utilities consisting of the elements using power for the operation, such as the water recirculation pump enabling a continuous flow of water into the stack for the electrochemical reaction itself and for the thermal management of the stack; process-value-measuring devices (i.e. pressure sensor, flow meter, gas sensors);

- Process cooling consisting of heat exchangers for the thermal management of the pumped water to remove heat from the circulation loop and to keep the stack at the proper temperature range;

- Gas cooling consisting of heat exchangers for the thermal management of the gases produced during the electrolysis process;

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- Gas purification to clean the hydrogen product stream to the desired level of quality consisting of: de-oxidation stage, to recombine catalytically residual traces of oxygen that could be present due to crossover effects; gas dryer to remove residual moisture down to the parts per million (ppm) level; buffer tank for compensation of variable hydrogen production;

- Gas compression composed of the following: pressure control valve for hydrogen and oxygen to operate the electrolyser system at the desired pressure level (either pressure balanced or differential pressure); compressor, to bring the gas pressure to the specified value; high-pressure storage tanks for the final storage of the gas produced by the electrolyser.

A schematic layout that shows the working principle of the PEM electrolyser is shown in Figure *35*.

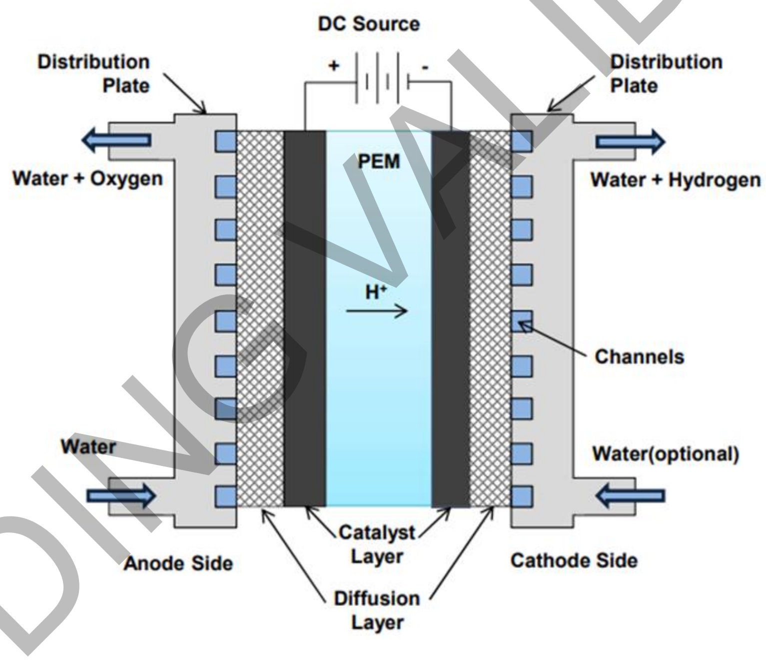

Figure 35 - PEM schematic layout (Sood et al., 2020).

The principle of PEM electrolysis is presented in the following equations:

anode: $$H_2O \rightarrow \frac{1}{2}O_2 + 2H^+ + 2e^-$$

cathode: $$2H^+ + 2e^- \rightarrow H_2(g)$$

overall: $$H_2O \rightarrow \frac{1}{2}O_2 + H_2(g)$$

Modern methods for PEM modelling are described in several recent sources, e.g., (Ma et al.,2021, Sood et al.,2020, Olivier et al.,2017, De Lorenzo et al.,2021, and Aubras et al.,2021).

Main operating data for PEM are presented in Table *16*.

Parameter	Value
Input electrical capacity for PEM system, MW(e)	≤ 1
Energy consumption, kWh/Nm^3	4.5
Hydrogen production, Nm^3/h	10-30
Production pressure, MPa	1.4
Temperature, °C	90
Water Consumption, l/kg H_2	10-11.1
Capital cost, USD/kg H_2 (DOE, 2020)	0.4
Capital cost, USD/kW (Christensen, 2020)	325-1781
Fixed operational and maintenance cost, USD/kg H_2 (DOE, 2020)	0.24

Table 16 – PEM data.

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6. Water Desalination

Water supply for population is already strong stake item all over the world and the situation will deteriorate due to the tensions generated by global warming. Geographers predicts that the major part of the population will live in a strip of land bordering the oceans.

In this context, desalination technologies will take an important part in the mix of solutions required to produce pure water for populations, industry and agriculture.

In the decarbonization context, energy supply by nuclear source for desalination plant, considering the massive quantity of energy required, makes sense.

The most commonly used desalination technologies are reverse osmosis (RO) and thermal processes such as multi-stage flash (MSF) and multi-effect distillation (MED). They are described in the following sections.

6.1 Sea Water Reverse Osmosis

Hybrid energy systems (HES) are capital intensive technologies that should operate at full capacities to maximize profits. Instead of wasting an excess generation capacity at negative profit during off peak hours when electricity prices are low, nuclear renewable HES could result in positive profits by storing and/or utilizing surplus thermal and/or electrical energy to produce useful storable products. Depending on the selected geographical location for TANDEM project, the surplus thermal and/or electrical energy could be used to produce fresh water by desalination.

Sea Water Reverse Osmosis (SWRO) is an energy-intensive technology with greenhouse gas (GHG) emission associated with fossil fuel energy use. Thus, there is an interest in both the greening of SWRO and reducing its specific energy consumption.

6.1.1 Technology Selection

Desalination technologies can be classified by their separation mechanism into thermal and membrane-based desalination. Thermal desalination separates salt from water by evaporation and condensation, whereas in membrane desalination water diffuses through a membrane, while salts are almost completely retained. To evaporate, heat and electricity are necessary, while membranes only need electrical energy and have a considerably low consumption. An overview of available desalination techniques is given in Table *17*.

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Thermal desalination technologies	Membrane based desalination technologies
Multi-stage flash distillation (MSF)	Reverse osmosis (RO)
Multi-effect distillation (MED)	Nanofiltration (NF)
Vapour compression distillation (VCD)	Electrodialysis (ED)

Table 17 - Applied desalination technologies.

The most commonly used desalination technologies are reverse osmosis (RO) and thermal processes such as multi-stage flash (MSF) and multi-effect distillation (MED).

The decision for a certain desalination technology is influenced by feed water salinity, required product quality as well as by site-specific factors such as labour cost, available area, energy cost and local demand for electricity.

In a report by the International Atomic Energy Agency (IAEA, 2007) based on country case studies showed that costs would be in the range (US$) 0.5 to 0.94/m^3 for RO, US$ 0.6 to 0.96/m^3 for MED, and US$ 1.18 to 1.48/m^3 for MSF processes. In Europe, reverse osmosis, due to its lower energy consumption has gained much wider acceptance than its thermal alternatives.

There are references in literature about coupling RO desalination plant in HES. The excess electricity from SMRs and renewable energy production park is used to power the desalination plant. A combination of a variety of desalination techniques (thermal or membrane in single or hybrid mode) have been shown to be successfully coupled with different types of nuclear power plants to produce water and electricity at different scales. Many countries are using nuclear desalination system which includes Kazakhstan, India and Japan.

6.1.2 Component coupling with the HES

Seawater desalination is expensive and energy-intensive and influences the environment, extremely. The use of the nuclear energy as an alternative to fossil fuel-based plants reduces the CO_2 emissions associated with desalinated water production.

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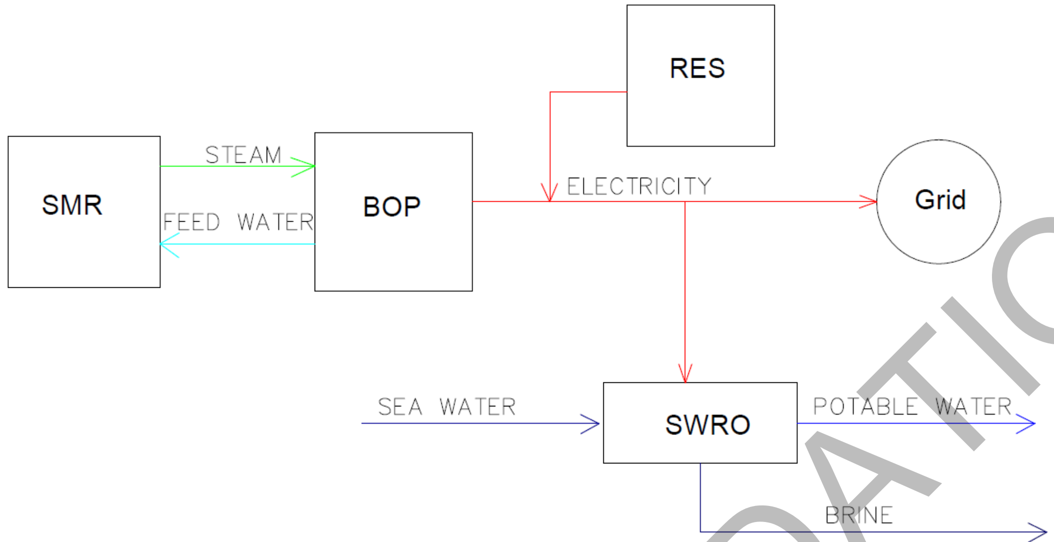

Figure 36 – SWRO coupled with the HES (created by EAI in the scope of the TANDEM project).

A 0D modelling is proposed, where the desalination plant is considered as a black box coupled to the HES with the use of the electricity generated by HES. *Figure 36* shows how this technology is coupled.

6.1.3 Main system architecture and operating data

The desalination plant can be used to produce not only the required potable water demand but also desalinated water and demineralized water required for various services of BOP.

RO process utilizes a semi-permeable membrane, which allows water to pass through but not salts, to separate the fresh water from the saline feed water. The desalination plant operates on automatic depending on the levels in the desalinated water tank.

This technology works better in continuous operation to avoid membrane flushing and chemical cleaning. Therefore, a minimum electrical consumption shall be considered to ensure that the RO plant is operated continuously with a minimum load, even when no renewable energy power is provided to the system.

Main components of the system

RO process utilizes a semi-permeable membrane, which allows water to pass through but not salts, to separate the fresh water from the saline feed water. As illustrated in

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Figure 38, a typical SWRO plant consists of five main components, i.e., feed water pre-treatment, high-pressure (HP) pumping, membrane separation unit, energy recovery system and permeate post treatment:

- Raw water pre-treatment includes all activities to adjust the intake water to the quality required by membranes. Usually this pre-treatment consists of a filtration stage where solid suspended are removed from the feed-water and chemicals are added to prevent scaling and fouling;
- The pumping system is required to overcome height differences within the distribution chain and to apply the necessary pressure to the feed;
- The membrane is capable of separating salt from water with a rejection of 98–99.5%, depending on the membranes in use;
- The energy recovery system (ERS) is responsible for the transfer of potential energy from the concentrate to the feed. Electricity has the highest share of reverse osmosis desalination costs. *Figure 37* shows the power breakdown for different stages of seawater reverse osmosis (SWRO). As it is obvious, the SWRO process has the most share in power consumption accounting for 68%.

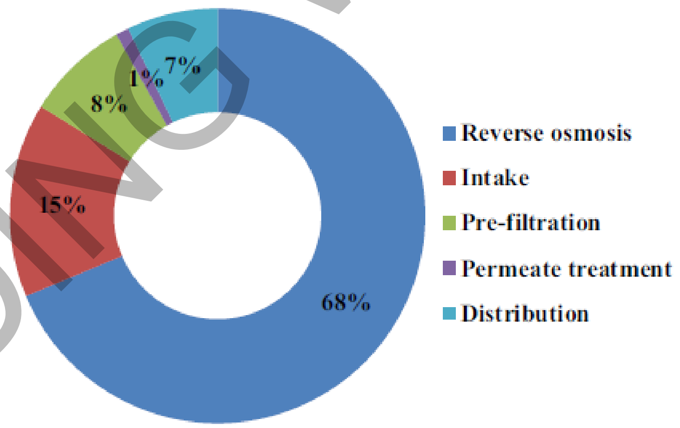

Figure 37 - The power consumption across applications or across different stages of SWRO (Esmaeilion, 2020).

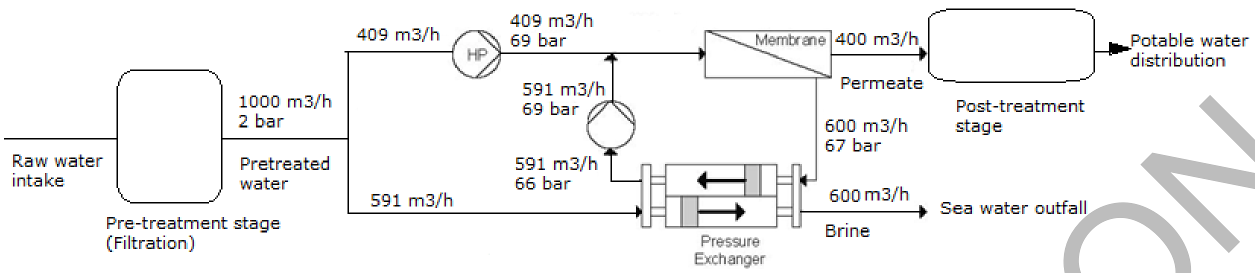

Figure 38 - Process scheme with pressure exchanger (created by EAI in the scope of the TANDEM project).

There are several technologies to recover this energy, and some of them are as follows:

- Energy recovery turbines (ERT): mostly based on the Pelton wheel;
- Pressure exchanger (PX): an isobaric device used to rotate a ceramic rotor and allow the direct impact of the feed and brine flows;
- Dual Work Exchanger Energy (DWEER): it is an isobaric device and uses a piston and valve to separate feedwater and saline;
- Turbo charger: a turbine to drive the centrifugal pump;
- In post-treatment permeate is re-mineralised, re-hardened, disinfected by chlorination and adjusted to drinking water standards.

The configuration of the RO (number of passes, stages, pressure vessels and RO elements) depends on the quality of raw water.

Figure 38 shows the process scheme of a RO desalination plant with a pressure exchanger as energy recovery device.

Main operating data

Main operating data that can be useful to assess the NHES are indicated in Table *18*.

Main Operating Data of a RO desalination plant	
Technical data	
Maximum operating temperature (°C)	45

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TDS in feed water (mg/l)	50-48,000
TDS in product water (mg/l)	< 500
Membrane type for RO desalination	- plate and frame - tubular - spiral wound - hollow fibre
SWRO recovery percentage (1st pass)	40-49%
Electricity consumption (kWh/m^3)	3-5
Production capacity (m^3/day)	0.4-70,000
Typical design life (years)	20-30
Economic data	
CAPEX, €/(m^3/h)	15,000-25,000 (Note 1)
OPEX fixed, €/(m^3)	0.08 (Note 2)
OPEX variable (€/m^3)	
- Chemicals	0.06-0.08 (Note 2)
- Replacement of membranes and cartridge filters	0.02-0.04 (Note 2)
NOTES Note 1: Estimated prices based on supplier information for large RO desalination plants (100,000-200,000 m^3/day). Costs of SW intake and brine discharge to the sea are not included. Note 2: Data obtained from Moser et al. (2014) and Corporation Corporacion Coquimbo and Aqua Advise (2014).	

Table 18 – RO Main operating data.

The value of electricity required for driving a RO desalination unit is comprised of the following components:

$$ERO = ESWP + EHPP + ERP + EPWP$$

where, ESWP is the electricity consumption of seawater pumps (MW), EHPP shows the value of the high-pressure pump consumption (MW), ERP is the electricity consumption of recirculation pumps and EPWP is the product water pump electricity consumption (MW).

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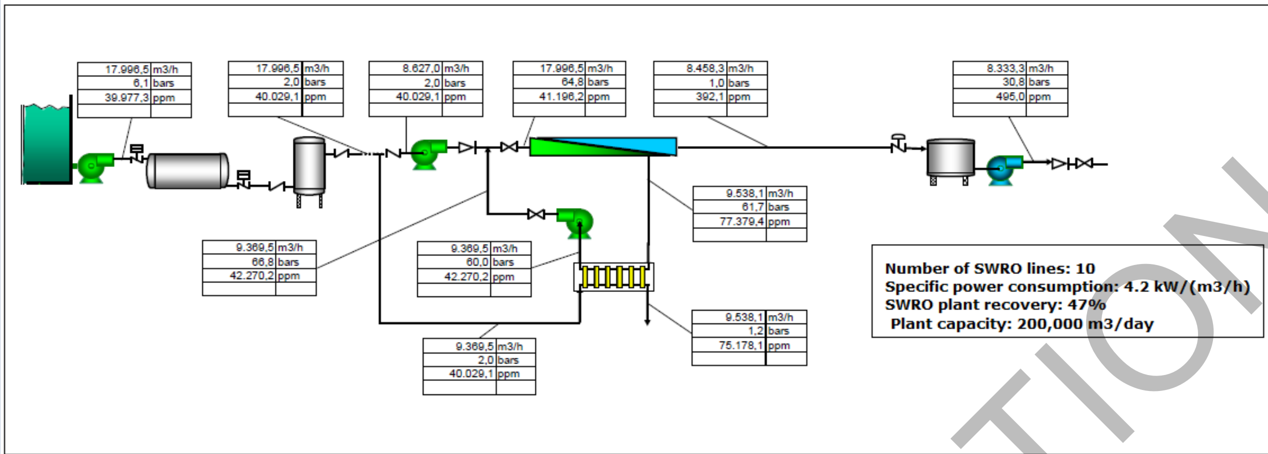

Figure 39 - Desalination water balance (created by EAI in the scope of the TANDEM project).

Figure 39 shows the water balance and electrical consumptions of a desalination plant of 200,000 m^3/day. As stated above, the specific consumption is between 3-5 kW/(m^3/h), in this particular case is of 4.2 kW/(m^3/h).

The desalination plant showed above consists of ten trains of 8333.3 m^3/h. *Figure 40* shows the electrical consumption and the flow rate, from 0 to 100% of rated flow, as a time function. The plant start-up is performed sequentially. First the pre-treatment starts. The time required to produce water with the quality needed to feed the reverse osmosis depends on the sea water quality (suspended solids, organic material, etc.). Once sea water quality is suitable for RO membranes, the first desalination train starts. When the product water obtained from the first train has the quality required, the second train starts and so on.

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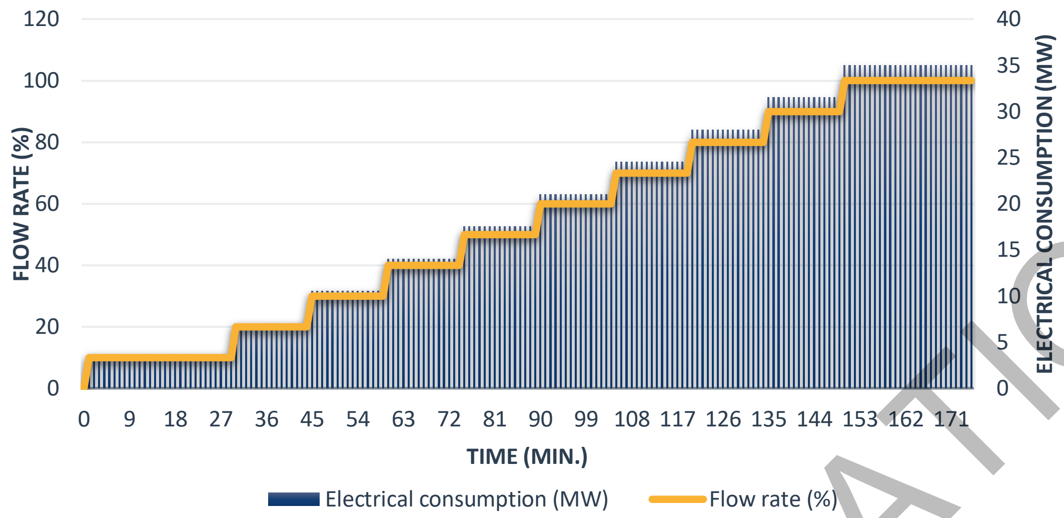

Figure 40 - Flow rate and electrical consumption of a desalination plant of 10 SWRO trains vs. time (created by EAI in the scope of the TANDEM project).

6.1.4 Proposed coupling with the E-SMR and HES

A configuration of the proposed HES has been already shown in *Figure 36*. Steam is produced from a nuclear small modular reactor (SMR), which drives the steam turbines to generate electricity for the grid. Part of the electrical energy produced by the SMR is used to feed a RO desalination plant, reducing the electrical power to be transmitted to the grid. Additional electricity is generated via renewable energy, for example with solar PV arrays or wind energy and transmitted to the grid, compensating for the energy not produced by the SMR.

Another possibility, it would be to couple HES with different desalination technologies to improve the performance of large-scale desalination plants. RO can be coupled with a thermal desalination plant, where the RO can operate at low recovery, producing permeate with relatively high TDS to be blended with a low TDS product from thermal desalination.

In *Figure 41* is depicted as an example of the simple hybrid scheme with different desalination technologies. In the simple option, the thermal unit is completely independent of the RO unit and just the rejected water or produced water can be passed through the same pipes.

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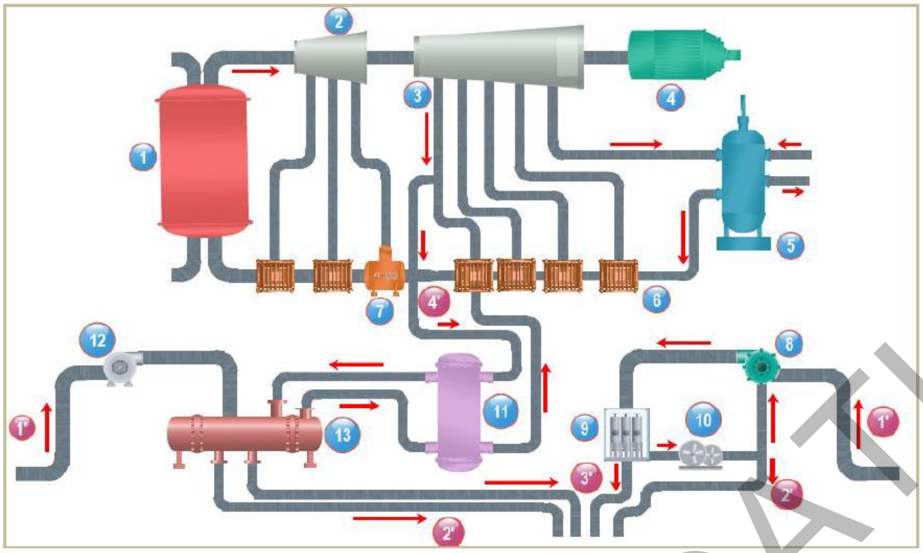

Figure 41 - Schematic diagram of typical simple hybrid desalination plant combined with nuclear plant. 1—steam generator, 2—high-pressure turbine, 3—low-pressure turbine, 4—generator, 5—condenser of the nuclear power plant (NPP), 6—preheater, 7—deaerator, 8—high-pressure pump, 9—membrane modules, 10—energy recovery system of the reverse osmosis (RO) plant, 11—intermediate heat-exchanger, 12—intake water pump, 13—thermal DP, 10—seawater intake pipeline, 2'—rejected brine pipeline, 3'—produced freshwater pipeline, 4'—steam extraction pipeline (Ghazaie et al., 2020).

Since thermal desalination units generally are not easily affected by the high salinity and TDS of feed water, it is possible to partly or completely use the RO brine as the feed water for MED and MSF units. *Figure 42* shows this possibility. The main goal of this scheme is to reduce the total volume of intake water. This will reduce the required pumping power and therefore the cost of water production.

In the third suggested coupling scheme shown in *Figure 43*, the condenser cooling water is used as feed water of desalination plant. In this case, an increase in the feedwater temperature of RO membranes enhances their permeability, as a result of which, the RO plant recovery ratio usually increases by 1.5–3% per degree Celsius of temperature rise.

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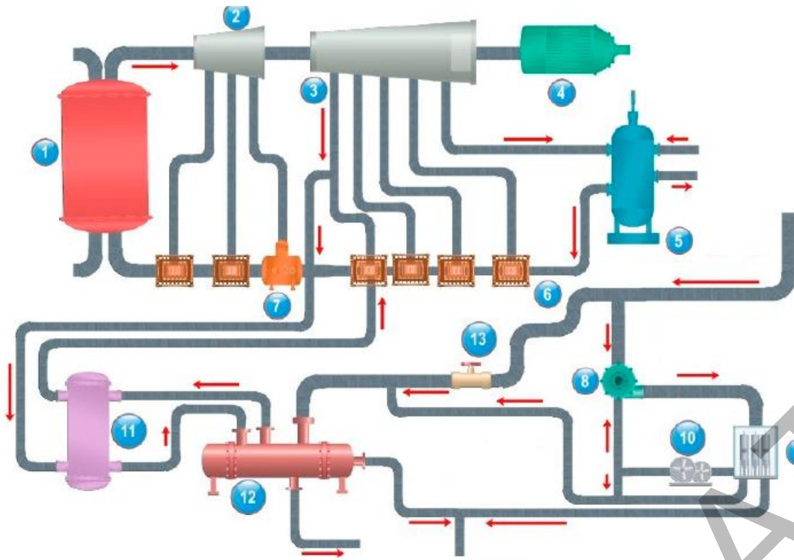

Figure 42 - Diagram of desalination plants (thermal + RO) coupled with SMR. 1—steam generator, 2—high-pressure turbine, 3—low-pressure turbine, 4—generator, 5—condenser of the NPP, 6—preheater, 7—deaerator, 8—high-pressure pump, 9—membrane modules, 10—energy recovery system of RO plant, 11—intermediate heat-exchanger, 12—thermal DP, 13—bypass valve (Ghazaie et al., 2020).

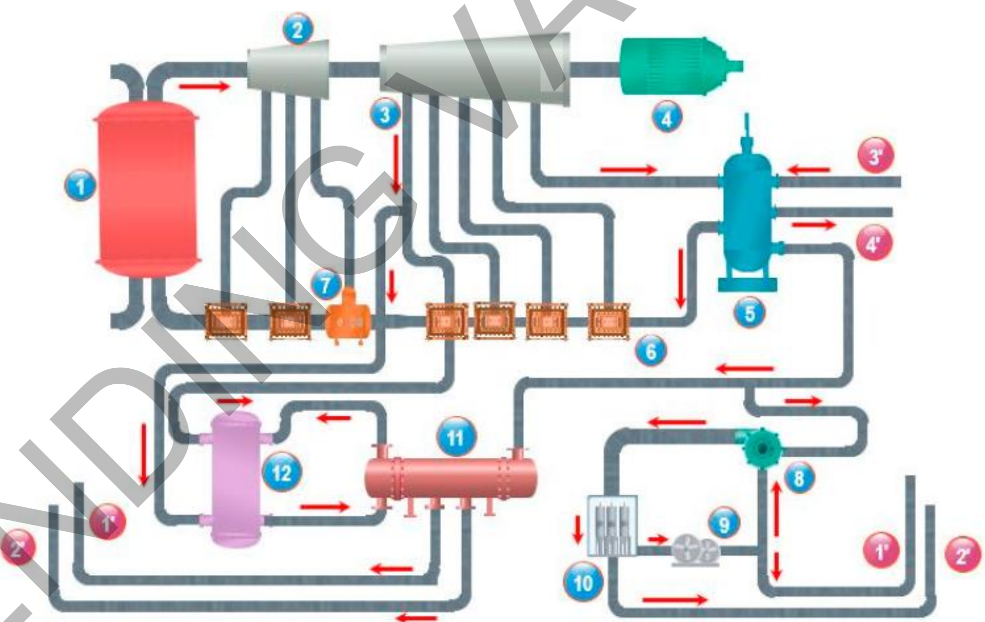

Figure 43 - The third scheme of DP coupling with SMR; 1—steam generator, 2—high-pressure turbine, 3—low-pressure turbine, 4—generator, 5—condenser of the NPP, 6—preheater, 7—deaerator, 8—high-pressure pump, 9—energy recovery system of RO plant, 10—membrane modules, 11—thermal DP, 12—intermediate heat-exchanger, 1’—rejected brine pipeline, 2’—produced freshwater pipeline, 3’—inlet water to NPP’s condenser, 4’—outlet water from NPP’s condenser (Ghazaie et al., 2020).

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Generally, the aforementioned applies to existing powers plants and thermal desalination plants, i.e., adding a RO plant will decrease the water cost and increase the plant flexibility. However, for a new plant, RO provides water at lower cost.

6.2 Sea Water Distillation

In this section, technologies that require to be supplied by both thermal energy and electricity are considered.

6.2.1 Technology Selection

The scope of distillation technologies can be, in a first approach, limited to two main technologies:

- MSF: Multi Stage Flash is a thermal desalination technology based on flashing process, shown in *Figure 44*;

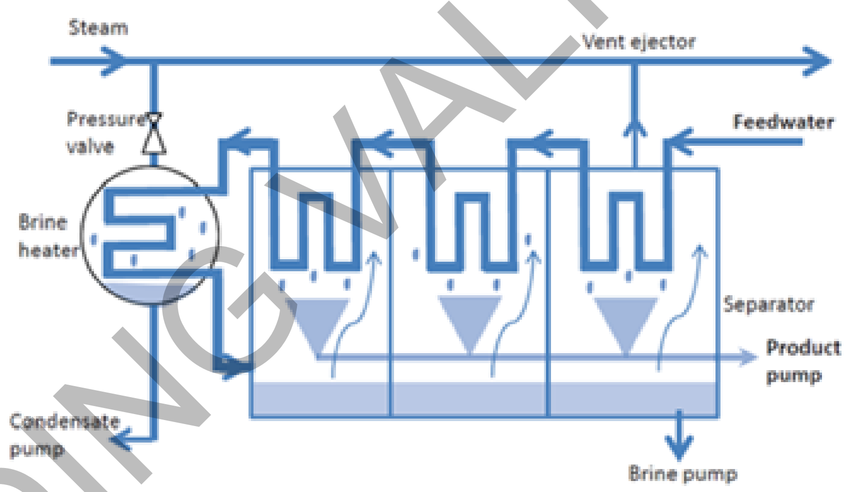

Figure 44 – MSF Technology (IEA-ETSAP and IRENA, 2012).

- MED: Multi-Effect Distillation (MED) is a thermal desalination technology that produces distilled quality water directly from seawater by using low / medium pressure steam and electricity, depicted in *Figure 45*.

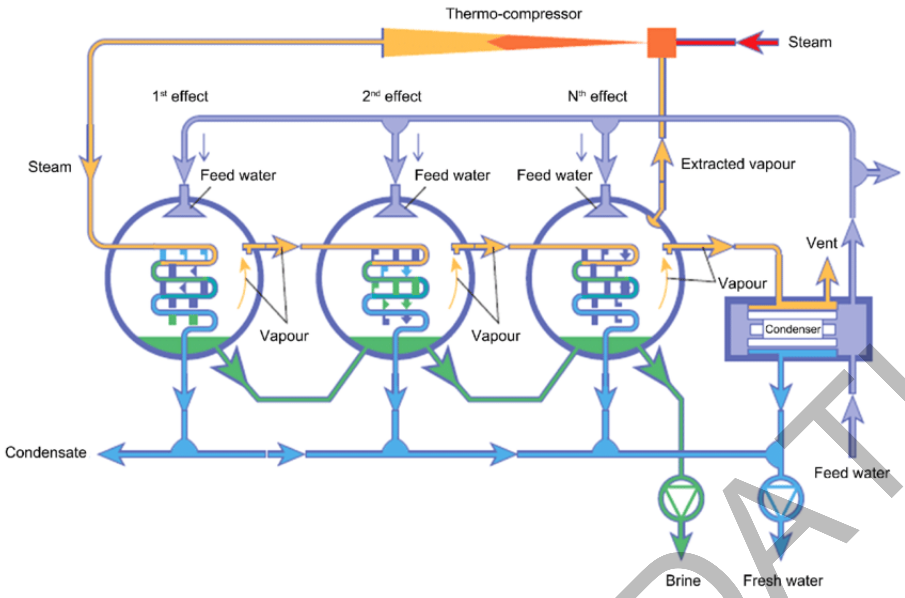

Figure 45 - MED Technology (Ghernaout and Elboughdiri, 2020).

For these two technologies, power plant with huge capacities are already in operation all over the world, with for example:

- MED:
  - TRAPANI powerplant in SICILY with 2x9000 m3/d of capacity;
  - Abutaraba LIBYA in 2009 with 13300 m3/d of capacity.
- MSF:
  - AL Khobar in Saoudia Arabie in 1894 with 223 000 m3/d of capacity;
  - Jebel Ali G Station, Dubai.

In all cases, the thermal energy in supplied by fossil sources.

The potential of nuclear cogeneration supply, particularly by SMR, is possible because the level of temperature required by distillation process is limited to 100-120°C (< to the maximum level of temperature that can supply a representative technology with 280/300°C).

6.2.2 Component Coupling with the HES

Principal scheme of a distillation system coupling with SMR is shown in *Figure 46*.

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For the TANDEM project purposes, Desalination process can be modelled as a unit which is supplied by heat (steam) and electricity regarding the energetic flow required. In case of electricity in excess, it can be evacuated to the grid to increase the economy of the system.

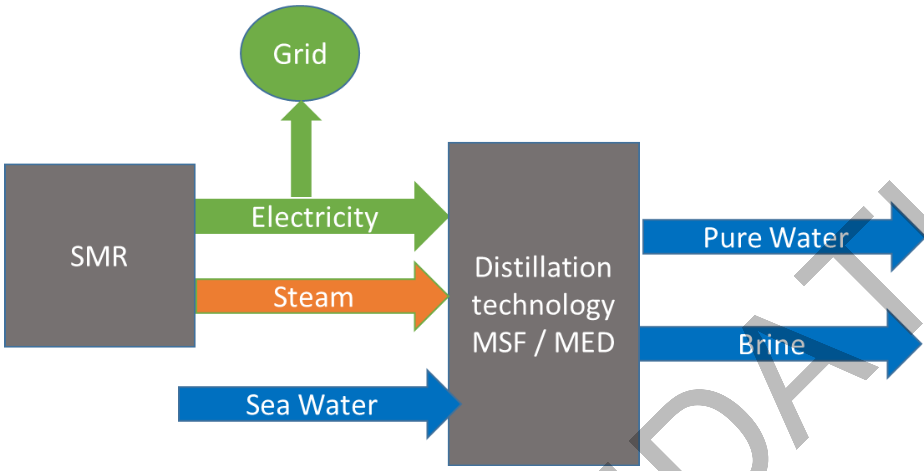

Figure 46 - Distillation technology coupled with the SMR (created by CEA in the scope of the TANDEM project).

6.2.3 Main system architecture and operating data

The performance of the coupled system depends on the connection point to the steam side of turbine. Regarding the level of temperature of the thermal energy supply required by desalination unit, some preliminary analysis could be done to optimize the connection point in the Rankine cycle. Main operating data for Desalination process is presented in Table *19*.

Parameter	MED	MSF
Electric demand (kWh/m^3)	1.5	3.5
Thermal demand (kWh/m^3)	50	70
Entrance temperature for thermal supply (°C)	70	120
Physical state of water for heat supply	Liquid water	Steam

Table 19 – MED and MSF main data.

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7. Synthetic Fuels

Synthetic methane production has been identified as a good candidate for long-term electricity storage, as well as an interesting alternative to decrease the CO_2 footprint of applications using currently natural gas as feedstock.

Indeed, the production of synthetic methane, also called methanation, consists in combining carbon dioxide (CO_2) and hydrogen (H_2) to generate methane (CH_4) by chemical reaction. The CO_2 can be sourced from Power Plants or from industries equipped with Carbon Capture units. The hydrogen can be originated from electrolysis plantCO_2. The global balance can thus be summarized by CO_2 plus water plus electricity and heat equal methane. Once produced, the methane can be transported and stored by existing infrastructure (including geological cavity). The methane can afterwards be re-used by Power Plants to generate again electricity. Also, it is a feedstock compatible with most of the applications using fossil natural gas nowadays.

Methanation enables consequently energy storage at very large scale and over long periods. It also enables fast energy release in case of electricity scarcity using existing gas Power Plants, but without CO_2 release to the atmosphere as the CO_2 is being used as feedstock for methanation.

The energy storage operated by methanation contributes to stabilise the electrical grid by consuming the excess of energy generated by the nuclear power plant. This will allow the entire dispatchment of energy from renewable generators and the power production of the nuclear reactor as stable as possible.

Therefore, this section is concentrating on the edges of methanation, enabling to understand the connections with associated technologies that will be numerically modelized in the TANDEM's framework.

7.1 Literature Survey

Lots of publications are available on the topic of synthetic methane production, also called methanation, for the interested reader.

Methanation is based on a single process technology (methanation reactor) driven by well-known chemical reactions. The publications are reflecting the relatively good readiness level of this process and showing continuous improvement of the catalysts and reactors design. However, it is to be noted that very few industrial plants are in operation nowadays around the world, mainly because of poor economical attractivity outside the framework of CO_2 emissions trading market and of electrical grid stability concerns.

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Ghaib and Ben-Fares (2018) give an overview of the technologies involved in synthetic methane value-chain. This publication is namely presenting the HELMETH project (see http://www.helmeth.eu/index.php) started in 2014 and partially financed by the European Union's Seventh Framework Program (FP7/2007-2013). It also presents the Audi *"e-gas plant"* in Werlte (northern Germany), an industrial Power-to-Methane facility including carbon capture unit:

> "*It was commissioned in 2013. CO_2 is captured from biogas by amine absorption. H_2 is generated by alkaline electrolyzers with a total capacity of 6 MW powered by an offshore wind park in the North Sea and stored in a tank at approximately 10 bar before it is fed into the methanation reactor. The intermediate storage of hydrogen allows a temporary decoupling of the unsteady operation of the electrolyzer from methanation reactor. The product gas is dried and fed as synthetic natural gas into the natural gas grid in Werlte. The heat released from the methanation reactor is used to regenerate the amine absorbent.*".

7.2 Component coupling with the HES

The synthetic methane production being a way to store energy, it gets intrinsically coupled with some of the nodes of the global electrical & energy system.

As this process is based on a chemical reaction, it is directly coupled with reactants availability: hydrogen and carbon dioxide.

The coupling with hydrogen implies indirectly a coupling with electricity and a small part of heat, depending on the hydrogen production technology. Therefore, hydrogen production is a way to convert electricity/heat into a chemical, H_2, not only for methanation purpose but also for direct use as combustible in thermal application or as feedstock to generate electricity back using fuel cells or gas turbines. The coupling with electricity/heat contributes to stabilizing the grid as the excess of electricity/heat can (partially) be consumed. The coupling with hydrogen helps enhancing the hydrogen production process by giving a solution to the challenge of hydrogen storage, as hydrogen is converted to methane.

The coupling of methanation with carbon dioxide is a coupling over the whole value chain, including carbon capture (e.g. coming from a Combine Cycle Gas Turbine (CCGT) or from the chemical industry), storage and transport facilities.

The methanation leads also to heat production at high and middle temperature, enabling electricity production with Steam Turbines and/or coupling with District Heating or thermal energy storage (see *Figure 47*).

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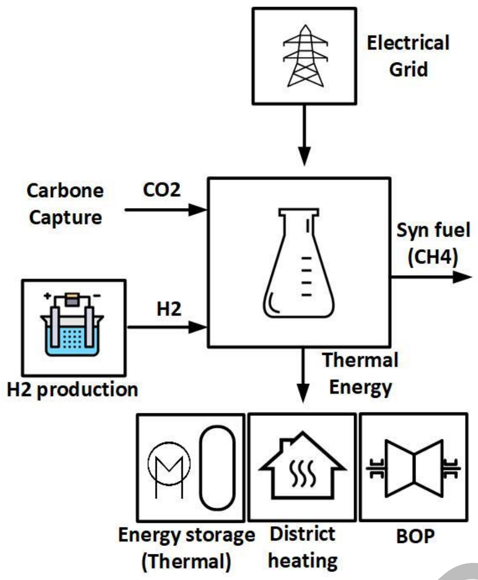

Figure 47 - Methanation system coupled with hybrid energy system (created by TRACTEBEL in the scope of the TANDEM project).

7.3 Main system architecture and operating data

The methanation reaction equation is globally expressed as follows:

$$4H_2 + CO_2 \rightleftharpoons CH_4 + 2H_2O$$

This reaction between gaseous components requires a catalyst and given pressure and temperature conditions to evolve towards the right side of the equation (meaning towards the production of methane). This reaction being exothermic and leading to a decrease of the number of molecules in the mixture, it is favoured (shifted to the right) by lower temperature and higher pressure. According to literature data (Katla et al., 2023), the process of catalytic methanation can be performed at a temperature between 250 °C and 550 °C and at pressure up to 100 bar.

The methanation process converts the hydrogen stream and carbon dioxide stream in humid methane stream. After purification, the methane can reach natural gas network specifications. The purification requires at least a cooling system to remove the water from the methane by condensation (e.g., cooling water). The remaining hydrogen and carbon dioxide in methane stream is generally not a problem for natural gas network.

The heat produced by the process is exported as steam. The steam can be used for electricity generation with a steam turbine and/or for district heating and/or for other industrial usages. *Figure 48* shows a schematic layout of the methanation process with the main inlet and outlet streams.

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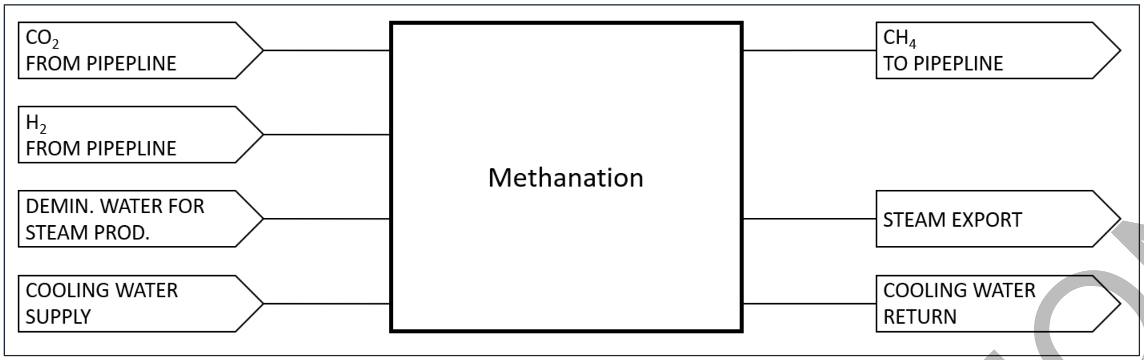

Figure 48 – Schematic layout of the methanation process (created by TRACTEBEL in the scope of the TANDEM project).

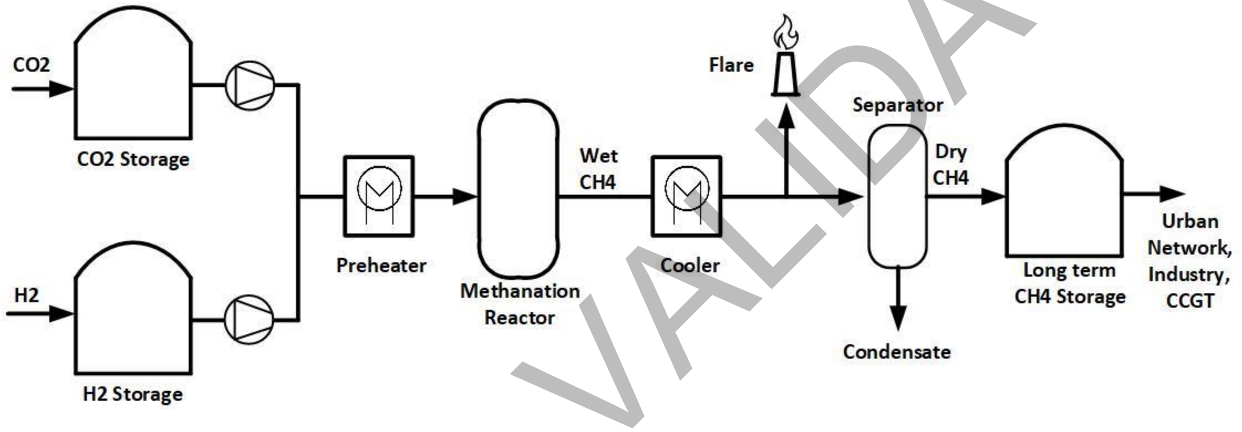

Figure 49 - Model flow diagram of methanation process (created by TRACTEBEL in the scope of the TANDEM project).

In general, the synthetic methane production unit requires:

- H_2 and CO_2 storage and/or reliable supply from distribution network or from producers' storages;
- Heating system upstream the reactor;
- Cooling system for purification;
- CH_4 distribution network or storage (gaseous or liquid);
- Excess heat consumer (steam turbine, district heating, other);
- Utilities.

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Figure *49* shows the model flow diagram of the methanation process.

The main operating data of the methanation process can be summarized as following:

1. Operating temperature: 250 to 550 °C.
2. Operating pressure: up to 100 bar (abs)
3. Mass balance:

   For 1,0 t of H_2 consumed, there are:

- 5,5 t of CO_2 consumed;
- 2,0 t of Dry Gas produced;
- 4,5 t of H_2O produced.

At this stage, the abovementioned data are considered to be enough to have a preliminary idea about the modelling of the methanation process to be performed in future works within the TANDEM project (i.e., within WP2). Therefore, during the modelling phase other valuable parameters will be issued.

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8. Wind Energy

Reducing emissions and moving towards the decarbonization of energy are two fundamental objectives for safeguarding the planet. An effective tool to achieve clean and efficient energy supply is combining renewable energy such as wind power into HES.

Energy systems hybridization with on/off shore wind farms connecting them to a local electrical distribution network along with other energy sources allow to configure an energy hub which could be capable of automatically responding to fluctuations in energy production, but also demand by making more responsible use of energy.

HES are capital intensive technologies that should operate at full capacities to maximize profits. Therefore, instead of wasting an excess generation capacity at negative profit during off peak hours when electricity prices are low, HES could result in positive profits by storing and/or utilizing surplus thermal and/or electrical energy to produce useful storable products.

Wind turbines are an important source of intermittent renewable energy, and are used to lower energy costs and reduce reliance on fossil fuels.

8.1 Technology Selection

A wind turbine converts the kinetic energy of wind into electrical energy for distribution. Wind turbines are of the vertical three-blade rotor type, each blade controlled by an independent pitch change system, and with an active yaw control system. Wind turbine components include the control system and frequency drive cabinets that allow the wind turbine to operate at variable speed, maximizing the power produced at all times and minimizing loads and noise.

8.2 Component Coupling with the HES

An effective tool to achieve clean and efficient energy supply is combining renewable energy such as wind power into HES.

The configurations of the proposed HES associated to the wind farms are shown in *Figure 50* and *Figure 51*.

On/off shore wind farms could be coupled to a local distribution network where other energy plants can be connected as for example a SMR, photovoltaic plant, hydraulic plant, biomass plant, waste to energy plant or solar thermal power plant that may or may not be supplemented by storage systems. End consumers are fed from this local distribution network. In addition, this local grid is connected to the global distribution/transmission grid. This configuration

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incorporates a control system capable of automatically responding to fluctuations in energy production, but also demand in which a more responsible use is made from the generating plants to the end consumers. The flow of energy could be bidirectional in such a way energy not only goes from generation plants to consumers, but end users could be able to generate their own energy and deliver their surplus to other users. For a global overview about the introduction of a Wind Farm in the HES, see *Figure 75*. Other configurations with respect to HES considering the different power outputs from NPP are the following:

a) Part of the thermal energy produced by the NPP is used in other processes (e.g. water desalination); as a result, the Power Conversion System (PCS) reduces the electrical power to be transmitted to the grid. In this case the wind farm will directly transmit its power output to the grid, compensating for the energy not produced by the PCS (see *Figure 50*).

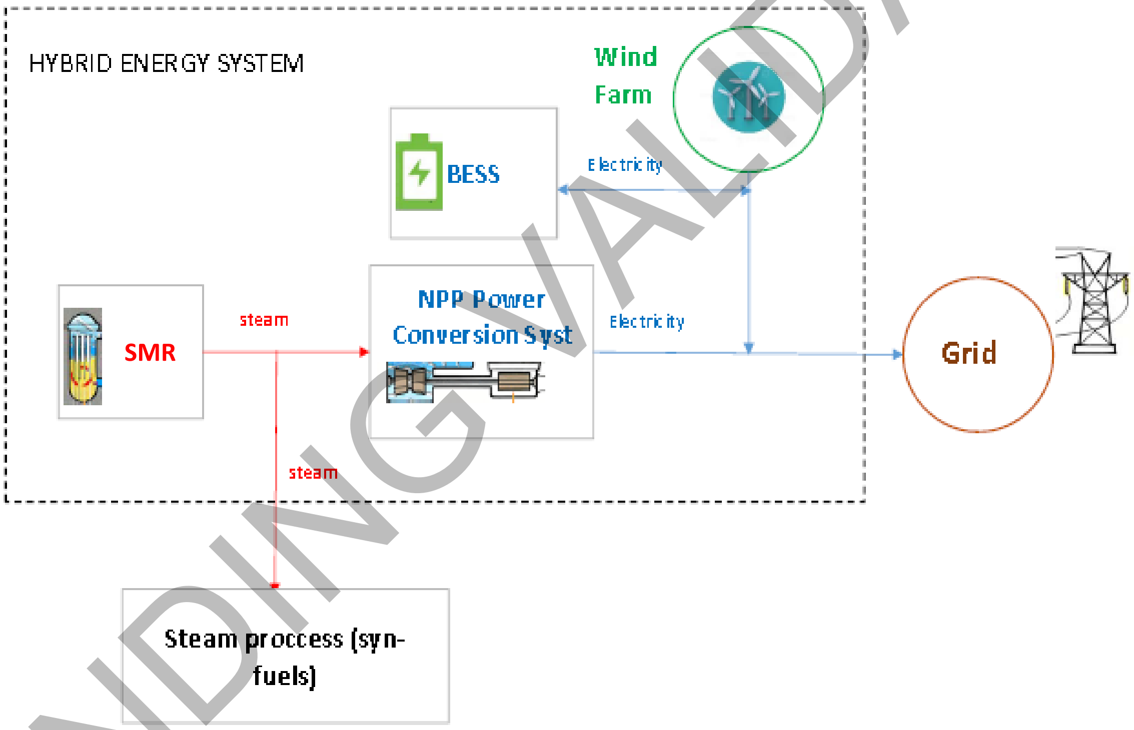

Figure 50 - Topology with flexible thermal load (created by EAI in the scope of the TANDEM project).

b) Part of the electrical energy generated by the Power Conversion System (PCS) is used to feed the power consumers of other processes (e.g. a desalination plant or a hydrogen production facility). Here the wind farm could feed these auxiliary consumptions and discharge any surplus energy to the grid (see *Figure 51*).

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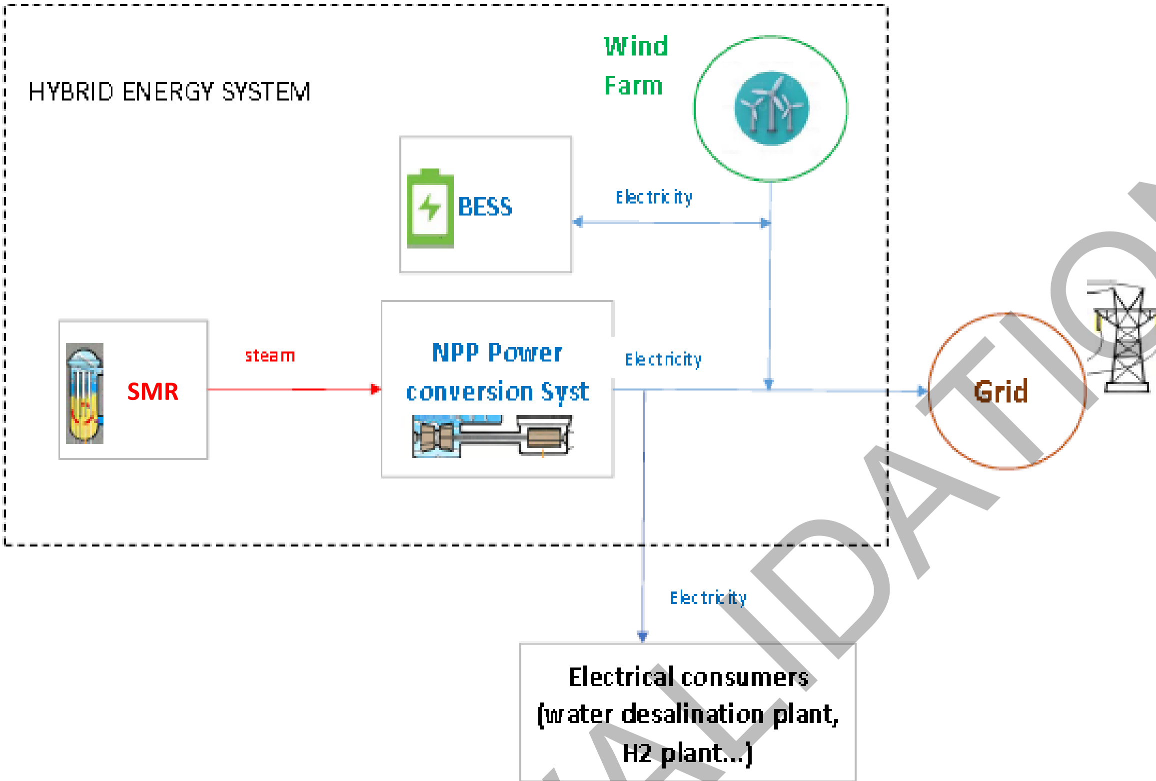

Figure 51 - Topology with flexible electrical load (created by EAI in the scope of the TANDEM project).

As wind may not always be available, it would be convenient to envisage installing an energy storage system, for instance with batteries (BESS), to guarantee a more stable and efficient supply.

8.3 Main system components and relative operating data

The on/off shore wind farm is a power production system based on wind turbines that will be interconnected via underground or submarine Medium Voltage (MV) circuits to the transformer substation of the plant. This substation will feature MV switchgear assemblies to receive the power from the wind turbine lines, as well as a step-up transformer to raise the voltage for grid coupling.

The electrical generator located in the equipment nacelle of the wind turbine produces Low Voltage (LV) power, typically at 690 V or 720 V or higher. The voltage level is then raised to MV by means of a transformer. Control cabinets and a frequency drive allow the wind turbine to operate at variable speed, maximizing power production at all times. Depending on the class and type of wind turbine, the power converter and the transformer can be found in the nacelle. The configuration of the electrical power system of the wind farm is shown in *Figure 55* and *Figure 56*. Wind turbines are divided into three main components:

- Rotor which includes the blades;
- Generator including control electronics system, gearbox and adjustable-speed drive located in the nacelle;
- Structure including tower and rotor yaw mechanism.

Choosing the right wind turbine according to wind and terrain conditions is a key factor in wind farm design. To this end, it is necessary to measure the wind force at different heights, to determine the proper height for the blades and select the right turbine. The main parameters of wind turbines are listed in *Table 20*:

Main characteristics of wind turbines	Onshore	Offshore
Rated active power	2 – 7 MW	6 – 15 MW
Rotor diameter	> 140 m	> 150 m
Tower height	Site and country specific	Site specific
Blade length	> 70 m	> 75 m
Rated generator voltage	690 - 720 V	690 - 720 V or higher
Rated power factor	~ 0.90 (leading) - 0.95 (lagging) (*)	~ 0.90 (leading) - 0.95 (lagging) (*)
(*) Leading: reactive power absorption by the generator **Lagging: reactive power generation by the generator**		

Table 20 – Main parameters of wind turbines.

Wind turbines differs among classes, types, operation modes and capabilities. However, with certain differences and limitations, all of them can be understood as current sources connected to the grid.

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It is assumed that the wind turbine pitch control is able to deal with different wind conditions and the wind turbine electric control is able to deliver the energy in a controlled manner for both active and reactive power. The limitations and expected behaviour can be defined using the following wind turbine performance curves (see *Figure 52* and *Figure 53*):

a) Active power production versus wind speed: the wind turbine generator performance curve represents the power production versus wind speed. There are three different operation regions:

- For speed below Cut-in speed: wind turbine state will be off. The cut-in speed is the threshold when the blades start rotating and generating power.
- Between Cut-in and Rated wind speed: the wind turbine can operate at partial load. As wind speeds increase, more electricity is generated until it reaches a limit, known as the rated speed. This is the point that the turbine produces its maximum, or rated power.
- As the wind speed continues to increase, the power generated by the turbine remains constant to rated power until it eventually hits a Cut-out speed and shuts down to prevent unnecessary strain on the rotor.

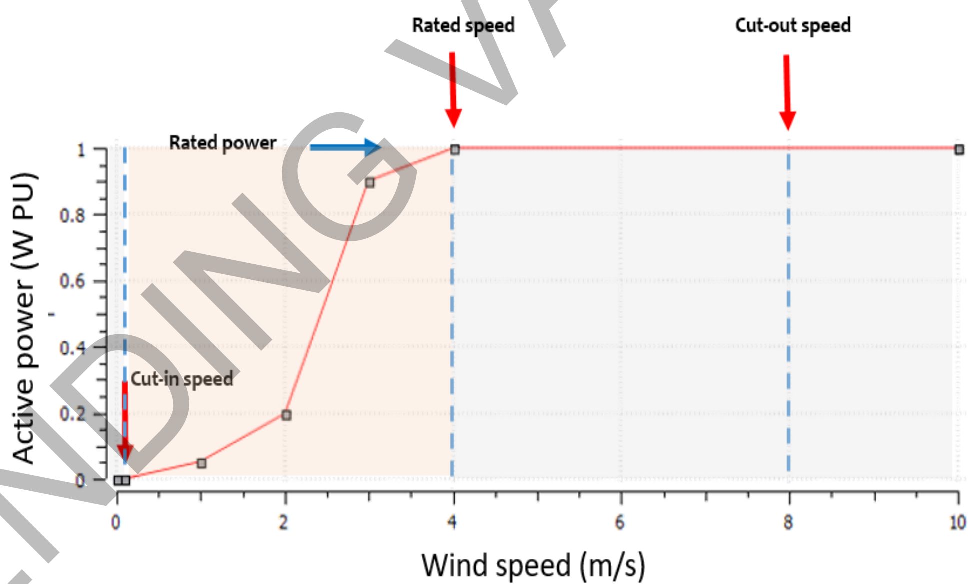

Figure 52 - Active power production versus wind speed (created by EAI in the scope of the TANDEM project).

b) The active-reactive (P-Q) capability chart: it represents the active power P (x axis) and reactive power Q (y axis) capability of wind turbine. It defines the regions in power terms where a wind turbine can operate. Basically, the amount of reactive power (either

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inductive or capacitive) which can be supported for each active power operation point. That means that active power is first priority, and reference reactive is only delivered if it is in the operation region.

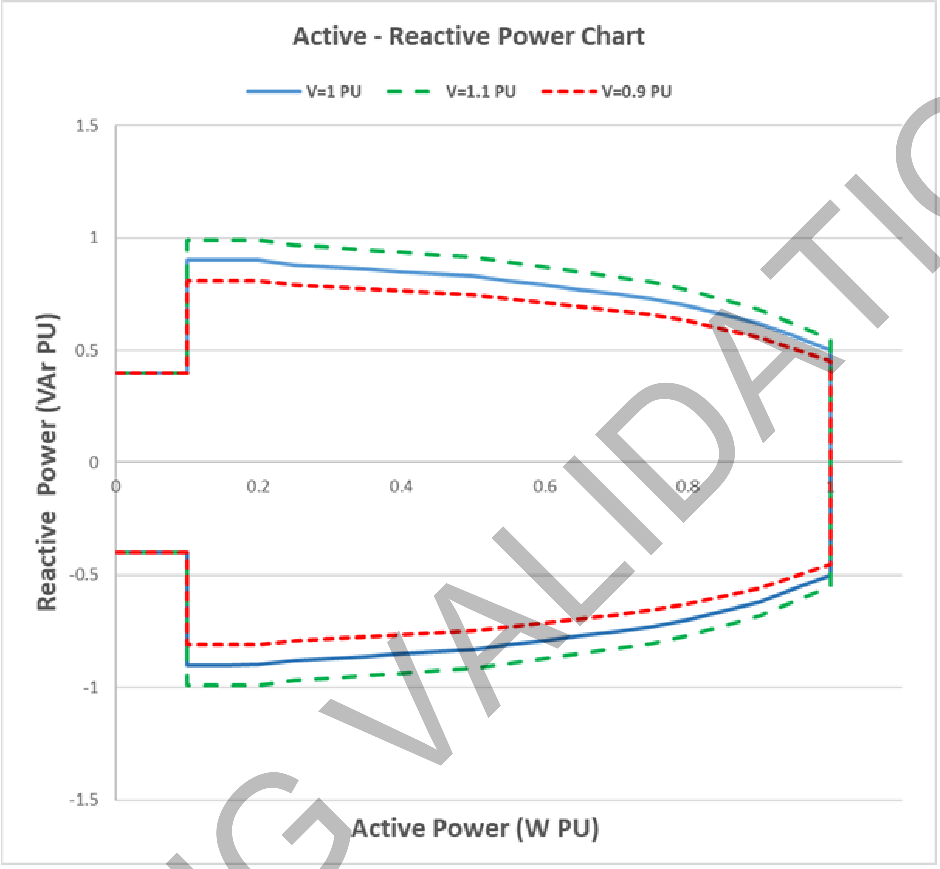

Figure 53 - Active-reactive (P-Q) capability chart (created by EAI in the scope of the TANDEM project).

Generally, the P-Q capability curve has a "D" shape but occasionally manufacturers will supply a rectangular capability curve.

The wind turbine electrical generator is asynchronous and features a drive system allowing it to operate at variable speed by controlling the rotor current frequency. Electrically, the generator-converter unit is comparable to that of a synchronous generator, which ensures optimal coupling to the grid with smooth connection and disconnection processes. In addition, it can work with variable speed to optimize operation and maximize the power generated at each wind speed. It also enables management of the reactive power transmitted in collaboration with the remote-control system.

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The transformer of the wind turbine will be of the three-phase, encapsulated winding dry type, with MV output (e.g. 30 kV) and different apparent power ranges.

In short, the wind turbine generator is a device that transform kinetic energy of the wind into electrical energy. Firstly, this kinetic energy is transformed into mechanical energy by the blades; secondly, the mechanical energy is transformed into electrical by the electric generator. Therefore, the wind turbine model could be represented by the rotor (blade) in combination with the electrical components, like generators, power converters and transformers. The wind turbine generator model could consider a number of wind turbine generators grouped in a cluster.

Figure 54 shows a scheme of a wind turbine components.

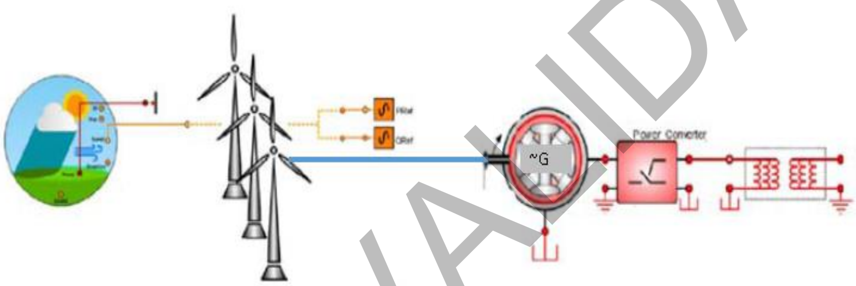

Figure 54 - Wind turbine components (created by EAI in the scope of the TANDEM project).

The different wind turbines in a wind farm will be interconnected via the underground MV circuits to the plant substation.

The configuration of the power system of the wind farm is shown in *Figure 55*. The MV system comprises the following equipment:

- MV distribution switchgear assembly connected to the power transformer of each wind turbine and to the plant substation. Each assembly is made up of an incoming feeder cabinet, circuit breaker of the wind turbine generator feeder and outgoing disconnectors, and is located in the basement of the tower.
- MV cables made up of single-core aluminum conductors of different cross-sections. Their purpose is to connect the plant substation with the switchgear assemblies located in the bottom part of each wind turbine tower. Cables will be directly buried in trenches.

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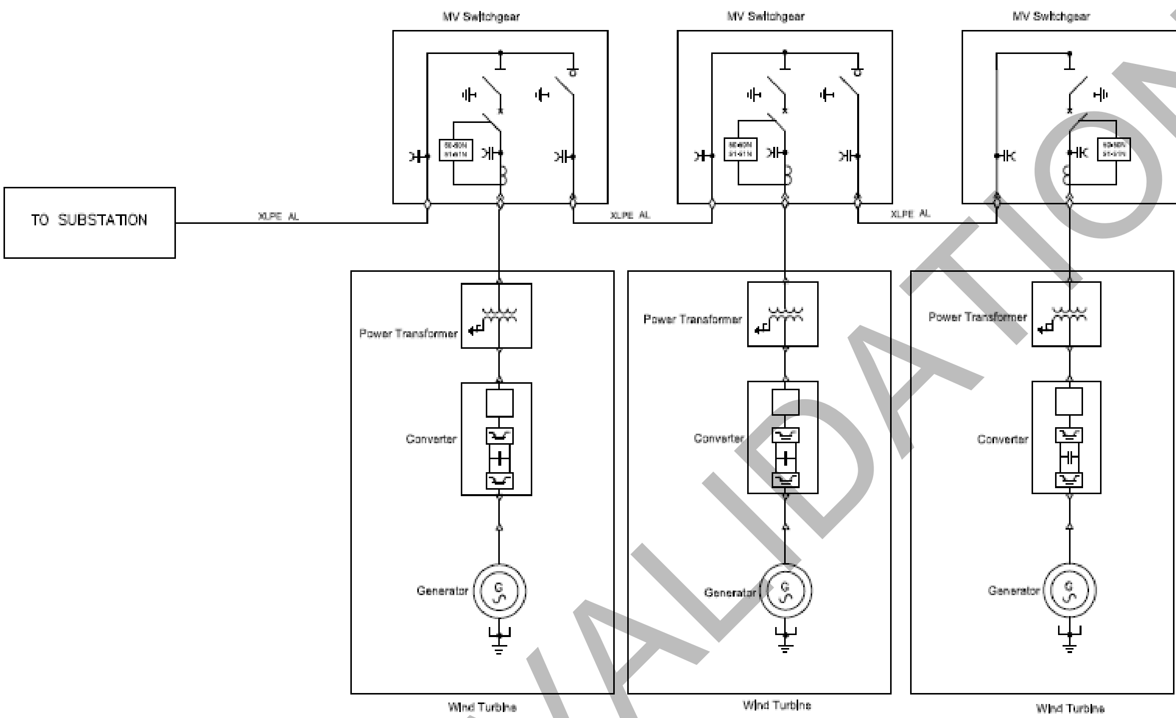

Figure 55 - Wind Farm Single Line Diagram (created by EAI in the scope of the TANDEM project).

There will also be MV switchgear assemblies on the plant substation side, to connect the wind turbine lines to a step-up transformer, so as to raise the voltage for grid connection if necessary (see *Figure 56*).

Typically, the transformer will be three-phase, two-winding, mineral-oil immersed, with ONAN/ONAF cooling. The sizing, impedance, transformation ratio and vector group all depend on the specific requirements of the project, site and grid connection. The transformer will typically be equipped with the following elements:

- Bushings for cable connection on the MV side;
- Bushings for cable, overhead or GIS connection on the HV side;
- On-load tap changer (OLTC), if necessary for grid connection;

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- Current transformers on both sides for thermal image device and electrical protections, as necessary; and

- Protection and monitoring devices (Buchholz relay, pressure relief valves, thermal image device, oil level gauges, top oil thermometer, etc).

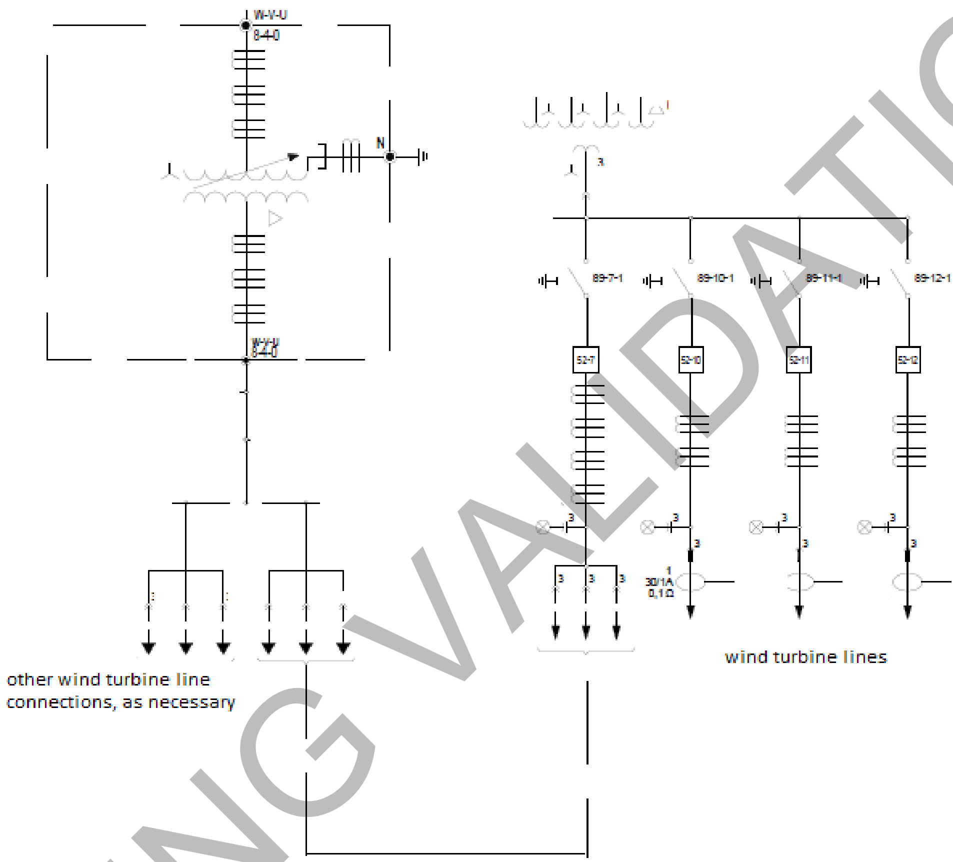

Figure 56 - Wind Farm Connection to the Plant Substation (created by EAI in the scope of the TANDEM project).

Main operating data

In the document by [COMMISSION REGULATION (EU) 2016/631] some requirements to be applied to New Power Generating Modules (wind generation) in a Member State of the European Union are set, if they are to be connected to a transmission, distribution or closed distribution network. Depending on the electrical power maximum capacity generated and the rated voltage of power generating modules in the connection point different requirements shall be applicable.

- Type A: Connection point is below 110 kV and maximum capacity less than 1 MW.

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- Type B: Connection point is below 110 kV and maximum capacity between 1 MW and 50 MW.

- Type C: Connection point is below 110 kV and maximum capacity between 50 MW and 75 MW.

- Type D: Connection point at 110 kV or above.

A general description of the different requirements is listed below applicable to Continental Europe but not all of them apply to all types of power generating modules (for a full description, see (COMMISSION REGULATION (EU) 2016/631):

- Power Park Modules shall be capable of staying connected to the network and operating within the frequency ranges and time periods specified in *Table 21*:

Synchronous Area	Frequency Range	Time period for operation
Continental Europe	47.5 Hz – 48.5 Hz	To be specified by each TSO, but not less than 30 minutes
	48.5 Hz – 49.0 Hz	To be specified by each TSO, but not less than the period for 47.5 Hz – 48.5 Hz
	49.0 Hz – 51.0 Hz	Unlimited
	51.0 Hz – 51.5 Hz	30 minutes

Table 21 – Frequency range and time period of operation for Power Park Modules (COMMISSION REGULATION (EU) 2016/631).

- Power Park Modules shall be capable of staying connected to the network and operating within network voltage range at the coupling point, expressed as the ratio of connection point voltage to nominal voltage (per unit), and the time periods specified in the following tables (shown for type D Power Generating Modules):

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In case of 110 kV to 300 kV, the operation data are described in *Table 22*:

Synchronous Area	Voltage Range	Time period for operation
Continental Europe	0.85 pu – 0.90 pu	60 minutes
	0.90 pu – 1.118 pu	unlimited
	1.118 pu – 1.15 pu	To be specified by each TSO, but not less than 20 minutes and not more than 60 minutes.

Table 22 – Voltage Range and Time Period of operation for 110-330 kV (COMMISSION REGULATION (EU) 2016/631).

In case of 300 kV to 400 kV, instead, they are listed in *Table 23*:

Synchronous Area	Voltage Range	Time period for operation
Continental Europe	0.85 pu – 0.90 pu	60 minutes
	0.90 pu – 1.05 pu	unlimited
	1.05 pu – 1.1 pu	To be specified by each TSO, but not less than 20 minutes and not more than 60 minutes

Table 23 - Voltage Range and Time Period of operation for 300-400 kV (COMMISSION REGULATION (EU) 2016/631).

- Frequency stability requirements (active power/frequency control):

  - Limited Frequency Sensitive Mode – Over frequency (LFSM-O);
  - Frequency Sensitive Mode (FSM); and

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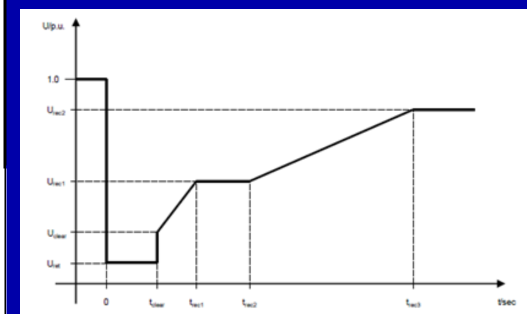
- Limited Frequency Sensitive Mode – Underfrequency (LFSM-U).

- Analysis of the robustness of Power Park Modules with regard to fault-ride-through capability (this requirement applies to type B, C and D Power Park Modules), see *Figure 57*.



Type B & C:

Voltage parameters (pu)		Time parameters (seconds)	
U_{ret}:	0,05-0,15	t_{clear}:	0,14-0,15 (or 0,14-0,25 if system protection and secure operation so require)
U_{clear}:	U_{ret}-0,15	t_{rec1}:	t_{clear}
U_{rec1}:	U_{clear}	t_{rec2}:	t_{rec1}
U_{rec2}:	0,85	t_{rec3}:	1,5-3,0

Type D:

Voltage parameters (pu)		Time parameters (seconds)	
U_{ret}:	0	t_{clear}:	0,14-0,15 (or 0,14-0,25 if system protection and secure operation so require)
U_{clear}:	U_{ret}	t_{rec1}:	t_{clear}
U_{rec1}:	U_{clear}	t_{rec2}:	t_{rec1}
U_{rec2}:	0,85	t_{rec3}:	1,5-3,0

Figure 57 - Some data about robustness of Power Generating Modules for type B, C and D (COMMISSION REGULATION (EU) 2016/631).

- Voltage stability: Power Park Modules at maximum capability shall fulfil the following requirement (this requirement applies to type C and D Power Generating Modules), see *Figure 58*.

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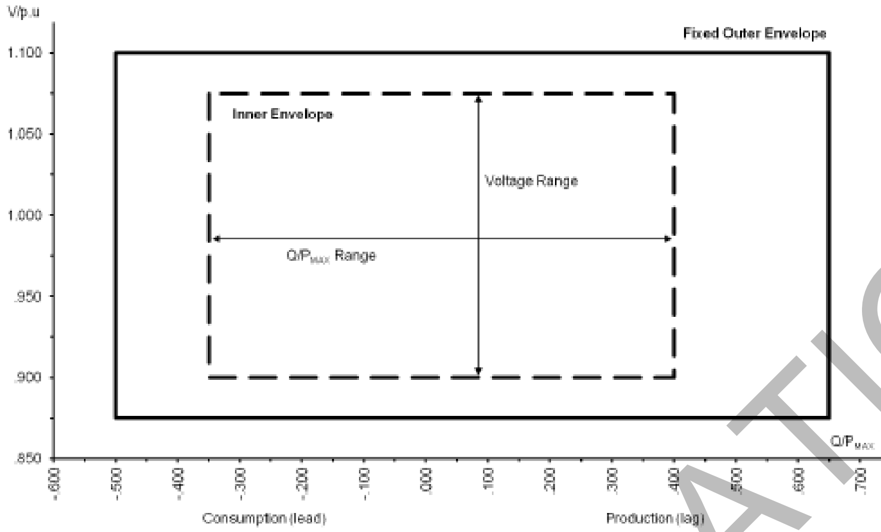

Figure 58 – Requirement for Power Park Modules at maximum capacity (COMMISSION REGULATION (EU) 2016/631).

Where:

Synchronous Area	Maximum range of Q/P_{max}	Maximum range of steady-state Voltage level in PU
Continental Europe	0.75	0.225

- The Power Park Module shall automatically provide reactive power either in voltage control mode, reactive power control mode or power factor control mode. It shall be able to (this requirement applies to type C and D Power Park Modules):

  - Contribute to voltage control at the connection point by reactive power exchange with the network, at a setpoint voltage covering at least 0.95 to 1.05 pu;
  - Set the reactive power setpoint anywhere in the reactive power range; and
  - Control the power factor at the connection point within the required reactive power range.

8.4 Proposed coupling with the E-SMR and HES

The topology when wind farm is linked to a local distribution grid is shown in *Figure 75*. On/off shore wind farm is coupled to a local distribution grid where other energy plants can be connected as for example a SMR, photovoltaic plant, hydraulic plant, biomass plant, waste to energy plant or solar thermal power plant that may or may not be supplemented storage systems. The single line diagram associated to this configuration is shown in *Figure 59*.

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The wind farm will be connected through a step-up transformer to the local grid substation where other plants pour their electrical energy. End consumers are fed from this local distribution network. In addition, this local grid is connected to the global distribution/transmission grid. A master controller manages the system globally and is responsible for optimizing the generation and storage process to better meet energy demand.

Reactive compensation equipment will be integrated in the substation to allow better control of reactive power.

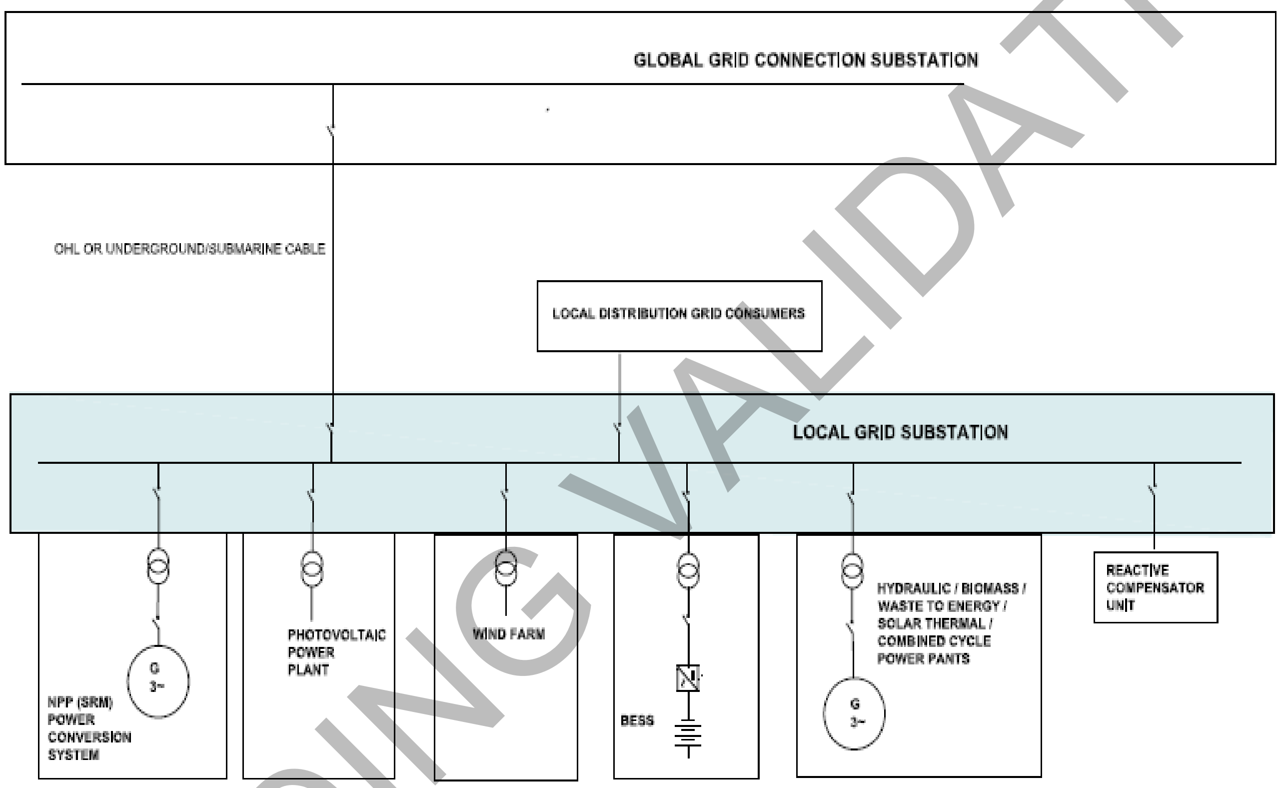

Figure 59 - Integrated local grid-renewable hybrid energy system Single Line Diagram (created by EAI in the frame of the TANDEM project).

Regarding the configurations of HES considering the different power outputs from NPP, thermal or electrical, the typologies are shown on previous *Figure 50* and *Figure 51*.

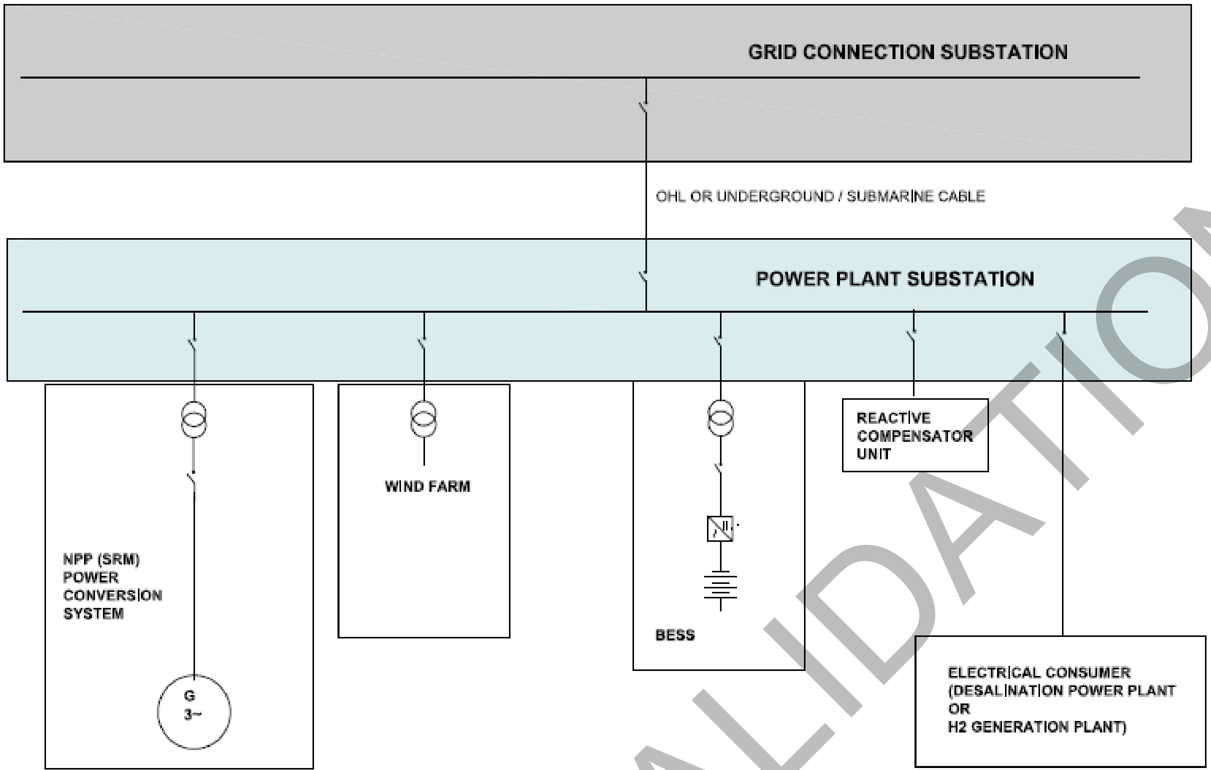

Figure 60 - Integrated nuclear-renewable hybrid energy system Single Line Diagram (created by EAI in the frame of the TANDEM project).

When part of the thermal energy produced by the NPP is used in other processes (e.g. fuel production) the PCS reduces the electrical power to be transmitted to the grid. In this case, the wind farm could directly transmit its power output to the grid, compensating for the energy not produced by the PCS (see *Figure 50*).

In the case that part of the electrical energy generated by the PCS is used to feed the power consumers of other processes (e.g. a desalination plant or a hydrogen production facility), the wind farm could feed these auxiliary consumptions and discharge any surplus energy to the grid (see *Figure 51*).

The wind farm will be connected to the same PCS substation that is associated with the NPP, through a step-up transformer to achieve nominal substation voltage, thereby allowing electric power to be fed into the grid as a complement to the PCS. Reactive compensation equipment will be integrated in the substation to allow better control of reactive power.

As wind may not always be available, it would be convenient to envisage installing an energy storage system, for instance with batteries (BESS), to guarantee a more stable and efficient supply. The general single line diagram of the HES with an NPP is shown in *Figure 60*.

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Although the sum of the power outputs from the PCS and the wind farm is greater than the power injection capacity into the grid, the power injected can never exceed this limit. To this end, a control system will monitor and ensure that the maximum power transmission level granted to the hybridized facility is never exceeded.

8.5 Final remarks

Wind energy is an important source of intermittent renewable energy that lowers energy costs and reduces reliance on fossil fuels. Hybrid generation plants with wind farms are an effective tool to supply clean and efficient energy. These facilities are revealed as fundamental since renewable energies are respectful with the environment and of an inexhaustible character and lead the effort to fight against climate change and universal access to energy.

Therefore, depending on the selected geographical location for TANDEM project, the wind power renewable energy could ensure a more stable and efficient supply. The design of these installations requires careful consideration of the following aspects as regards site location:

a) Wind

Wind power projects are limited by the resources available in the areas chosen for installing wind turbines, and wind speed and frequency are major factors to consider, which is why a wind resource study will be previously required.

Consideration of a smooth orography providing the easiest access possible is also very important.

b) Environmental impact

In accordance with applicable regulations, an environmental impact study will be carried out to be presented to the affected public administrations and interested persons in order to study the various effects they may have on the environment.

c) Grid requirements

Generating power by hybridization of renewable energies is a recent development, and specific regulation on the subject is still scarce in most parts of the world. Standardizing grid connection requirements, metering and traceability procedures for renewable energy in hybridization projects would be advisable;

Compliance with the applicable grid code has to be verified for any selected site. Therefore, in addition to complying with requirements for voltage and frequency

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variations, any site should be subject to the necessary studies applicable depending on the type of power generating modules:

- Power Plant short-circuit calculation: calculation of the total contribution of the plant to the grid at the Point of Connection (PoC).
- Reactive power capability: fulfilment of the grid requirement as regards reactive power in the PoC. All reactive power scenarios (from leading to lagging) will be considered for the full range of voltage at the PoC.
- Harmonic distortion: the total harmonic distortion induced by the plant at the PoC shall not exceed the established limits.
- Frequency response in Frequency Sensitive Mode (FSM): FSM means the operating mode in which the active power output changes in response to a change in system frequency, in such a way that it assists with the recovery to target frequency. The plant shall be capable of activating the power frequency response in FSM according to the parameters specified by the grid operator.
- Dynamic Voltage and Reactive Power Analysis: analysis of plant capability to provide reactive power automatically.
- Fault Ride-through Analysis: analysis of the power generation capability to remain connected to the offsite grid after a short-circuit.

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9. District Heating

District heating is an efficient and centralized method to provide heat to buildings in densely populated areas. This heat is used to heat the building and warm tap water. This is widely used in colder environments such Northern Europe and Baltics. At one level, a similar method is process heat which is heat used in different industry processes such as paper, pulp and petrochemical industries. Process heat is not discussed in detail in this report.

In recent years district cooling has become the more popular way to implement cooling of the buildings. In coarse way it can be thought as a "reversed district heating". District heating and cooling have some synergies with each other, therefore it is briefly touched in this chapter.

District heating, or thermal energy supply system (DHS), is traditionally well developed also in the Czech Republic. Approximately 1.7 million households are connected to DHS systems, which is more than 4 million inhabitants or 40% of the population. Almost half of the heat supplied from DHS goes to the residential sector, 28% to industry and the rest is supplied to the tertiary sector (services, healthcare and education).

9.1 General description of district heating systems

Typically, in district heating systems, water in liquid or gas phase is the carrier of thermal energy. District heating is used to heat buildings and warm tap water. This means households, office buildings etc. Process heat is used in various industry processes. However, transportation of heat through long distances is not economically feasible due to pumping costs and heat losses. Therefore, this means that the power plants are located quite near (tens of kilometres) to the consumer.

District heating system consists of following items:

- transfer pipe (hot and cold legs)
- power plants which produce heat and possible also electricity
- district heating network (two or four pipelines, i.e., two pipelines for central heating and two pipelines for warm tap water)
- buildings which use the heat
- possible heat storages (typically water)

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The district heating network of Helsinki city is Finland's largest and it is operated by Helen oy which is owned by the city. Total length of district heating network in Helsinki in year 2020 was 1400 km (2800 km if both legs are calculated separately) (see the following www.helen.fi).

Based on what can be found on https://www.loimua.fi/kaukolampo/, typical consumers and their heat demand in Finland are the following:

- office buildings
  - large office building 100-300 kW
  - medium 40 -100 kW
- dwelling houses (apartment house, town houses)
  - small town house 10-20kW
  - apartment house 40 – 100 kW
- public services (schools, hospitals etc)
  - 100 -300 kW

Traditionally, district heating has been produced in following power plants:

- heat only boilers (HOB)
- combined heat and power production (CHP)
- gas-turbine combined heat production

The main source of energy used for district heating applications is usually coal -lignite-, oil, biomass or natural gas. Nevertheless, large nuclear power plants are also used in some countries (see the WNA website). However, as the work to reduce CO_2 emissions progresses, it is obvious that new technologies are needed (see, e.g., the following website).

A coarse estimation can be made, according to which future district heating architectures will consists of the following technologies:

- smart operation (digitalisation etc)
- reduced temperatures
- usage of waste heat

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- electricity integration
- sustainable burning (biomass, biogass and hydrogen) might be needed in limited scale

Some of the main parameters of a district heating system are now introduced. For instance, in Finland district heating network temperatures are the following (see this link):

- Hot leg (inlet) temperature varies between 65 – 115 °C
- Cold leg (outlet) temperature varies between 40 – 60 °C

In the Czech Republic district heating network temperature values are following (see the work by (Karafiát, 2016)):

- Steam leg (outlet) temperature varies between 180 – 240 °C (steam)
- Steam leg (inlet) temperature varies between 40 – 70 °C (condensate)
- Hot leg (outlet) temperature varies between 110 – 160 °C (max 180 °C)
- Cold leg (inlet) temperature varies between 50 – 80 °C
- Warm leg (outlet) temperature varies between 70 - 90 °C
- Cold leg (inlet) temperature varies between 40 – 60 °C

Temperatures might vary between networks and countries as presented above. In future, temperatures might decrease below 100 °C as the technologies in production and consumption of the network evolve. Due to the high levels of temperature, district heating pipes are exposed to heat losses. Heat losses depend on the temperature difference between the pipe and surrounding environment (usually ground, which stay above 0°C). However, district heating pipes are thermally insulated to reduce heat dispersions towards the surrounding environment. Moreover, flowing water in the pipes is naturally subjected to pressure losses. Therefore, if district heat is transported through long distances, intermediate pumping stations are needed to cover pressure losses.

In the work by (Laitinen, 2018), it is estimated that heat and pressure losses for long distance transfer pipeline (80 km) are the following:

- pressure losses need to stay between 0,5 – 1 bar /km

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- heat losses 174 W/m

Operating temperatures are higher during the cold months from November to end of March (i.e., outside temperature and district heating temperature are linked). In other words, consumption of district heating varies seasonally (yearly) and daily.

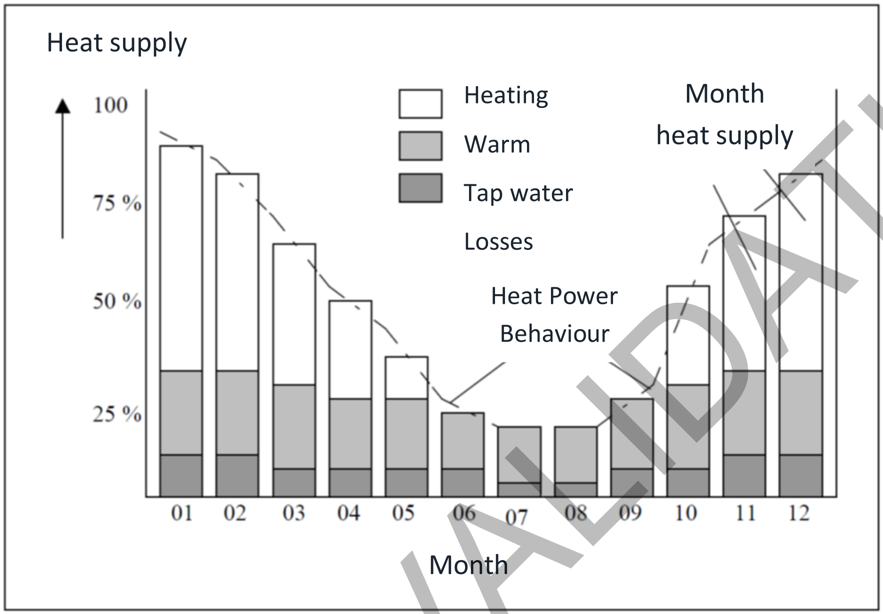

Figure 61 - Typical diagram of heat consumption for heating and warm tap water by month during the year in Czech Republic (Karafiát, 2016).

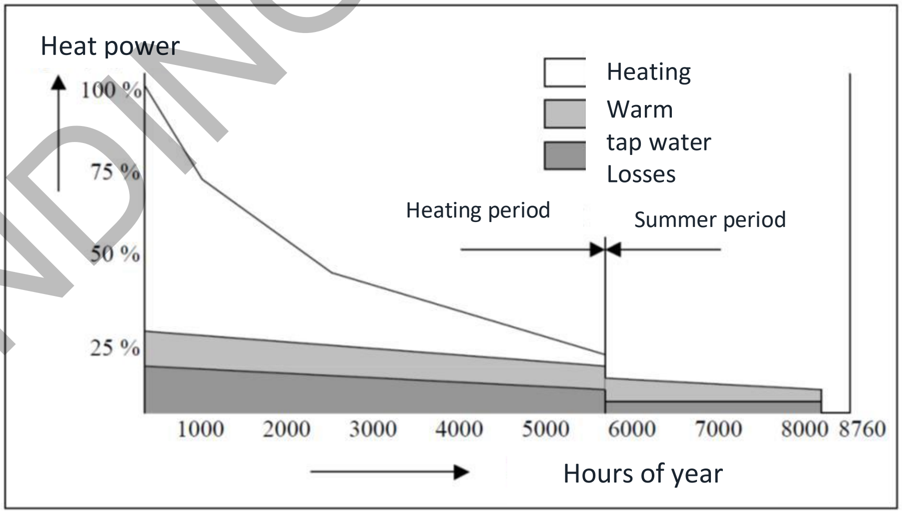

Figure 62 - Typical diagram of the duration of thermal output demand of a hot water DHS in Czech Republic (Karafiát, 2016).

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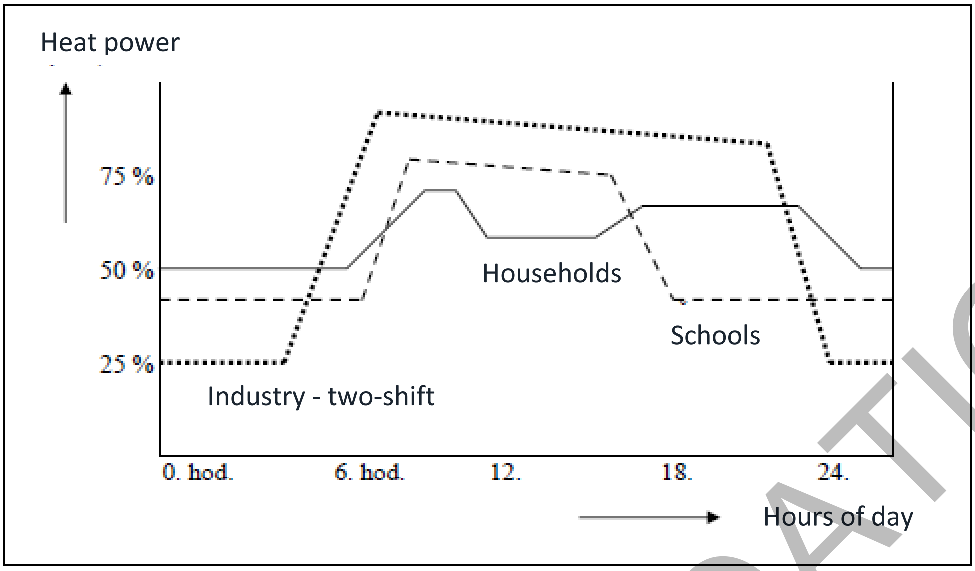

Figure 63 - Typical courses of daily heat needs for heating for different types of consumers in Czech Republic (Karafiát, 2016).

During summer, it can be very low, and during winter months, peak consumption can be even 10x higher depending on the size of the network and consumers. This can be seen from also data presented in the database by (Helen,2023) and the work by (Lindroos et al.,2019). Usually, in daily variation the heat consumption peaks during the day hours. Typical diagrams for the Czech Republic are presented in *Figure 61*, *Figure 62* and *Figure 63*.

Helen has constructed many heat storages. In 2018 they started to construct a heat storage in an old oil storage caves (see the following link). The parameters of this heat storage are the following:

- temperature 45 – 100 °C
- efficient water volume 260 000 m^3
- energy storage capacity 11 600 MWh, annual capacity 140 000 MWh
- charge and discharge power 120 MW

On https://www.globalheatingairconditioning.com/blog/how-does-a-heat-pump-work/, some data of district heating production can be found. Usage of different fuels for district heating production in Finland in 2021 is illustrated in the *Figure 64* and *Table 24*, whereas *Figure 65* shows the usage of fuels for DH in Czech Republic, also listed in *Table 25*.

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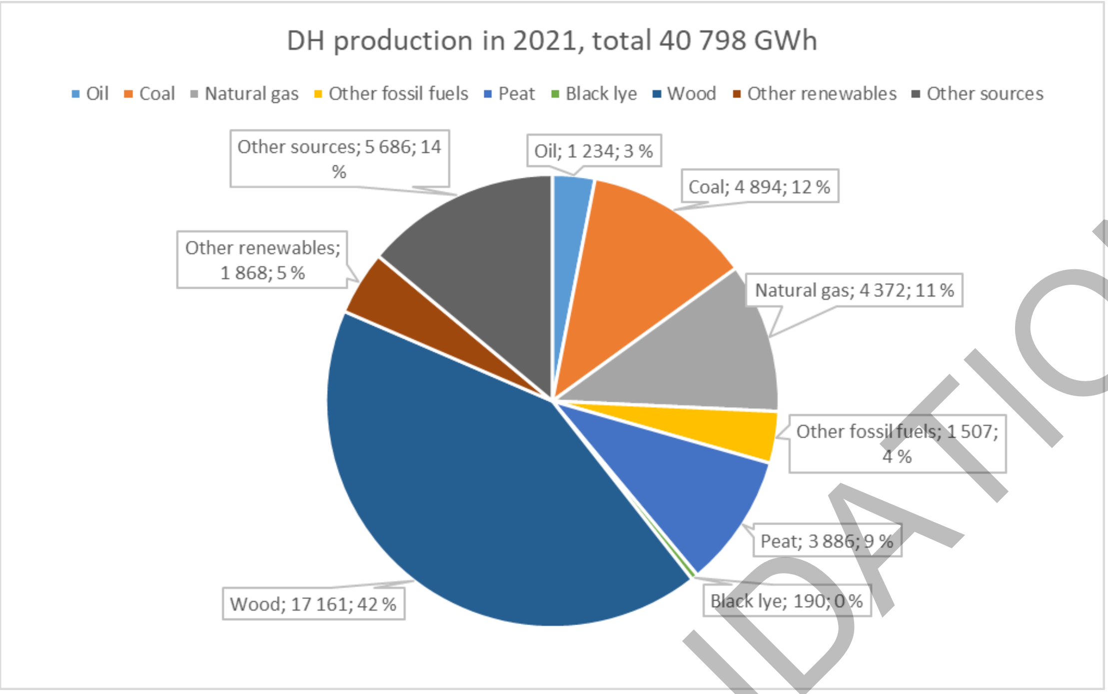

Figure 64 - District heat supply as well as the fuels used for DH and cogeneration 2021 in Finland (District heating production in Finland, Statistic Finland The material was downloaded from Statistic Finland's interface service on 12 April 203 with CC BY License 4.0)

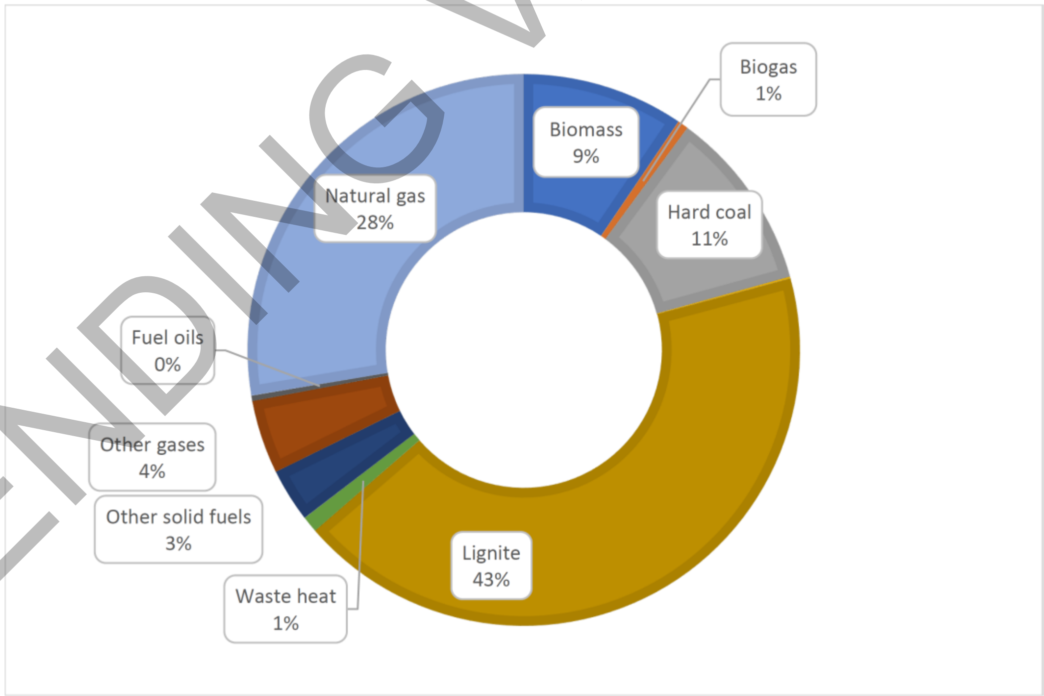

Figure 65 - Total heat supply in 2021 in Czech Republic (created by UJV in the scope of the TANDEM project).

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Total district heat supply	39,1 TWh
District heat production by fuels	33,7 TWh
Net production of electricity in CHP production	9,9 TWh
Fuel energy consumed	52,0 TWh
Heat recovery and heat produced by heat pumps	5,4 TWh

Table 24 - District heat supply as well as the fuels used for DH and cogeneration in 2021 in Finland

Total heat supply	25,67 TWh
Heat consumption by national economy sector	23,38 TWh
Industry	6,118 TWh
Energy	0,6124 TWh
Transport	0,2059 TWh
Construction	0,0647 TWh
Farming and forestry	0,1176 TWh
Households	10,21 TWh
Retail, services, schools, health care	5,558 TWh

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Other	0,492 TWh
Heat production from CHP	27,50 TWh
Gross heat production	44,9 TWh
Heat produced by heat pumps	0,027 TWh
Heat supplied by nnuclear power plants	0,0586 TWh

Table 25 - Total heat supply in 2021 in Czech Republic.

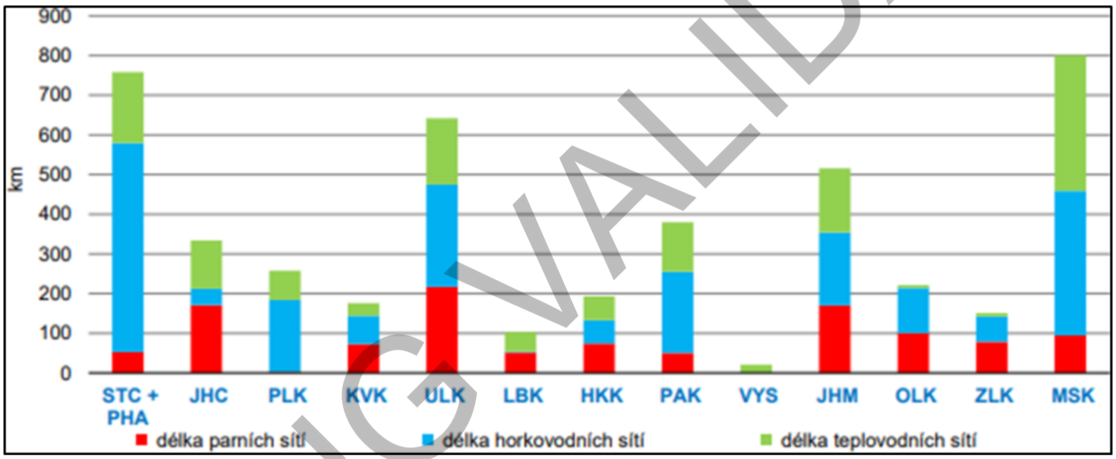

Figure 66 - Lengths of thermal networks in the decisive locations of DHS in the Czech Republic by region.

Délka parních síti - Length of steam networks
Délka horkovodních sítí - Length of hotwater networks (water with a temperature above 110 °C)
Délka teplovodních sítí - Length of warmwater networks (water with a temperature up to 110 °C)

PHA	*Prague*
JHČ	*Jihočeský (South Bohemian) Region*
JHM	*Jihomoravský (South Moravian) Region*
KVK	*Karlovarský (Karlovy Vary) Region*
VYS	*Vysočina Region*
HKK	*Královéhradecký (Hradec Králové) Region*
LBK	*Liberecký (Liberec) Region*
MSK	*Moravskoslezský (Moravian-Silesian) Region*
OLK	*Olomoucký Olomouc) Region PAK Pardubický (Pardubice) Region*
PLK	*Plzeňský (Plzeň) Region*
STČ	*Středočeský (Central Bohemian) Region*
ULK	*Ústecký (Ústí nad Labem) Region*

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ZLK *Zlínský (Zlín)*

Figure 66, whose data are taken from a report issued by the Czech Ministry of Industrial and Trade in 2022 (see [Assessment of decarbonization of district heating in the Czech Republic]), shows the length of thermal networks in Czech Republic. History of energy sources for production of district heating in Finland and Czech Republic is illustrated in *Figure 67* and *Figure 68* respectively.

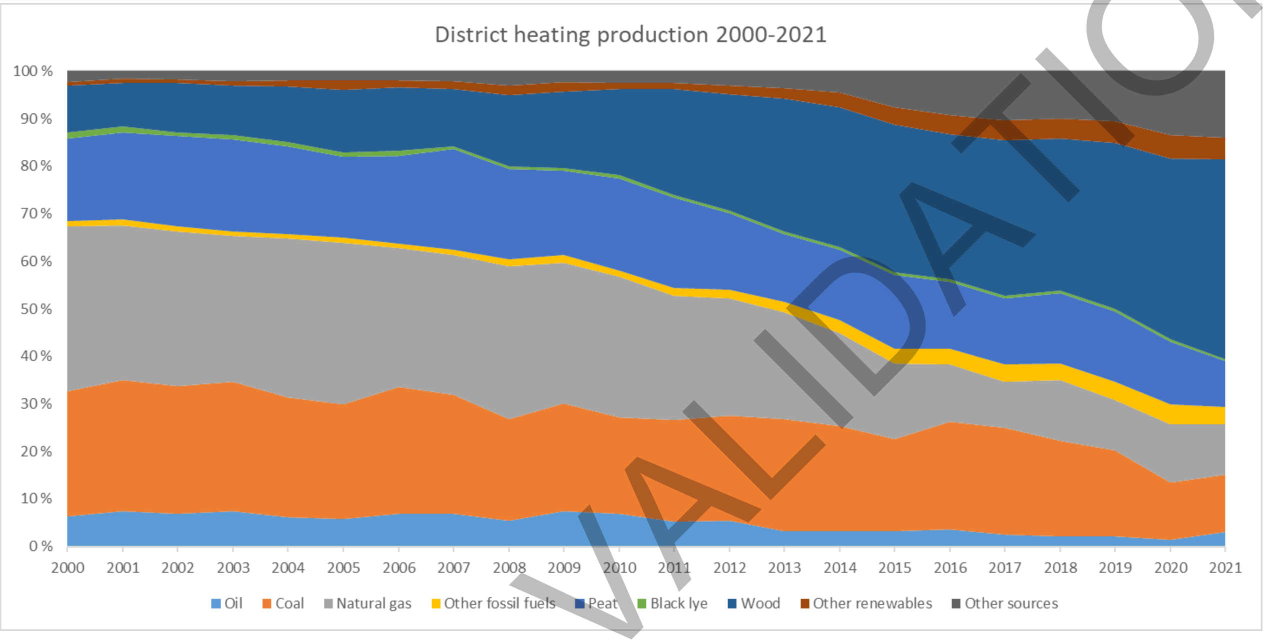

Figure 67 - Energy sources for district heat supply (District heating production in Finland, Statistic Finland The material was downloaded from Statistic Finland's interface service on 12 April 203 with CC BY License 4.0).

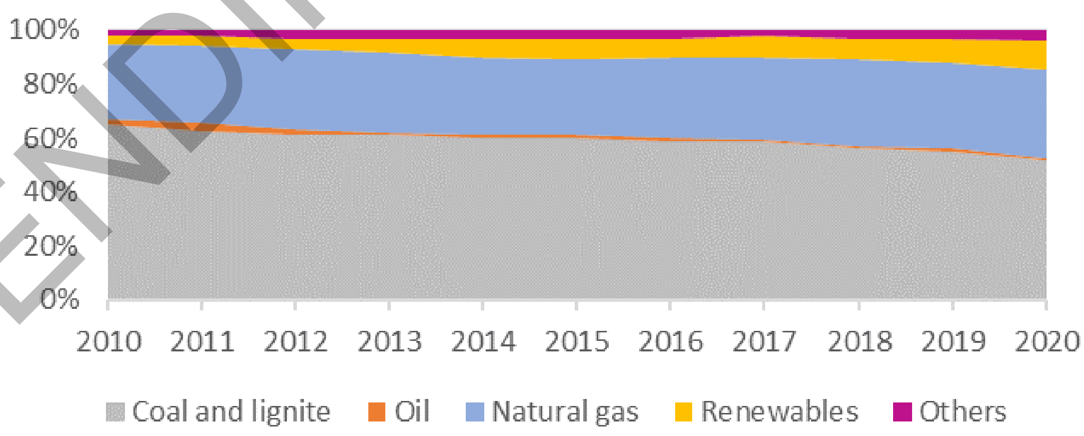

Figure 68 - Energy sources for heat supply in the Czech Republic (created by UJV in the scope of the TANDEM project).

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In the following sections, a brief overview of different district heating production modes is given.

9.1.1 Heat Only Boiler

Heat Only Boilers (HOB) are mainly used to produce district heating andthermal energy is their only product. The size scale in terms of power level is rather wide from few tens of kilowatts to few hundred of megawatts. Typically, they have one or multiple boilers which use either fuel oil, natural gas or biomass or electric coils. Depending on the network portfolio, heat only boilers can be used as baseload or in peak load power plants. Again, depending on the network portfolio, a heat storage can be connected directly to the HOB.

Nuclear heat boiler concepts are being developed, for example, in China and Finland (see, again, the WNA website and the presentation by Leppänen, 2022). The technical concept is rather simple. The reactor core heats water (i.e. primary circuit) which flows into a heat exchanger which is connected directly to an end user network (i.e. district heating network) or to secondary circuit which is then connected to the end user network. With this way it is ensured that the primary circuit water is not in direct contact with the district heating circuit.

The reactor core can be in a pressure vessel or in a non-pressurised open pool. Heat only boiler reactors also have less systems than power plants which produce electricity, hence they are smaller plants. The smaller size of the plant directly influences also safety. Due to the lower primary circuit pressure, smaller reactor core and other features, it has been suggested that emergency planning zone could be smaller than "conventional nuclear power plants". This means that heat only boiler reactors could be situated in cities or near to them, fulfilling the general requirement of proximity for district heating thermal energy producers.

9.1.2 Combined Heat and Power

The terms “Combined heat and power” mean that part of the steam commonly used to produce electricity via steam turbines is used, instead, to produce heat in a separate heat exchanger. This decreases electrical power level but enhances the overall efficiency of the power plant from about 30% to even 70 - 80%. Typically, ratio of the conversion is at least 1:4, i.e., with one unit of not-produced electricity, four units of thermal energy are produced.

Steam is produced in boilers which typically use the following fuels as primary energy source:

- coal
- biomass
- municipality waste

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- black liquor recovery boiler (usually industry use, pulp factories)
- oil or natural gas

There are multiple ways to configure the turbine system to be coupled with a heat exchanger to produce district heat, e.g., (EPA, 2015):

- bled steam either from the turbine or from reheater. In this case, the condenser is normally present in the steam cycle
- back-pressure turbine. In this case, instead, the condenser is not present as the heat exchanger for the district heating network plays its role.

Depending on the design of the turbine island plant, the power output levels can be controlled from their nominal levels. Typically, CHP plants provide base load during heating season which is typically from October to April. Thus, power levels are not changed that often. However, as district heating demand is not high during summer time, the plant operator could want to produce only electricity. Depending on the network portfolio, a heat storage can be connected to the plant. Back-pressure turbine configuration is interesting option when there is no access to heat sink. In these cases, the district heating network is the heat sink. However, if there is no need for district heating, then electricity cannot be produced.

9.1.3 Gas turbine combined power plants

Efficiency of gas turbine power plant is typically about 35% and it can be increased up to 60% by adding heat recovery boiler. Heat recovery boiler means that heat of the flue gases is used to produce steam, which is then supplied to a steam turbine generator system. By adding district heating production to this plant (in a similar way as described in the previous section), the overall efficiency of the plant can be increased even more. Gas turbines use natural gas or oil as fuel. In future, possibly hydrogen or biogas. Similarly, to CHP plants, even in this case there is clear integration between the production of district heating and electricity.

Combined heat and power plants are usually rather close to the city or even inside the supplied area. Although electricity distribution networks are not scope of this section, it must be mentioned that having an electricity production system inside the city is good also for the electricity grid.

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9.1.4 Heat Recovery – High Energy Sources

"High energy sources" typically refer to excess or waste heat from industry processes, which can be used directly in district heating production. Temperatures of these high industry processes are over 100 °C, otherwise they cannot be used. Nevertheless, the new-generation of DH systems will use water at temperatures lower than 100°C, making the integration in the DH grid of a large range of industries more feasible. Typical examples are petrochemical industry, oil industry, pulp mills etc. By choosing the medium wisely even lower temperatures (geothermal) can be used.

Waste heat is utilized by implementing heat exchangers connected to industry process and district heating network. Industry facility should be quite near the district heating network. Otherwise, is not economically feasible transport the heat as the investment and O&M costs of the transfer heat network can be high. This depends on the scale of the waste heat.

9.1.5 Heat Recovery – Low Energy Sources

With "low energy sources" we refer to heat sources which temperature is so low that it cannot be used directly for district heating applications. In this case, heat pump technology is used to increase temperature. Heat pump is a device which uses reversed Carnot cycle. For instance, the refrigerator is basically a heat pump. Heat pumps can be used to cool or heat and some technologies of heat pumps allow them to be used in both modes. The coefficient of performance (COP) value refers to the efficiency of the heat pump, which is defined as following:

$$COP = \frac{useful\ heating\ or\ cooling}{net\ work}$$

This means that, if a heat pump has a COP value equal to 2, 4MWh of heat energy can be achieved with 2 MWh of consumed electricity. COP value depends on the used technology and temperature of the source. The environment can be either gas (e.g. air) or liquid. Typically, COP values ranges from 2 to 5. When the temperature of the environment decreases, COP value decreases as well. The technology of heat pumps is rapidly evolving, meaning that the COP values are increasing, the size of heat pumps is increasing and so on.

A basic operating scheme of a heat pump is illustrated in *Figure 69*.

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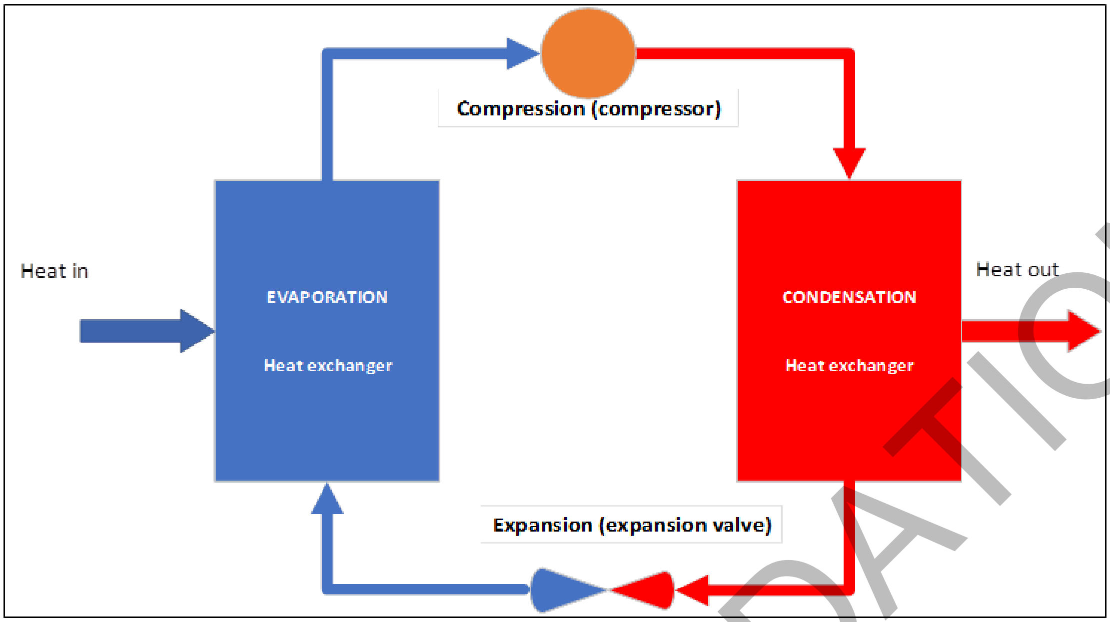

Figure 69 - Behaviour of the heat pump (created by FORTUM in the scope of the TANDEM project).

Heat pumps are used a lot in heating and cooling of buildings (households, office buildings etc). The heat is typically extracted or inserted into ambient air or ground. However, their role in centralized district heating production is increasing. In *Figure 70* and Table *26* efficiency and COP of the heat pumps are presented

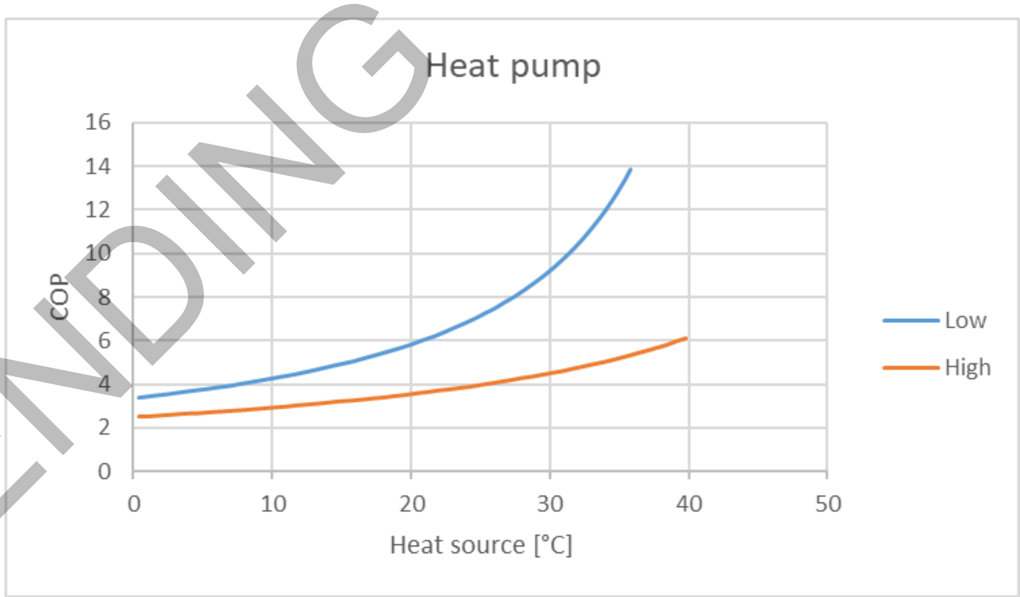

Figure 70 - COP values as function of source temperature for two output levels (created by FORTUM in the scope of the TANDEM project).

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	Air source			Excess heat			Seawater	
Size	1 MW	3 MW	10 MW	1 MW	3 MW	10 MW	20 MW	65 MW
η-Lorenz, 2020	47 %	53 %	60 %	40 %	45 %	50 %	63 %	47 %*
η-Lorenz, 2050	51%	58%	62%	44%	49%	54%	65%	47%*

*The Lorenz efficiency is based on a CO_2 heat pump. The Lorentz efficiency is based on the design temperatures seen in the datasheet.

Table 26 - Efficiency estimations for the heat pumps (From Danish Energy Agency).

They can be used to implement waste heat which temperature is low (< 100°C). Some examples of energy sources are hereafter listed:

- excess heat from data centres;
- waste water;
- lakes or sea;
- geothermal;
- air.

Some would say that warmed cooling water of nuclear power plant is waste heat. In theory, this heat could be used in district heating production with heat pumps. Nevertheless, this approach would require electricity, thus operating nuclear power plant in CHP configuration could be better choice.

Especially during summer time, heat in the district cooling (centralized cooling, i.e., reversed district heating) network can be used to produce district heating.

Heat pumps integrate heating, cooling and electricity. This opens up new opportunities together with heat storages.

9.2 Component Coupling with the HES

Heat only boilers (nuclear), combined heat and power (nuclear) and heat recovery (heat pumps) are proposed to be modelled because usage of nuclear in district heating is now a possible and efficient way to produce district heating and electricity. Heat pumps are proposed because it is

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CO_2 free (assuming that it uses CO_2 free electricity) way and integrates district heating and cooling to electricity. *Figure 71*, *Figure 72* and *Figure 74* depict the three envisaged configurations.

District Heating

The district heating component or model is rather simple. It consists of the following components:

- hot leg pipe (outlet from power plant) that has fluid (water), temperature, mass flow, pressure (if needed) at least parameters
- cold leg pipe (inlet to powerplant), same parameter
- consumption as boundary condition (power as function of time)
- heat exchanger in the power plant but this can be considered in the power plant model
- heat loss [power / distance]
- pressure loss [pressure / distance]

The district heating network (i.e. the pipes) works as buffer or even as heat storage. It is recommended to be modelled with 1D components.

Heat only boiler (nuclear)

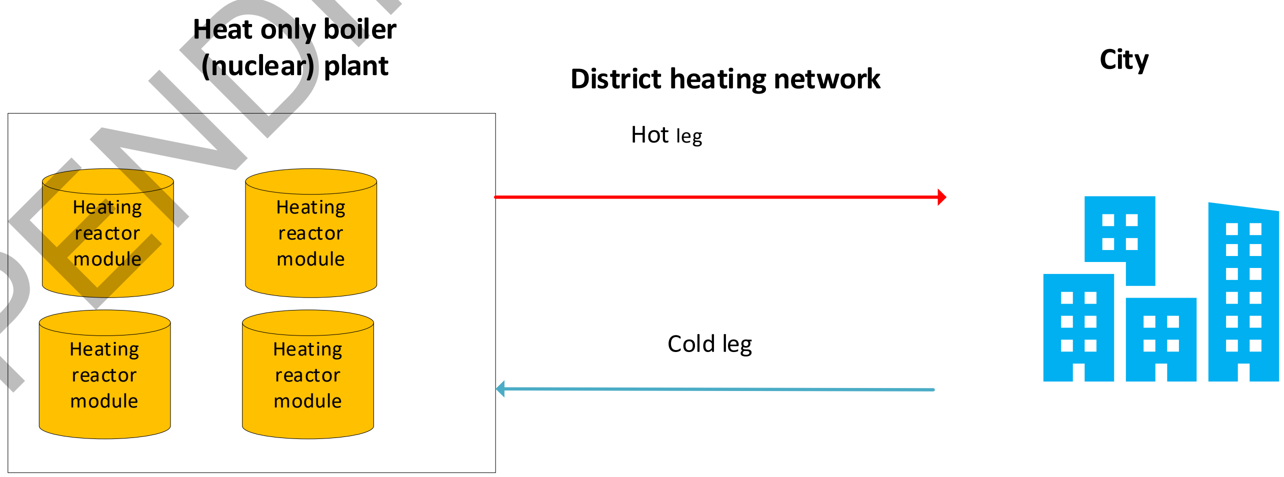

Figure 71 - Heat only boiler model (created by FORTUM in the scope of the TANDEM project).

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The model is rather simple. It can be modelled as one "heat source" with following parameters:

- power level (as function of time)
- outlet temperature (link to district heating component)
- inlet temperature (link to district heating component)
- ramp up (fuel type and boiler have an effect)
- ramp down (fuel type and boiler have an effect)
- costs (CAPEX and OPEX)

To simulate non-nuclear heat only boiler, the same component can be used with different parameters.

Combined heat and power (nuclear)

Combined heat and power model is almost the same as the NPP model except modification to turbine island (turbine, district heating exchangers etc).

- electricity power level (as function of time, depends on electrical power level)
- district heating power level (as function of time, depends on electrical power level)
- electricity efficiency in maximum power [MWe/MWth]
- electricity efficiency in minimum power [MWe/MWth]
- district heat efficiency in maximum power [MWdh/MWth]
- district heat efficiency in minimum power [MWdh/MWth]
- district heating outlet temperature (link to district heating component)
- district heating inlet temperature (link to district heating component)
- ramp up (turbine-generator, fuel type and boiler have an effect)
- ramp down (turbine-generator, fuel type and boiler have an effect)

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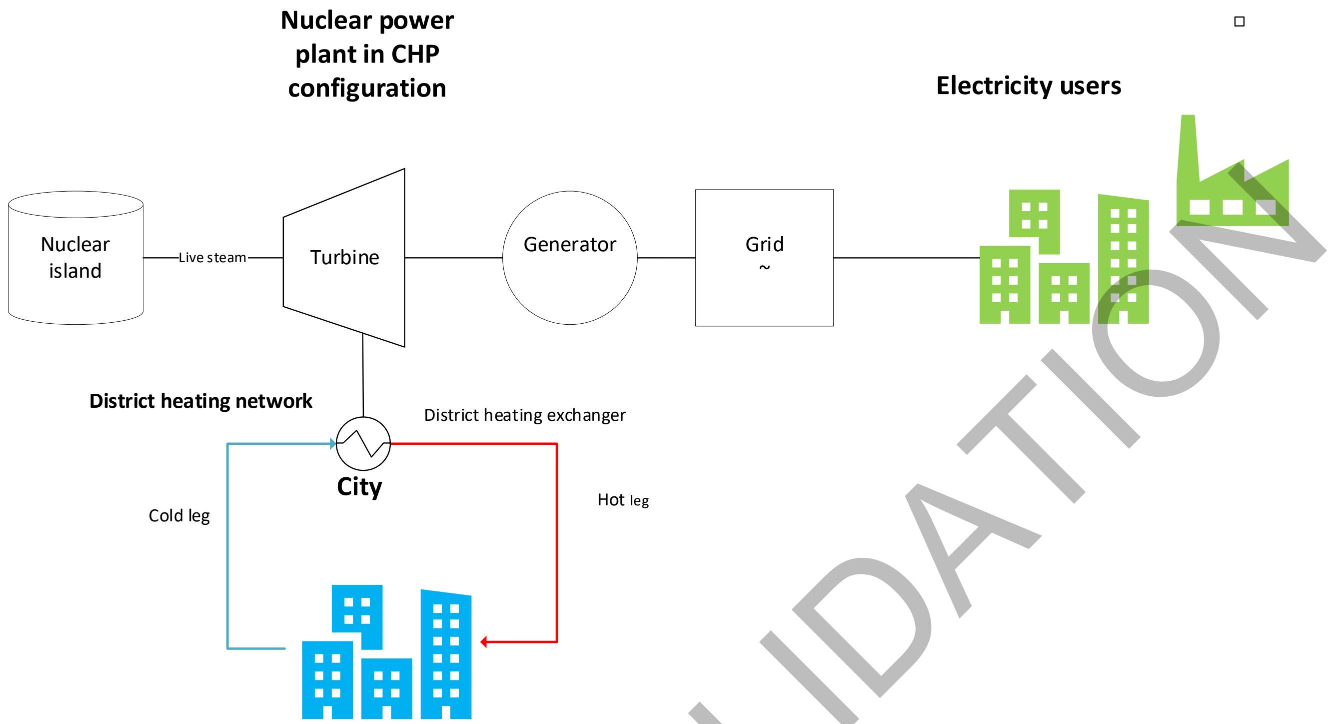

Figure 72 - Nuclear power plant in CHP configuration (created by FORTUM in the scope of the TANDEM project).

Exact location of the take-off line (to the district heating exchangers) depends on the design and how the turbine island / balance of plant is optimized. There are multiple options:

1. intermediate heating or take off from the intermediate turbine (if it exists) - between high-pressure and low-pressure turbines (recommended)
2. take-off from the low-pressure turbine
3. after low-pressure turbine, replacing the condenser

There are some publicly available studies about how this could be done. One of them is the work by (Laitinen, 2018).

If a pressurised water reactor is modified into CHP use, this take-off line can be directly connected to district heating network. In case of boiling water reactor take-off line is connected to heat exchanger of intermediate circuit which is connected to district heating exchanger.

Figure 73 presents the simplified approach for the first option just discussed (i.e., steam bled from the intermediate turbine or between high-pressure and low-pressure turbine).

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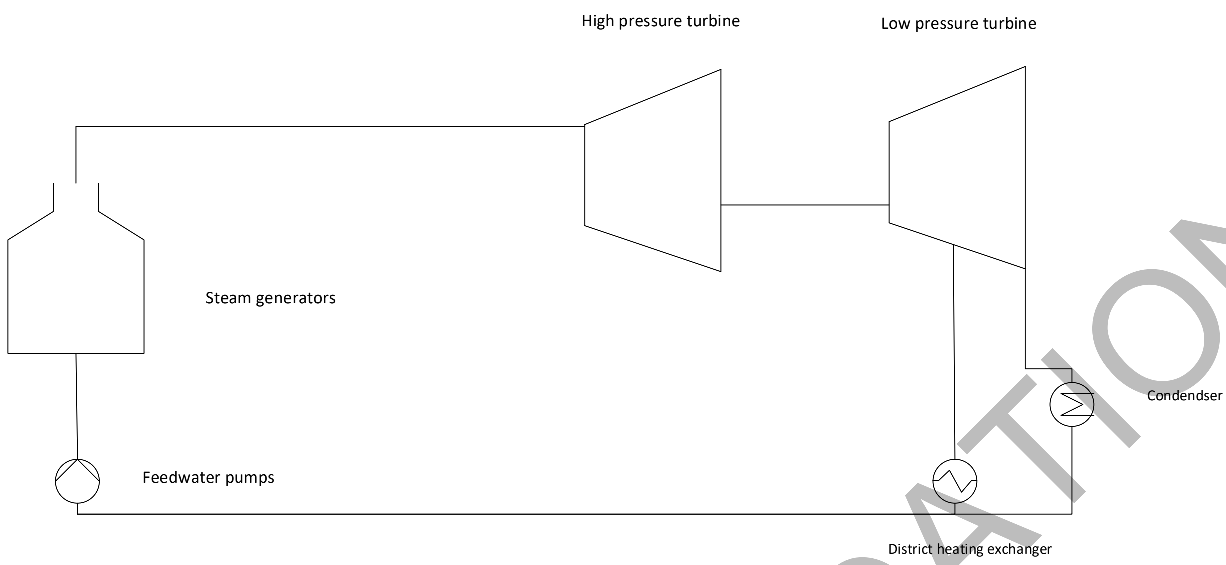

Figure 73 - Simplified diagram for option 1 (created by FORTUM in the scope of the TANDEM project).

Heat pump facility

The model is rather simple. It can be modelled as one "heat source" with the following parameters:

- electrical power level (required electrical power level, as function of time)
- produced power level (depends on COP and required electrical power level, as function of time)
- inlet temperature (heat source which can be assumed as infinite)
- outlet temperature (depends on power level and COP, link to district heating component)
- ramp up
- ramp down
- COP curve (depends on inlet temperature and assumed curve, as function of inlet temperature)

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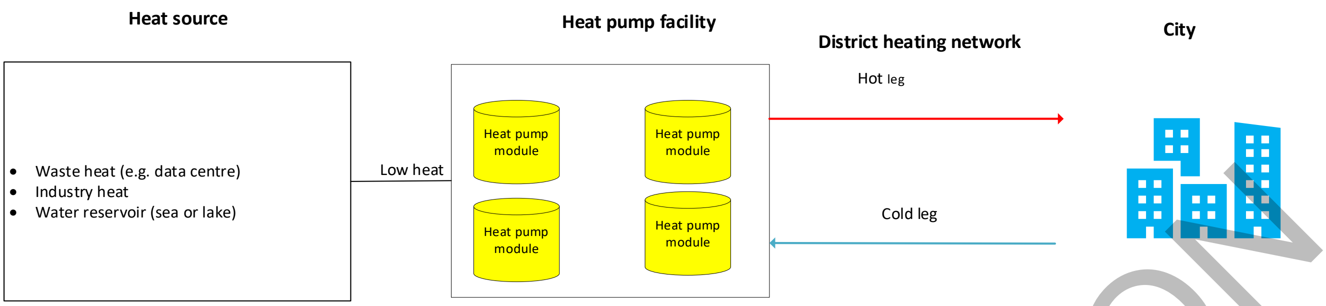

Figure 74 - Heat pump facility (created by FORTUM in the scope of the TANDEM project).

9.3 Main System Architecture and Operating Data

In this section, the main system architectures (if more than one can be possibly adopted) and the main operating data are defined.

9.3.1 General System Architecture

To simplify modelling and simulation work, the following assumptions are proposed:

- winter time – heating season
- summer time – no heating season should be simulated to illustrate that nuclear CHP can be used in other operation modes
- multiple DH consumers
  - multiple smaller cities (peak load of hundreds of megawatts) -> heat only boilers and other facilities
  - 1-2 larger cities -> nuclear CHP and other facilities
- heat pumps should be considered as they could have a great impact on DH systems in future scenarios
- scenarios:
  - 2035 – biomass still needed
  - 2050 – biomass probably not needed anymore
- Other production facilities and heat storages should be modelled based on the scenario in question.

Parameters for other district heating and electricity production methods can be found from (Lindroos et al., 2019) and the Danish Energy Agency website.

9.3.2 Main operating data

In this section, a preliminary list of the main operating data which would be needed to perform the modelling of a DH system is given. However, their sizing values are still missing and will be provided in a later phase directly to WP2 partners. The main parameters for each addressed case are listed in Table *27*, Table *28* and Table *29*.

Heat only boiler

1D modelling is required. Detailed parameters can be provided in later phase.

Parameter	Value
Power level (as a function of time)	MW
Outlet temperature (linked to district heating component)	°C
Inlet temperature (linked to district heating component)	°C
Ramp up (fuel type and boiler have an effect)	%/s
Ramp down (fuel type and boiler have an effect)	%/s
Minimum online time	h
Maximum online time	h
Maintenance break time	h
Variable costs	

Table 27 - Main parameters needed to model DH with HOB.

Combined heat and power (nuclear)

1D modelling is required. E-SMR component should be used as basis. The CHP configuration and its behaviour depends on design. It is recommended to consider a pressurised water reactor which uses bleedings from the low-pressure turbine. Detailed parameters can be provided in later phase.

Parameter	Value
Electricity power level (as a function of time, depends on electrical power level)	MW
District heating power level (as function of time, depends on electrical power level)	°C
Electricity efficiency in maximum power [MWe/MWth]	°C

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Electricity efficiency in minimum power [MWe/MWth]	
District heating efficiency in maximum power [MWdh/MWth]	
District heating efficiency in minimum power [MWdh/MWth]	
District heating outlet temperature (linked to district heating component)	
District heating inlet temperature (linked to district heating component)	
Ramp up (turbine-generator)	%/s
Ramp down (turbine-generator)	%/s
Minimum online time	h
Maximum online time	h
Maintenance break time	h
Variable costs	

Table 28 - Main parameters needed to model DH with nuclear CHP.

Heat pump

1D modelling is required. The definition of the model depends on scenarios and what kind of "waste heat sources" are estimated. Detailed parameters can be provided in a later phase.

Parameter	Value
Electrical power level (required electrical power level, as a function of time)	MW
Produced power level (depends on COP and required electrical power level, as a function of time)	MW
Inlet temperature (heat source which can be assumed as infinite)	°C
Outlet temperature (depends on power level and COP, linked to district heating component)	°C
Ramp up	%/s
Ramp down	%/s
COP curve (depends on inlet temperature and assumed curve, as a function of inlet tempter)	Table

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Minimum online time	
Maximum online time	
Maintenance break time	
Variable costs	

Table 29 – Main parameters needed to model DH with Heat Pumps.

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10. Electrical Grid

The electrical grid is an element that connects different electricity producers to end-users and plays, in that sense, an unavoidable role in the energy future. The European electrical grid is growing rapidly to improve its geographical robustness, to respond to the industry decarbonization and to connect an increasingly decentralized and plural production and storage facilities. Therefore, the electrical grid is an essential element to tackle the integration of SMR into hybrid energy network.

10.1 Literature Survey

The electrical grid is mainly composed of the following components:

- Lines and cables permitting the electricity transmission and distribution from the power plants to the final users;
- Power transformers used to adapt the voltage level (high, medium and low voltage);
- Compensation devices used to improve the efficiency, the stability and the security of the electrical grid;
- Protections of the different components present in the electrical grid. Disconnectors are also used to isolate part of the grid;
- HVDC technologies implemented to deal better with long distances and/or asynchronous areas.

These different components are not specific to a hybrid power system. All the components of the electrical grid may be used to interconnect similar or hybrid technologies. The power converters and transformers are used to make these interconnections possible.

10.1.1 Lines and cables

The electricity is transmitted and distributed from the different types of power plant to the final users through the overhead lines and cables.

The overhead lines are used at different voltage levels (110kV, 132-150kV, 220kV, 300-330kV, 380-400kV, 500kV, 750kV, …). The overhead lines are fixed at the top of towers. The configuration

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of the circuits and the form of the towers may be very varied. This topology is important to calculate accurately the electrical parameters of the lines.

The conductors are usually made of copper, aluminium or aluminium alloy. The sectional area may vary from a few mm² to more than a thousand mm² (e.g. depending on the voltage level, the line length).

The cables used for the transmission and the distribution of the electricity are even more varied. The cables may be first categorized as underground, submarine or aerial. The cables may be single-core or three-core depending on several parameters like the voltage level and the load capacity. Cables are also classified depending on the type of the core insulation (oil-impregnated paper, ethylene propylene rubber (EPR), cross-linked polyethylene (XLPE), …).

10.1.2 Power transformers

The transformer is a fundamental component of an electrical grid. It permits to increase the voltage level at very high value in order to decrease the transmission losses and the voltage drops. Generally, three banks of single-phase transformers are used to connect very large generators to transmission network. In the transmission and distribution network, three-phase power transformers are usually used (Tiels, 2008). At the distribution stage, the transformers adapt the voltage level according to the final users. The transformers also permit to connect together different technologies working at different voltage level or frequency.

The transformers are also used for the active and reactive power flow control (phase shifter PS and quadrature boosters QB). Transformers used for voltage control are equipped with off-load or on-load tap-changers that vary the number of turns on the associated winding and hence the turns ratio of the transformer.

10.1.3 Compensation devices

In the electrical grid, different compensation devices are used to improve the efficiency, the stability and the security of the power system network. These components are series and shunt reactors and capacitors.

Series reactors

The series reactors are used for the power flow control and to limit the sort-circuit currents. Air core reactors are usually used up to 36 kV but iron-cored reactors are generally used at higher voltages (Tiels, 2008). Series reactors have very low internal resistance which allows to flow the current in normal condition and block the current when required.

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Shunt reactors

The shunt reactors are used to absorb the reactive power due to the line or cable capacitance. The sending end voltage is higher than the receiving end voltage. The shunt reactors reduce the voltage when the receiving end voltage is higher than the sending end voltage.

Series capacitors

The series capacitors are also widely used in transmission and distribution networks. In distribution, they are mainly used to improve the voltage profile of heavily loaded feeders. In transmission, they are mainly used to increase network power transfer capabilities by improving generator and network transient stability, damping of power oscillations, network voltage stability or load sharing on parallel circuits.

Shunt capacitors

The shunt capacitors provide a source of reactive power supply and help to improve network voltage stability, voltage levels and power factors.

10.1.4 Protections and disconnections

The different components of the electrical grid are protected by protection devices. A complete protection system consists in different subsystems. A battery is needed to guarantee a reliable supply in case of fault. Indeed, the AC voltage of the line can be impacted by the fault and may thus not be of sufficient magnitude to correctly supply the protection system. The transducers are the current and the voltage transformers necessary to decrease the magnitude of the signals coming from the transmission lines to an acceptable level for data acquisition hardware. The relay is the logic element that initiate a tripping and closing signals to the circuit breaker. It disconnects the element operating abnormally from the power system in case of fault, and potentially, reconnects this element at the right time if the fault is transient. Finally, the circuit breaker is used to disconnect physically the faulty components from the power system if a tripping signal is sent by the relay. Moreover, circuit breakers and disconnectors are used as well for operationality, power dispatching and maintenance of an electrical network.

10.1.5 HDVC

The high voltage transmission of electricity is generally realised with alternative current at 50 Hz or 60 Hz depending on the country. However, the use of High-Voltage Direct Current (HVDC) presents several advantages (Spooten et al., 2022):

- Lower transmission losses;

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- No stability limitation of transmission length compared to AC transmission;
- High controllability, since the power flowing through an HVDC connection can be set by the control means of the converters;
- Interconnection of asynchronous areas and/or distant generating units, such as offshore wind farms;
- Smaller right of way, since fewer lines/cables are required to transfer the same power as an AC connection;
- Even if requiring costly conversion equipment at the terminal stations, their total transmission costs over long distances are reduced in comparison with the ones of AC lines (for the same distance).

The HVDC grid also permits to interconnect areas working at different frequency. The Nemo Link was the first interconnector between the UK (50 Hz) and the Belgium (50 Hz) (Spooten et al., 2022). This 1000 MW HVDC link is based on the Voltage-Source Converters (VSC) technology.

The ALEGrO link was the first cross-border link between Germany and Belgium (Spooten et al., 2022). It is also a 1000 MW HVDC-VSC link. In this case the choice if this technology was motivated be the need to control power flows on a link that is operated in parallel with AC corridors equipped with phase-shifting transformers.

10.2 Component coupling with the HES

Figure 75 gives a global overview of the main blocks that will be considered for the study and the modelling of the electrical grid that connect SMR to the hybrid energy system composed by, e.g., hydrogen production plant, wind turbine offshore park and energy storage.

The electrical grid is a key component since it electrically connects all the blocks developed in the TANDEM's framework project. The electrical flux flowing through the grid could be of two ways depending on the block: electrical producer (e.g., SMR, PV, wind turbine) and/or electrical consumer (e.g., hydrogen production, SMR auxiliaries).

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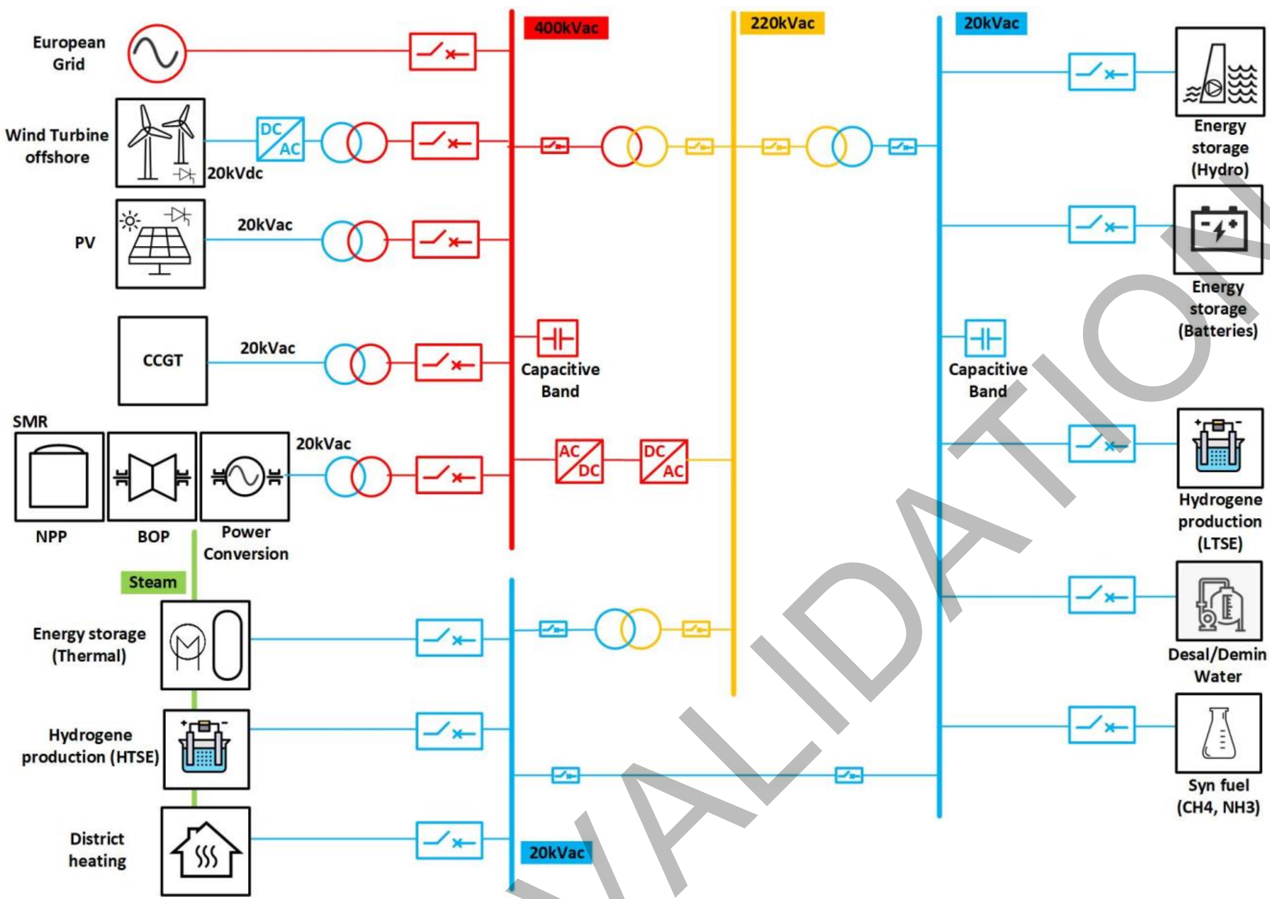

Figure 75 - Model Flow Diagram (created by TRACTEBEL in the scope of the TANDEM project).

Single phase RMS (Root Mean Square) voltage and current will be modelized since it fits to standard MODELICA library blocks while keeping technical representability needed for the TANDEM's project. Moreover, single phase RMS variables allows to keep computing effort reasonable if compared with three-phase sinusoidal variables.

The electrical grid model will consider different types of interconnected network, from local grid (e.g., 20kVac) to the European 400kVac grid.

The electrical grid model will be mainly composed of line impedances, transformers and switches. Main components are described hereunder.

10.3 Main operating data

10.3.1 Lines and cables

Different models may be used to represent an overhead line or a cable (see *Figure 76*). In the latter sketch, the models appear by increasing of level of accuracy (from the simple RL lumped parameters model to the distributed and frequency dependent parameters models) and

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therefore by increasing level of complexity. The model to use will depend on the type of application.

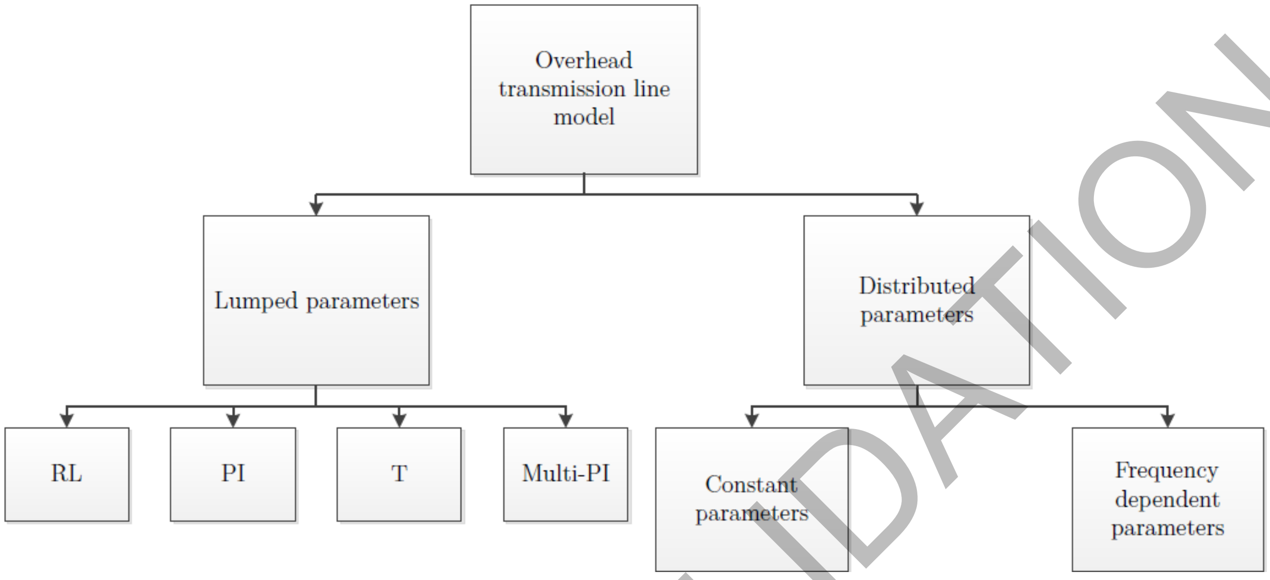

Figure 76 - Transmission line models (created by TRACTEBEL in the scope of the TANDEM project).

For steady-state studies, such as load flow and short-circuit studies, only positive and zero sequence parameters at power frequency are needed. In this case, the exact-PI model of line (see *Figure 77*) is the best choice.

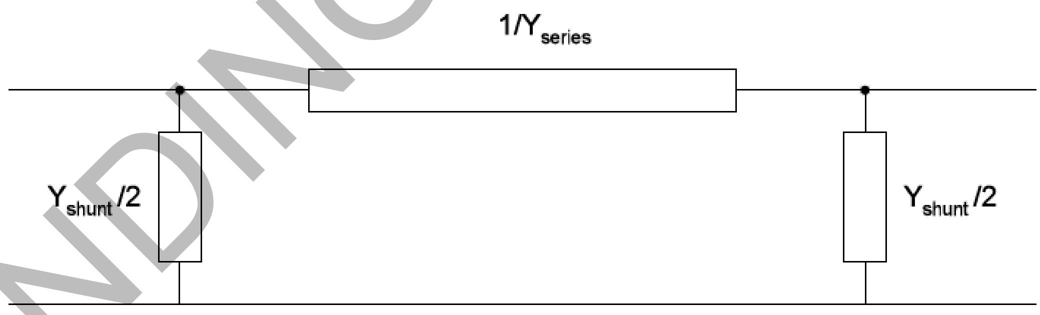

Figure 77 - Representation of the exact-pi model (Horowitz and Phadke, 2008).

with:

$$\frac{1}{Y_{series}} = \frac{(R' + j\omega L') \cdot l \cdot \sinh(\gamma \cdot l)}{\gamma \cdot l}$$

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$$Y_{shunt/2} = \frac{(j\omega C'/2) \cdot l \cdot tan\mathrm{h}(\gamma \cdot l/2)}{\gamma \cdot l/2}$$

where, *R'*, *L'* and *C'* are the resistance, inductance, and capacitance per unit length, *l* is the line length, and γ is the propagation constant which is equals to

$$\gamma = [(R' + j\omega L') \cdot j\omega C']^{1/2}$$

For transient studies, such as switching and lighting surge studies, the distributed and frequency dependent parameters models are the most suitable. The implementation of these models is based on the modal theory which represents a higher mathematical complexity (Meyer, 1981).

For the TANDEM project purposes, the overhead lines and cables may be modelled as a nominal-PI model as shown in *Figure 78*. This model approximates the exact-PI model which becomes less accurate while the line length increases.

Figure 78 - Nominal-PI model: positive sequence (left) and zero sequence (right) (Lundberg, 2016).

10.3.2 Power transformers

A transformer may be replaced in a power system by an equivalent circuit as represented in *Figure 79* with the self-impedance at both sides representing the winding resistances and the winding leakage reactances (Tleis, 2008). R_I represents the core iron losses (due to the hysteresis and eddy current) and X_M the core magnetising reactance. The relative magnitudes between the leakage impedances and magnetising reactance is very high and they are rarely considered together, so that the transformer may be represented either as a series impedance or as an excitation impedance, according to the problem being studied.

The equivalent circuit of *Figure 79* may be used for a three-phase transformer direct sequence by simply considered the direct sequence parameters (Tleis, 2008). For the zero sequence, the equivalent circuit shown in *Figure 80* may be used. Depending on the winding arrangement and the connection with the ground, the zero-sequence equivalent circuit must be adapted by closing the link a or b.

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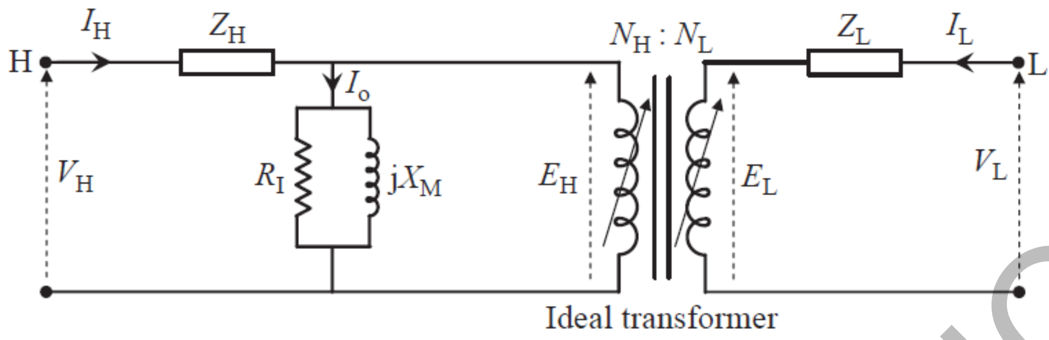

Figure 79 - Single-phase two windings transformer equivalent circuit (Tleis, 2008).

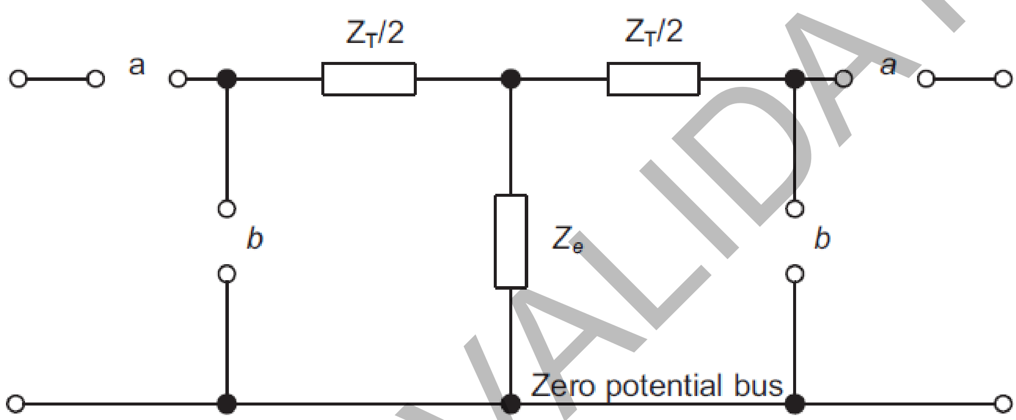

Figure 80 - Transformer zero sequence equivalent circuit (Tleis, 2008).

More complex models are widely present in the literature considering the saturation effect, the capacitances between windings and the ground, the asymmetry of three-phases transformers,… For the TANDEM project the models presented above are accurate enough until around 2kHz.

10.3.3 Compensation devices

Series reactors

A three-phase series reactor composed of three-limb core may be simply represented as three independent leakage impedances as shown in *Figure 81* (Tleis, 2008). Indeed, for this configuration there is practically no mutual inductive coupling between the phases of the reactor. Moreover, the phase windings are practically identical.

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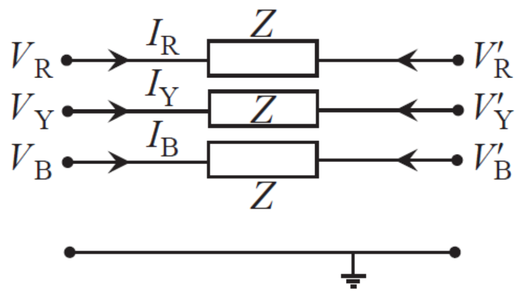

Figure 81 - Equivalent circuit of a 3-limb core series reactor (Tleis, 2008).

Shunt reactors

In three-phase shunt reactors, there is practically negligible mutual coupling between the phases. Three-phase shunt reactors may be represented as shown in *Figure 82* (Tleis, 2008).

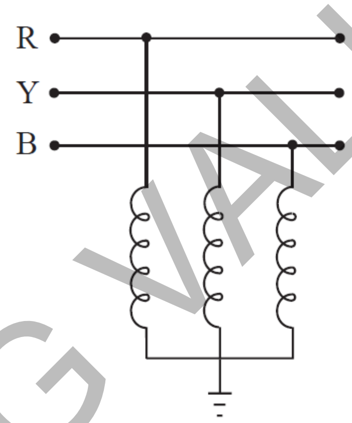

Figure 82 - Three-phase shunt reactor (Tleis, 2008).

The resistive part of the shunt reactor is normally neglected since, by design, these are required to have very high X/R ratios to minimise active power losses.

Series capacitors

The *Figure 83* shows some possible configurations for a series capacitor connection on a line. In normal condition this compensation device may be represented as three identical and independent reactances.

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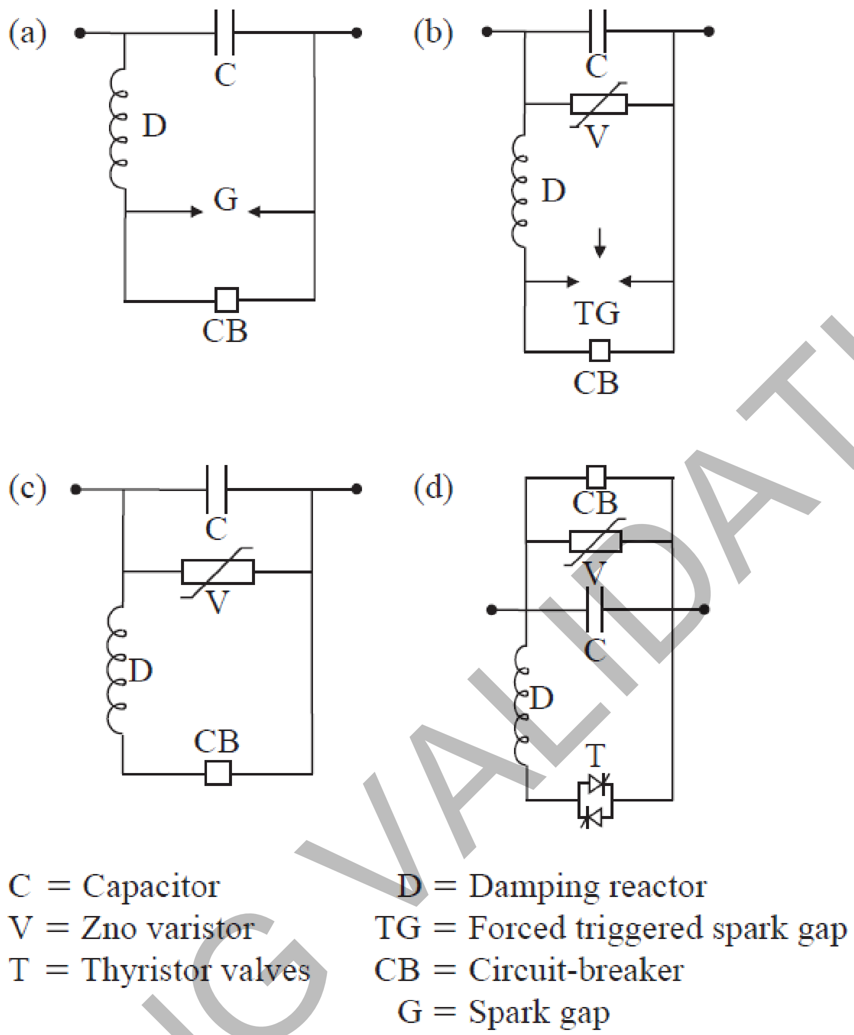

Figure 83 - Typical series capacitor schemes (Tleis, 2008).

In parallel of the capacitance there is a protection device permitting to protect the capacitance against overvoltage during a short-circuit. During the short-circuit, the capacitance is bypassed. In modern series capacitor devices, non-linear resistors like MOV's are used to provide this overvoltage protection. The non-linear behaviour of the varistors may be also implemented in order to have an accurate model in the case of short-circuit faults.

Shunt capacitors

The shunt capacitors may also be represented as 3 independent capacitances since the mutual coupling between the phases is negligible (see *Figure 84*).

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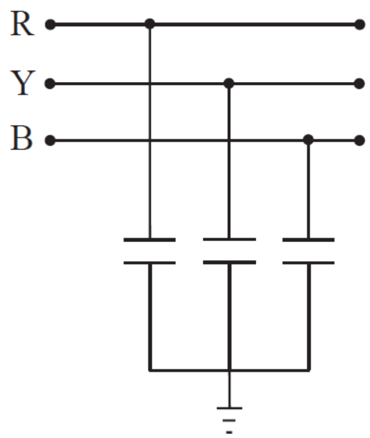

Figure 84 - Three-phase shunt capacitor (Tleis, 2008).

10.3.4 Protections and disconnections

For the TANDEM project, it is not required to implement the complete protection system since only steady-state RMS voltage is studied. The accurate model of the protections and the disconnectors may be useful only if a transient study is performed (i.e. arc-extinction study). The circuit breakers and the disconnectors will be then simply represented as ideal switches.

10.3.5 HDVC

The *Figure 85* shows a meshed network based on the HVDC technology (Spooten et al., 2022).

The converters may be based on different technologies like the IGBT-based Voltage-Source Converters (VSC), the thyristors-based Line-Commutated Converters (LCC). The DC/DC converters may be used to connect several HVDC links together.

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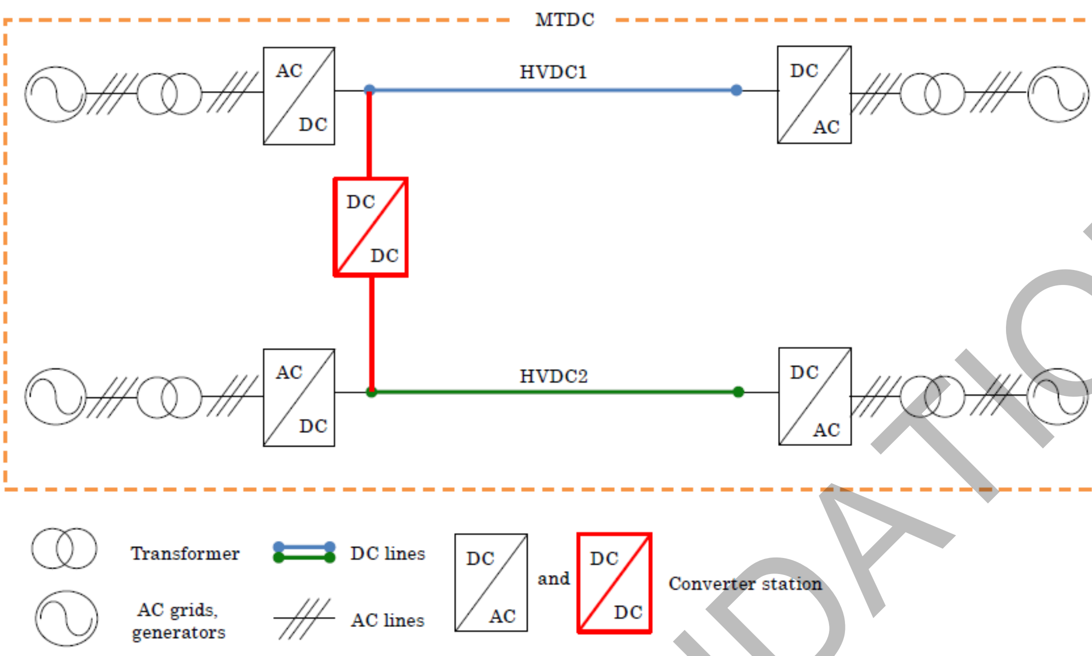

Figure 85 – Multi-Terminals DC Systems including AC/DC and DC/DC HVDC converters (Spooten et al., 2022).

10.4 Main components of the system and operating data

10.4.1 Lines and cables

The calculation of the different parameters of the overhead lines and cables depends on a lot of factors like the voltage level, the tower topology, the transposition scheme, the earth resistivity, the line and cables material, the sectional area.

Voltage kV	Material	Section mm²	N°/phase	Rd Ω/km	Xd Ω/km	Bd/2 µS/km	R0 Ω/km	X0 Ω/km	B0/2 µS/km
380	AMS-AC	593	2	0.0396	0.3244	1.7477	0.1372	0.8021	0.9489
220	AMS	228	2	0.1775	0.4518	1.4949	0.3273	0.8529	1.2996
150	AMS	926	2	0.0229	0.2842	2.0317	0.1096	0.8097	1.1282
70	AMSz	298	1	0.1345	0.3937	1.4642	0.2796	1.4756	0.7759

Table 30 – Overhead line direct and zero sequence parameters.

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Voltage kV	Type	Material	Section mm²	Rd Ω/km	Xd Ω/km	Bd/2 µS/km	R0 Ω/km	X0 Ω/km	B0/2 µS/km
150	EXeLW	XLPE+Cu	500	0.0489	0.1323	21.692	0.2348	0.1655	21.693
70	EXeLW	XLPE+Cu	240	0.0971	0.1335	24.308	0.3036	0.1836	24.308
36	EXeCW	XLPE+Cu	400	0.0602	0.1117	33.440	0.143	0.0730	33.440

Table 31 – Underground cable direct and zero sequence parameters.

These parameters may be calculated or found in the datasheet of the manufacturers. Some examples of parameters are shown in Table *30* for the overhead lines and in Table *31* for underground cables (Richards et al., 2011). The definition of the different parameters is shown in Figure *78*.

10.4.2 Power transformers

Some examples of parameters are shown in Table *32*, Table *33* and Table *34* for distribution and generator transformers (Richards et al., 2011).

MVA	Primary kV	Primary Taps	Secondary kV	Z% HV/LV	X/R ratio
7.5	33	+5.72% -17.16%	11	7.5	15
15	66	+9% -15%	11.5	15	14
30	33	+5.72% -17.16%	11	30	40
60	132	+10% -20%	33	16.7	28
90	132	+10% - 20%	66	15.1	41

Table 32 – Impedances of two winding distribution transformers – Primary voltage < 200kV.

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MVA	Primary kV	Primary Taps	Secondary kV	Tertiary kV	Z% HV/LV	X/R ratio
20	220	+12.5% -7.5%	6.9	-	9.9	18
74	345	+14.4% -10%	96	12	8.9	25
120	275	+10% -15%	34.5	-	22.5	63
180	275	+15% -15%	66	13	22.2	38
255	230	+10%	16.5	-	14.8	43

Table 33 – Impedances of two winding distribution transformers – Primary voltage > 200kV.

MVA	Primary kV	Primary Taps	Secondary kV	Z% HV/LV	X/R ratio
95	132	+10% -10%	11	13.5	46
250	300	+11.2% -17.6%	15	28.6	70
450	132	+10% -10%	19	14	49
900	525	+7% -13%	23	15.7	67

Table 34 – Impedances of generator transformers (three-phase units).

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11. Conclusion

In this framework, the light-water technology has been considered although there is the possibility, eventually, to extend the results also to AMR technologies.

In this document, a techno-economic description of all the components to be implemented in the two Hybrid Energy Systems addressed by TANDEM (i.e., energy hub in Southern Europe and District Heating in Northern Europe and Central Europe) is made, coming from a work led by Ansaldo Nucleare (ANN) and carried out by several partners on the basis of their own field of expertise. The collection of data was made by using a template made by ANN in order to get the information in the most homogeneous way.

After a description of all the possible technologies for each block (or module) of the Hybrid Energy System, each responsible partner with the aid of the supporter one(s) suggested a certain technology to be addressed in the modelling phase of the HES which will be carried out within WP2. Table *35* resumes the main outcomes of the work the present document aims to describe. As said in the relative sections for each module of the HES, some of the main information will be directly provided to the partners directly involved in the modelling phase (i.e., within WP2). Besides, some of the assumptions and suggestions made in this document may be subjected to changes during the prosecution of the project.

Block	Addressed Module	Suggested technology for modelling	Responsible Partner	Supporter(s)
NPP	E-SMR	**Dataset from ELSMOR**	CEA	EAI, FORTUM, TRACTEBEL
Balance Of Plant + PCS	-	**-**	TRACTEBEL	EAI
	Thermal Energy Storage	**Two-tank system with Thermal oil**	ENERGORISK	EAI, TRACTEBEL, CEA, EC-JRC

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Energy Storage	Electrical Energy Storage	**Li-ion, lead-acid, VRB, NAS**	ENERGORISK	-
Hydrogen Production	High Temperature Steam Electrolysis	**Solid Oxide Electrolyser**	CEA	EDF, ENERGORISK, TRACTEBEL, EC-JRC
	Low Temperature Electrolysis	**Polymer Electrolyte Membrane (PEM)**	ENERGORISK	TRACTEBEL, EC-JRC
Water Desalination	Reverse Osmosis	**SWRO plant as electrical user**	EAI	TARCTEBEL, EC-JRC
	Distillation	**MED or MSF**	CEA	EC-JRC
Synthetic Fuels	Methanation	-	TRACTEBEL	EC-JRC
Renewables	Wind Farm	-	EAI	EC-JRC
	Photovoltaic	**To be considered as aleatory source in the electrical load**		
District Heating	-	-	FORTUM	TRACTEBEL
Electrical Grid	-	-	TRACTEBEL	-

Table 35 - Summary of technologies for each module to be embedded in the Hybrid Systems addressed by TANDEM.

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