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Description of selected study cases for safety, techno-economic analysis andoptimisation

Authors : Antti RANTAKAULIO (FORTUM), Konsta VARRI, Jenni KOVALAINEN, Antti RANTAKAULIO, Christophe SCHNEIDESCH

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Summary

The primary objective of the TANDEM project is to conduct a comprehensive assessment of the nuclear safety, techno-economic aspects, and operational feasibility of Hybrid Energy Systems (HES) incorporating Small Modular Reactors (SMRs) in the net-zero energy transition targeted by the EU policies. Because of the close emergence of Light-Water SMR technologies, the project focuses on the analysis of LW-SMR integration within two distinct configurations of representative hybrid energy systems, each tailored to match the energy transition needs and constraints for reaching net-zero greenhouse gas emissions as identified in different parts of Europe. This document summarises the outcomes obtained in Tasks 1.1 - 1.3 (Goicea et al., De Angelis et al., Minchole et al., 2023) and provides specifications for the two energy study cases, which are established on the characterisation of two hybrid energy systems and their corresponding components. These systems are configured for both district heating and power supply as well as energy hub operations. The energy study cases will be implemented as use-cases in the TANDEM project to demonstrate the relevance and efficacy of the methods and tools developed by the project. They are correlated with two European energy scenarios, reflecting the most probable and available energy mix projections for the purpose of demonstrating the benefits of Small Modular Reactor (SMR) penetration during the timeframes of 2035 and 2050.

Approval

Date	By
2023-06-26 10:15:57	Dr. Christophe SCHNEIDESCH (ENGIE)
2023-06-26 11:43:41	Dr. Claire VAGLIO-GAUDARD (CEA)

D1.4 - Description of selected study cases for safety, techno-economic analysis and optimisation

WP1 - Task 1.4

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Konsta Värri (FORTUM)

Jenni Kovalainen (FORTUM)

Antti Rantakaulio (FORTUM)

Christophe Schneidesch (Tractebel)

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Abbreviations and Acronyms

Acronym	Description
CCGT	Combined Cycle Gas Turbine
CI/BOP	Conventional Island / Balance of Plant
CHP	Combined Heat and Power
COP	Coefficient Of Performance
DH	District Heating
EHub	Energy Hub
FoM	Figures of Merit
HES	Hybrid Energy System
HTSE	High-Temperature Steam Electrolyser
IRES	Intermittent Renewable Energy
LCOE	Levelized cost of electricity
LCOH	Levelized cost of heat
$LCOH_2$	Levelized cost of hydrogen
LTE	Low-Temperature Electrolyser
LW	Light-Water
LW-SMR	Light-Water Small Modular Reactor
NPP	Nuclear Power Plant
NPV	Net Present Value
PCS	Power Conversion System
PV	Photovoltaic
SMR	Small Modular Reactor
SWRO	Sea Water Reverse Osmosis
WP	Work Package

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Executive Summary

The primary objective of the TANDEM project is to conduct a comprehensive assessment of the nuclear safety, techno-economic aspects, and operational feasibility of Hybrid Energy Systems (HES) incorporating Small Modular Reactors (SMRs) in the net-zero energy transition targeted by the EU policies. Because of the close emergence of Light-Water SMR technologies, the project focuses on the analysis of LW-SMR integration within two distinct configurations of representative hybrid energy systems, each tailored to match the energy transition needs and constraints for reaching net-zero greenhouse gas emissions as identified in different parts of Europe.

This document summarises the outcomes obtained in Tasks 1.1 - 1.3 (Goicea et al., De Angelis et al., Minchole et al., 2023) and provides specifications for the two energy study cases, which are established on the characterisation of two hybrid energy systems and their corresponding components. These systems are configured for both district heating and power supply as well as energy hub operations. The energy study cases will be implemented as use-cases in the TANDEM project to demonstrate the relevance and efficacy of the methods and tools developed by the project. They are correlated with two European energy scenarios, reflecting the most probable and available energy mix projections for the purpose of demonstrating the benefits of Small Modular Reactor (SMR) penetration during the timeframes of 2035 and 2050.

Keywords

SMR, LW-SMR, Hybrid Energy Systems, Energy scenarios, Nuclear energy, District heating, Power supply, Energy Hub

1 Introduction

The primary objective of the TANDEM project is to conduct a comprehensive assessment of the nuclear safety, techno-economic aspects, and operational feasibility of Hybrid Energy Systems (HES) incorporating Light-Water Small Modular Reactors (LW-SMRs). The project focuses on the analysis of LW-SMR integration within two distinct configurations of hybrid energy systems, each tailored to match the energy transition needs and constraints for reaching net-zero greenhouse gas emissions as identified in different parts of Europe The first one aims to supply a district heating network and a power grid in Northern and Central Europe regions; the second configuration, is operated as an energy hub in Southern Europe, combining electrical power generation for the grid with cogenerated heat to produce valuable commodities, such as hydrogen. Those HES configurations are aimed to serve as demonstration (study) cases for LW-SMR integration; consequently they do not have the level of details of a real HES project but are designed to integrate the key relevant components of the future energy mix for the chosen study cases. Within the framework of WP1 in the TANDEM project, specific attention is given to the "Characterization of the studied hybrid systems". This involves defining the energy scenarios that will be adopted for the study, identifying the technologies to be considered and implemented within the outlined HES configurations, providing preliminary information for a techno-economic description of these technologies, and establishing the key performance indicators (referred to figures of merit or FoM) that will guide the assessment of techno-economic feasibility and operational viability.

Task 1.4 of the TANDEM project focuses on providing specifications for energy study cases, which are based on the characterisation of two hybrid energy systems and their components. These hybrid energy systems are aligned with the European energy scenarios, representing the most likely energy mix projections for 2035 and 2050. These study cases aim to demonstrate the benefits of SMR integration.

The specifications for the TANDEM energy study cases are detailed in the following sections. Firstly, the energy scenarios are outlined, providing a comprehensive overview of the contextual factors. Next, the architecture of the hybrid energy systems is described, including the identification of the components and the boundary conditions governing inputs and outputs. Lastly, the recommended technology of the HES components and their connectivity assumptions are defined.

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2 Proposed scenarios for the SMRs

The TANDEM project analyses hybrid energy systems configured on best-estimate projections of energy scenarios consistent with the European policy and the current knowledge of energy market evolution. The scenarios refer hence to the global energy frameworks where the demonstration cases are defined and analysed. Many scenarios present strategic plans for energy transition at different levels (national, regional and EU). While the EU's clean energy transition strategy heavily relies on substantial electrification of many sectors, supported by the accelerated deployment of renewable electricity generation capacity, all strategies take into account energy demand reductions supported by higher energy-efficiency targets in various segments. Due the international situation, the REpowerEU[1] update mostly implies a faster replacement of fossil fuels (mostly gas) by a mix of carbon neutral sources.

However, heating and cooling constitute about 50 % of the final energy demand in Europe and represent by far the most significant energy sector to be decarbonized. Consequently, all scenarios and demonstration cases must cover the two needs: electrical power supply and heat supply. For TANDEM, the scenarios target two timeframes, 2035 and 2050, based on most probable (and available) energy mix projections to support the benefit demonstration of SMR penetration. As such, for the gross electricity mix projection, TANDEM baseline relies on one of the net-zero options, where the nuclear capacity share does not vary significantly. Therefore, with respect to SMR penetration, only two scenarios are considered in EU, a high SMR deployment scenario and a low SMR deployment scenario, with emphasis on the SMR technologies (Figure 1). The two scenarios have the same fixed figure for the large reactors installed capacity, the only variable being the SMRs installed capacity. Considering a fixed gross production capacity per timeframe, SMR penetration is combined with other energy sources aiming at an integrated energy system where the CO_2-intensive emitters are replaced by low CO_2 emitters in a credible projection for both timeframes. This option particularizes the economical properties of the various energy production/conversion means as system components to be considered.

[1] REPowerEU - EEAS - European Union https://www.eeas.europa.eu
A plan to rapidly reduce dependence on Russian fossil fuels and fast forward the green transition

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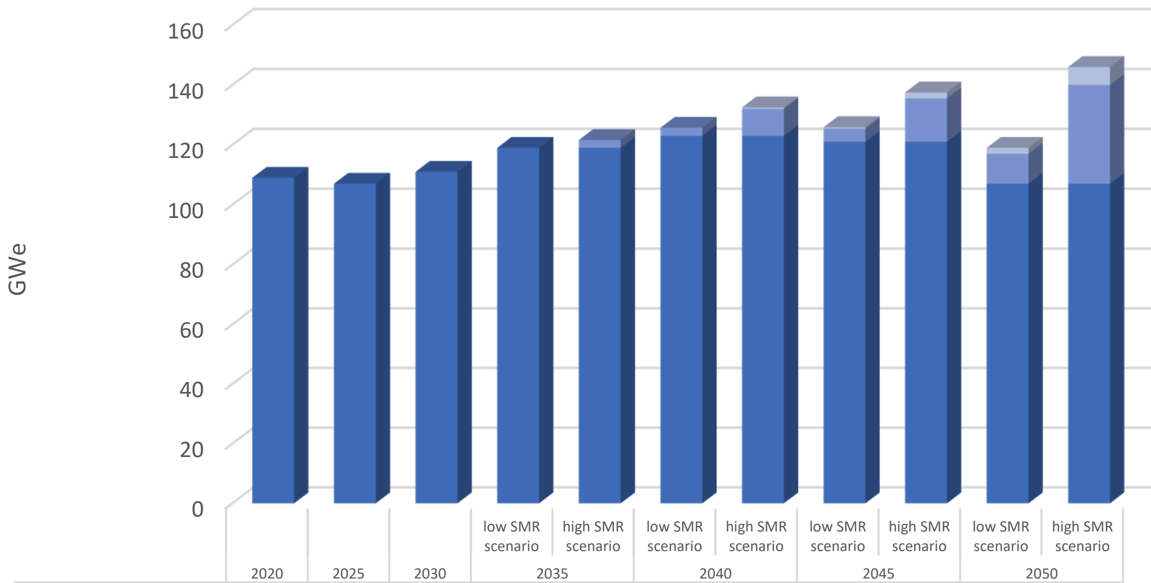

	2020	2025	2030	2035 low SMR scenario	2035 high SMR scenario	2040 low SMR scenario	2040 high SMR scenario	2045 low SMR scenario	2045 high SMR scenario	2050 low SMR scenario	2050 high SMR scenario
SMR for heat production							0,5	0,5	2	2	6
SMRs for power production					2,6	2,7	9	4,4	14,5	10	33
Large reactors	109	107	111	119	119	123	123	121	121	107	107

Figure 1. Background for European nuclear production from (Goicea et al., 2023)

3 General architecture of the hybrid energy systems

As outlined at the beginning of the report, the TANDEM project analyses two different HES configurations in the projected 2035 and 2050 timeframes. The HES configurations are tailored to be integrated local heat and electricity power systems, connected to a wider regional or national electricity grid.

Considering 2035 as the time perspective when the first SMRs are operated in Europe, the TANDEM interest in the 2035 demonstration cases lies in comparing HES configurations with and without SMR contribution to the local energy mix.

Therefore, the 2035 low and high SMR (penetration) deployment scenarios for the study cases define, for the low SMR penetration, a local HES configuration combining energy production/conversion means without local nuclear generation to ensure specified energy segment's needs. For the high SMR penetration, the same local HES configuration with the same energy segments needs has some of its CO_2 intensive emitter sources replaced by SMR power generation. SMRs are here to serve as multipurpose power sources, not for strict electrical power generation but mostly as combined heat and power generators if not in some variants solely for heat production (in this case considered to fulfil a HOB, Heat Only Boiler, role as common district heating application).

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It should be noted that the 2035 high SMR scenario introduces SMRs for both heat and electricity production which in some point does not apparently match the projected nuclear production shares for heat identified in the background for European nuclear production (Figure 1). However, it is considered that a local HES cogeneration perspective is not in sharp contradiction with the overall European landscape.

In addition, the projected 2035 timeframe led to make choices for the CO_2 intensive emitter sources to be replaced by SMRs in the analysis. The coal fired power units are currently the strongest CO_2 emitters with a clear benefit in being replaced by SMRs if only for their CO_2 footprint, and as such are considered as a first key target for energy sector decarbonization. However, partly because of the rather obvious conclusion for coal fired units replacement, gas fired units are preferred in the study for their significant cogeneration role in the 2035 horizon energy landscape.

The 2050 context, as a long term perspective, is hard to differentiate with respect to the different shares in the production/conversion means. The 2050 study cases focus therefore on the high SMR penetration where it is assumed from the various energy transition policies that all fossil fuelled energy sources have disappeared from the mix.

The sections 3.1 and 3.2 provides the selected TANDEM composition of the study cases for the district heating and energy hub configurations (also referred to as "selected HES architectures"). It should be noted that the layouts of the HES architectures are only intended to identify the key components to be considered in the study cases as well as to determine how those components are interconnected. Those schematic architectures do not prevail on the capacity associated to each of its constitutive components which are to be scaled either in properties or in numbers to fulfil the final energy segments requirements. Layout components properties and scaling is the role of WP3.

3.1 Hybrid energy system configuration for district heating and power supply

This section discusses the HES configuration for district heating and power supply (DH-configurated HES). The HES for district heating and power supply is envisaged at a significant local scale, e.g., for a large urban area. Overall, the primary goal is to decarbonise the production of heat and electricity with emphasis on heating. The SMR capacity is related to local needs.

An analysis of the general trends for district heating evolution towards net-zero highlights the following DH architecture requirements:

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- Maximize the use of CHP by increasing CHP penetration but with low-carbon fuels
- Favour heating plants that deliver higher heating efficiencies
- Scale up the use of heat pumps
- Develop large-volume seasonal heat storage to accommodate fluctuating supply and demand from RES

The choice of heating solutions depends on the area where DH is used. DH is mainly a solution in Northern and Central Europe with growth for specific technology deployment conditioned by national resource limits (biomass, wind). Two variation case studies for DH-configurated HES are therefore based on specific regional needs and policies in:

- Nordics as per an energy system in Finland,
- Central Europe as per an energy system in Czech Republic.

These two variants have therefore some inherent differences. Primarily the Czech case study incorporates large NPPs that are currently used for combined heat and power production (CHP), the capacity of which is planned to grow from 2035 to 2050. Large NPP is not part of the Finnish case.

In the TANDEM DH-configurated HES, the local electrical grid is supplied by a mix of IRES and power stations combined with electrical storage as identified in energy transition scenarios. The level of modelling detail for the components is adapted to the duality demonstration of combined heat and electricity mix, i.e. very explicit for downstream application requiring both power and heat and simplified for those which are using only power.

For heat, the representativeness objective of significant local scale leads to select an architecture on 4 distinct DH network blocks, to cope for delocalized production and heat transport over long distances separating consumption from production. This is designed to match real infrastructures constraints in the DH heat transport and usage which are to be accounted for in the analysis. One example is possible bottlenecks appearing during load variations in the transport lines from production to consumption sites.

To keep the study cases to a useful conceptual level, two out of the 4 distinct DH blocks are considered as simplified local heat networks that function independently and are modelled as additional heat sinks or heat outputs based on a predetermined production/usage timeseries.

The two major blocks share basically the same composition of key components, aligned to allow capturing the DH energy transition as acknowledged by the field, i.e. efficient CHP in the form of CCGT, heat pumps and heat storage, each one of those leaving the door open for a specific technological implementation to cover local specifications. However, those two blocks differ by the CCGT connectivity layout, one covering the case of direct heat storage from plant.

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The scenarios cover timeframes for 2035 and 2050. The 2035 timeframe compares the low and high SMR deployment by replacing one CHP with a cogeneration SMR while in 2050 only the high scenario is considered. The conceptual layouts of DH-configurated HES cases are provided by Figure 2 and 3 and the associated scenarios are summarized in Table 1, as identified for the Finland variant.

For the Czech Republic DH-variant, a large NPP is connected to the grid and the heat network in one of the two detailed DH-blocks (Figure 2 and Figure 3). National specifications are applied to characterise the properties of the components both in terms of the energy mix share and in terms of load variation.

Table 1. District Heating configuration scenarios

Timeframe	Low SMR deployment scenario	High SMR deployment scenario
2035	No SMRs	Single SMR CHP replacing a CCGT unit
2050	-	SMR CHPs & SMR HOBs covering the heat demand

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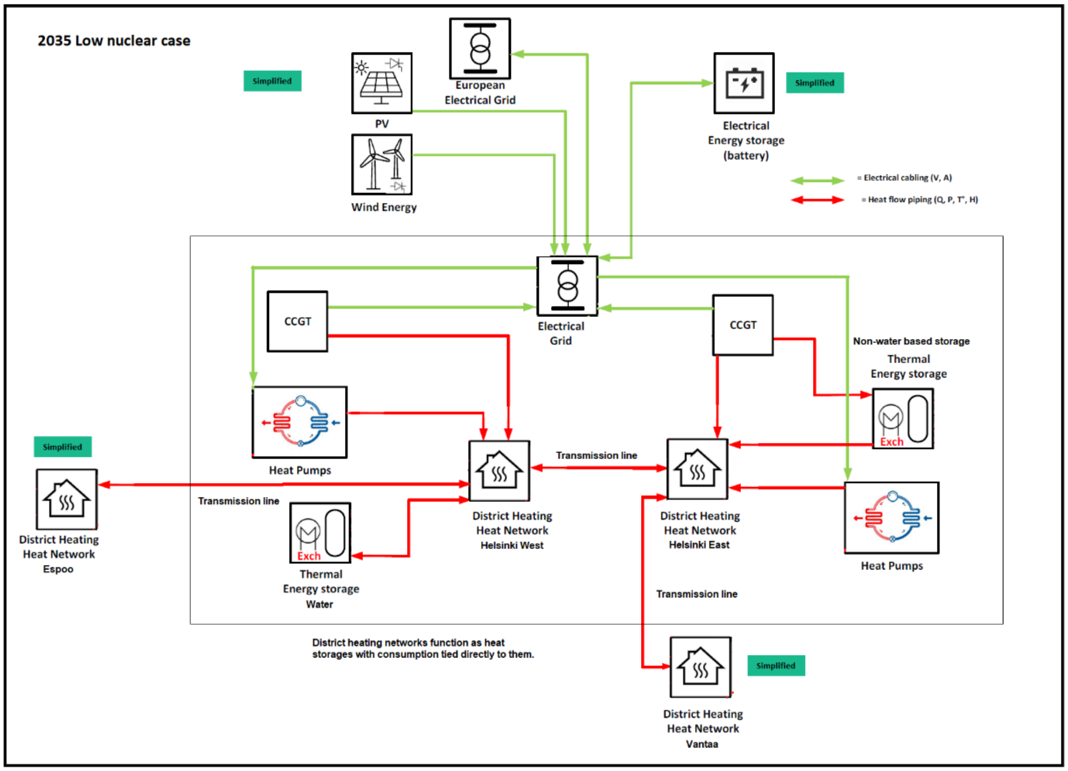

Figure 3. Conceptual layout of the hybrid energy system for district heat and power supply regarding the low SMR deployment scenario in 2035 – Finland case

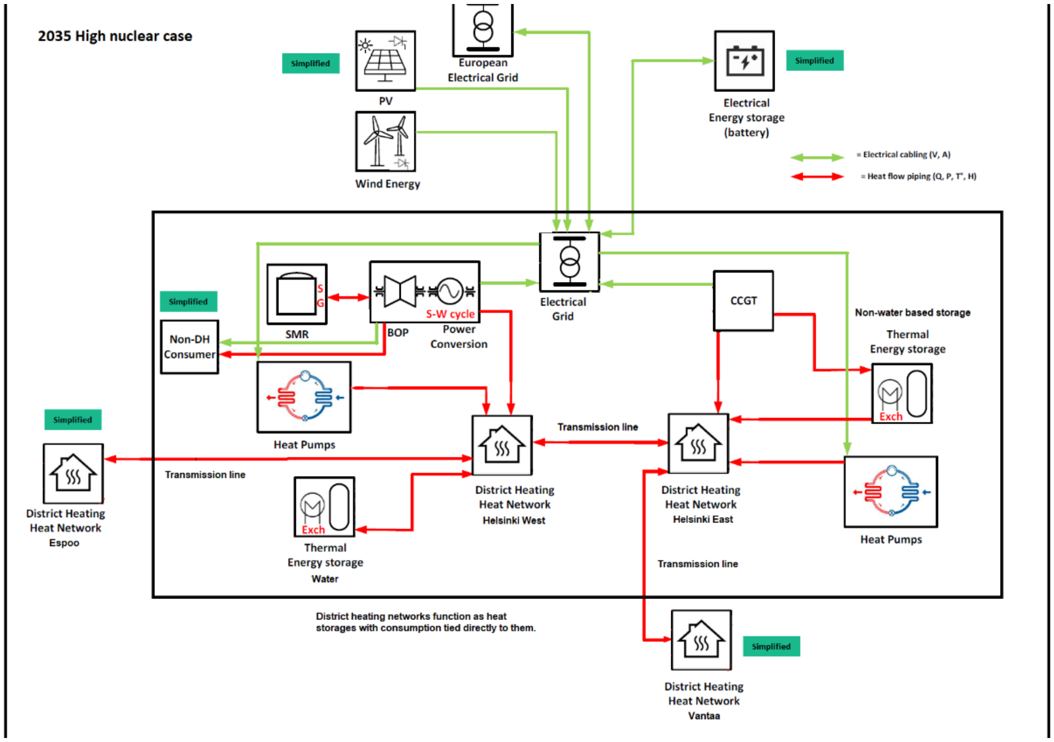

Figure 2. Conceptual layout of the hybrid energy system for district heat and power supply regarding the high SMR deployment scenario in 2035 – Finland case

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The goal of the study of this HES configuration is therefore to show the benefit by progressively replacing existing fossil fuel power plants by SMRs and combining them with heat pumps utilising waste heat and air-to-water options.

In 2035, the low SMR deployment scenario (Figure 2) does not include SMRs; power and heat are produced by a mix of IRES, heat pumps and CCGT CHPs. The high scenario for 2035 will include a single SMR CHP replacing one of the CCGT plants (Figure 2). For 2050, in the single high SMR deployment scenario, SMR CHPs and SMR heat only boilers (HOBs) replace all of the CCGT plants present in Figure 2. HOB is a power plant which produces only district heat.

It is assumed that the existing district heating infrastructure is used and heat production for district heating network is provided by heat pumps, and nuclear power combined with CHP and HOBs. If current district heating infrastructure is not used, house-specific electricity-based solutions are needed. Hence, the transmission network load increases and investments in the network are needed. Despite of the coefficient of performance (COP) of heat pumps, electricity is needed, although that is hardly a problem in a centralised solution.

Contemporary large NPPs are usually far away from major urban areas, where the demand for heating (or cooling) is. SMRs could resolve the problem with district heating, where the plants need to be located where the demand is, since SMRs could be built closer to cities due to their smaller size and new safety approaches. Moreover, the SMR heat could be used for other non-district heating consumer, and connected to a thermal energy storage. The complexity of the thermal energy storages is related to its seasonal, daily and weekly variation. Therefore, its connection and its role to the district heating network will have to be addressed.

Nevertheless, problems of the regional electricity transmission network may arise. In Finland, current CHPs (Hanasaari and Salmisaari in Helsinki) are located in the middle of residential areas and the production of electricity is “in the middle of consumption". When some amount of CHPs is removed, production or a transmission network is needed to replace it. It was decided to exclude this from the architecture. Proximity also affects pumping costs (OPEX) and infrastructure costs (CAPEX). It is decided to use the same approach as in the energy hub (black box).

The consumption of district heating varies both on an annual basis according to the seasons and outside temperature, as well as in the shorter term according to the weekly and daily rhythm. Since the district heating temperature (all production modes produce heat with the same temperature level) depends on the outside temperature, therefore for example in Finland and Czech Republic, heat supply is highest during the cold months (November to March – see an illustration for Finland in Figure 4). Furthermore in residential buildings, the daily variation of heat consumption is greatest in spring and autumn, when the outdoor temperature varies the most. During the day, there are usually two peaks in heat demand: in the morning and in the afternoon after working hours. During summer, outside the heating season, the excess heat could be used e.g., for hydrogen production and/or other non-district heating consumer.

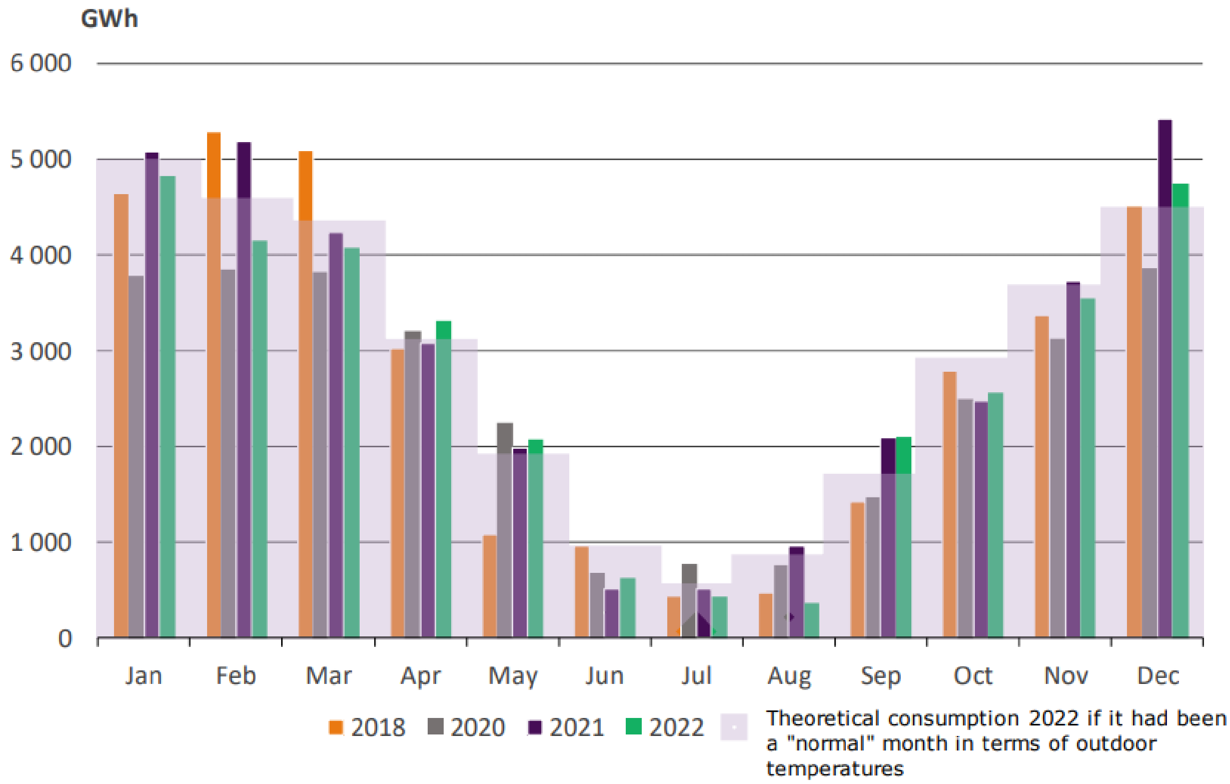

Figure 4. Monthly district heat demand in Finland (Finnish Energy, 2022)

3.2 Hybrid energy system configuration for an energy hub

The Energy Hub is a HES concept where multiple energy carriers issued from various energy sources can be converted, stored, and supplied for end-user segments. Such concept is growing in interest to answer the challenges set by the net-zero energy transition as it allows optimized use of resources for increasing the overall system performance in terms of infrastructure, flexibility, and sustainability. Energy hubs often appear in modern energy systems management in connection with renewables, cogeneration and energy storage.

In TANDEM, the HES for energy hub (EHub-configuration) for SMR integration demonstration is inspired from a harbour-like infrastructure (Figure 5), which can be characterized as a complex distribution network of in-out energy carrier fluxes (power, heat, gas, hydrogen,…) among various end-user segments

For demonstration purposes and in order to keep a good balance between modelling complexity and representativeness of the EHub-configurated HES architecture, only electrical power and heat are considered as distributed energy carrier fluxes. It has therefore a local architecture nature and can be considered as a dual purpose power and heat infrastructure connected to a regional or national electricity grid.

The study cases must be aligned with the decarbonization goals of net-zero transition and hence, typical end-user segments beyond pure power grid supply are to be considered :

- Hydrogen production as a must with respect to current market evolution,
- Additional industrial end-uses can be added like demineralized water production,
- Additional conventional end-uses can be added like heat supply to local buildings or local industry processes.

Figure 5. Harbour like infrastructure of the Energy hub configuration

For the hydrogen production, a High-Temperature Stream Electrolyser (HTSE) component is explicitly integrated in the HES as it represents a promising technology taking high level benefit of combined heat and power generation. The hydrogen itself may serve multiple commodity segments which can be considered as part of the value chain of hydrogen. The TANDEM choice is to limit the study to hydrogen production and not to extend the modelling to a complete value chain. If possible, additional commodities could be added and analysed in an extended phase on a case by case basis.

The production of synthetic fuels is not explicitly integrated in the HES. Other downstream applications, using only electricity – such as hydrogen production with Low-Temperature Electrolyser (LTE), desalination by reverse osmosis - are taken into account in the HES through

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boundary conditions (in the form of imposed predetermined fixed or adaptative power flux output). Other industrial needs – such as the needs for blast furnace in heavy industry – can also be covered by boundary conditions.

Thermal storage is explicitly integrated into the HES whereas hydro storage and batteries are considered through boundary conditions.

In the study cases, the level of modelling detail for the components is adapted to the duality demonstration of combined heat and electricity mix, i.e. very explicit for downstream application requiring both power and heat and simplified for those which are using only power.

For the SMR penetration demonstration purpose, two timeframes of 2035 and 2050 are analysed. In the HES configuration corresponding to the low SMR deployment scenario for 2035, which does not include any SMR in its architecture for energy production, power and heat are produced by a mix of IRES and CCGT/CHPs, servicing the selected end-user segments as illustrated by Figure 6.

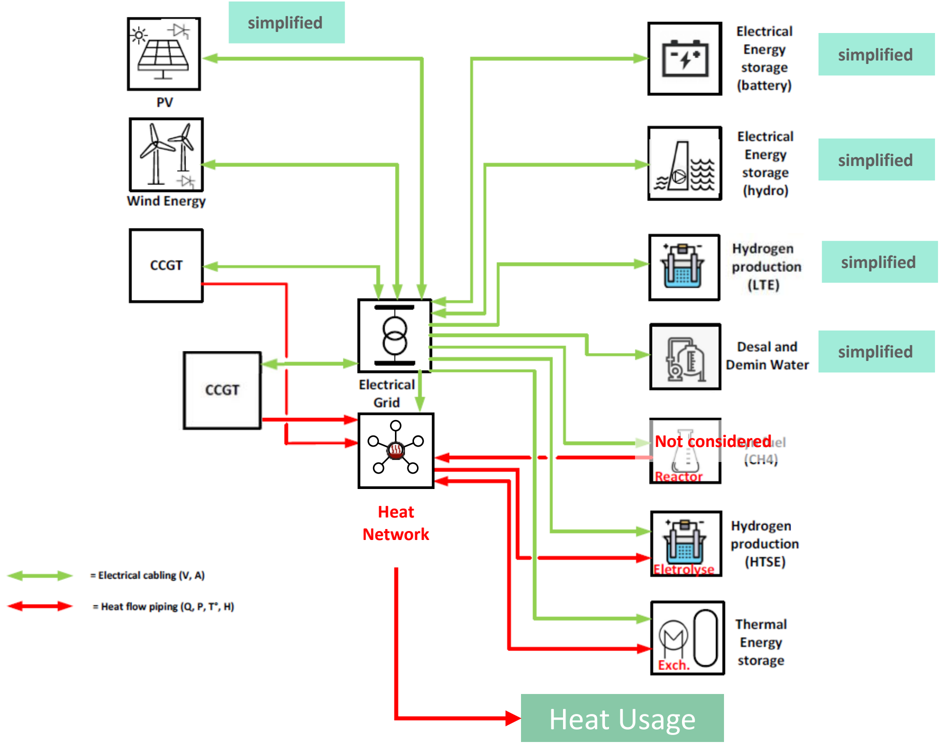

Figure 6. Conceptual layout of the hybrid energy system for the energy hub regarding the low SMR deployment scenario in 2035

As for the high SMR deployment scenario:

- in 2035, one CCGT/CHPs power/heat is replaced by one SMR,
- in 2050, two CCGT/CHPs power/heat are replaced by two SMRs.

We do not consider any low scenario for 2050, only the high SMR deployment scenario. If there is additional time, doing sensitivity analysis on the high scenario that would cut away the SMR capacity and filling that with other available sources could be considered.

Figure 7 describes the EHub-configured HES in its high SMR deployment 2035 scenario.

The end-user segments production is modelled by predetermined imposed load demand with relevant associated time-dependent profiles (daily or seasonal).

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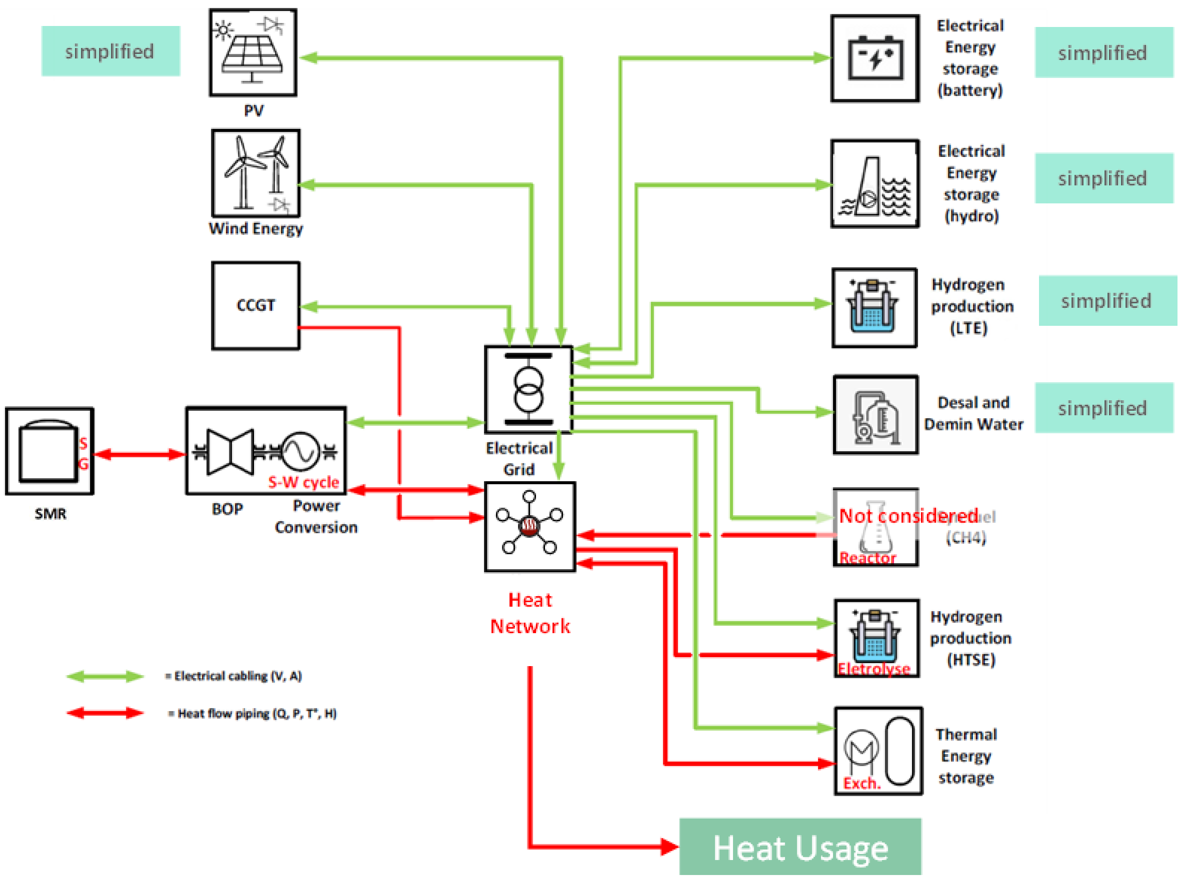

Figure 7. Conceptual layout Illustration of the hybrid energy system for the energy hub regarding the high SMR deployment scenario in 2035

4 Summary of recommended technologies in the hybrid energy systems

The objective is to give model details in terms of

- Recommendations for most relevant technologies,
- Interfaces with components/safety codes,
- Demonstration cases for hybrid energy systems using both electricity and heat vectors,
- HES architecture which must contain components allowing such demonstration.

The level of detail for the Modelica modules will be adapted as required, i.e.,

1. very explicit for explicit downstream application requiring both power and heat,
2. simplified for those which are using only power.

The value chain of the hydrogen production (as well as the value chain of any product of the industrial application/energy conversion module) will not be taken into consideration in the analysis. The production of H_2 will be set as imposed output (full capacity) over a given time slot – the latter is set by WP3 which can use this as a variable boundary condition to perform sensitivity studies. The level of H_2 production will be a modelling choice in the form of a global (lumped) answer to the current understanding of the industrial users' needs.

The question came about the connectivity of the modules with the SMR. It has been decided that for the reference cases all those modules are connected to grid and heat network, in particular HTSE. The reason is that if the HTSE is directly linked downstream to the SMR, the CI/BOP Modelica module will have a different structure than the one with grid and heat network connection. To avoid additional layers of modelling complexity, only grid/network connection will be considered for the Modelica architecture.

However, modelling requirements for WP3 have no such strong connexion-dependent constraints, therefore, in WP3, opportunity will be offered to compare the reference configuration (grid and heat network connectivity) with the alternative option (SMR connectivity). WP3 models can thus be used as workbench for the determination/optimisation of the best connectivity to be used. The heat network for the EHub-configuration will be modelled as a simplified black box; for the DH-configuration, the heat network will require more detailed modelling.

The tables below summarise the main outcomes of the selection process for the different technologies associated to each component of the TANDEM study cases. Each one of those corresponds to a Modelica module developed in WP2 for the TANDEM open source library. The conceptual HES layouts in chapters 3.1 and 3.2 illustrate the interconnections between the different blocks and modules. When a module is considered as simplified, it is represented either by a simple (set of) boundary conditions or black box with very few internal drivers.

4.1 Technology table for DH configuration

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Table 2. Technologies in DH configuration

Block	Addressed Module	Suggested technology	Information
Energy production	Wind	To be considered as aleatory source in the electrical load	Detailed, dynamic grid supply, connected to electrical grid
	Photovoltaics	Details are not fixed	Net load with a contribution considered in a stochastic way, simplified
	CCGT	Details are not fixed	Connected to electrical grid and DH grid, simplified
	Heat pumps	Details are not fixed	Connected to electrical grid (inlet) and DH grid
NPP	E-SMR	Dataset from ELSMOR (not yet publicly available)	Detailed core model, dynamic response to power/heat production changes
	SMR HOB		Simplified black box, connected to DH grid
	Large NPP		Simplified, only in the Czech case
Balance Of Plant + PCS	-		Detailed, allows power and heat production and possibly heat storage (on site). Connected to electrical grid and DH grid

Block	Addressed Module	Suggested technology	Information
Energy Storage	Thermal Energy Storage	Technology open	Detailed, connected to DH grid
	E-Batteries		Detailed model
Energy conversion	Hydrogen Production -High Temperature Steam Electrolysis	Solid Oxide Electrolyser	Detailed
District Heating	-	Simplified network	Divided into storages representing area distribution networks, transfer lines, heat sinks as end users and pumping
Electrical Grid, includes usage	-		Semi detailed, connects production and consumption

4.2 Technology table for Energy Hub configuration

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Table 3. Technologies in Energy Hub configuration

Block	Addressed Module	Suggested technology	Information
Energy production	Photovoltaics		Net load with a contribution considered in a stochastic way, simplified
	Wind	To be considered as aleatory source in the electrical load	Detailed, dynamic grid supply, connected to electrical grid
	CCGT	Details are not fixed	Connected to electrical grid and DH grid, simplifiled
NPP	E-SMR	Dataset from ELSMOR (not yet public)	Detailed core model, dynamic response to power/heat production changes
Balance Of Plant + PCS	-		Detailed, allows power and heat production and possibly heat storage (on site). Connected to electrical grid and DH grid
Energy Storage	Thermal Energy Storage	Technology open	Detailed, connected to DH grid
	E-Batteries		Simplified
Energy conversion	Hydrogen Production -High Temperature Steam Electrolysis	Solid Oxide Electrolyser	Detailed, H2 demonstration

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Block	Addressed Module	Suggested technology	Information
	Hydrogen Production -Low Temperature Electrolysis	Polymer Electrolyte Membrane (PEM)	Simplified
	Water Desalination - Reverse Osmosis	SWRO plant as electrical user	Simplified
Heat	-		Simplified (TBC). Connects production and consumption,
Electrical Grid, includes usage	-		Semi detailed, connects production and consumption

5 Techno-economic and environmental evaluation

To examine and optimize the profitability of the selected HES configurations based on NPV value, the list of the techno-economic and environmental parameters as described in (Minchole et al., 2023) will be required. Primarily the details are already included in (Minchole et al., 2023) but some general information has been lifted here.

For environmental considerations, the primary focus and the key figure of merit will be CO_2 emissions. For the financial considerations, NPV would be the clearest figure. LCOE, LCOH and $LCOH_2$ are good indicators of cost-effectiveness, but only inside a single combination of configuration and scenario and cannot be used for extrapolation to other energy scenarios.

The two HES configurations will require different approaches to what can be locked as a baseline assumption. This should be further enhanced with sensitivity analyses on many of the factors listed in (Minchole et al., 2023), this document being used as a basis for iterative analysis as work progresses.

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6 Overview and synthesis of scenarios

This document synthesises the outcomes and outputs of Tasks 1.1–1.3 (Goicea et al., De Angelis et al., Minchole et al., 2023) and presents a description of the architecture and components of the two hybrid energy systems to be studied by the project as demonstration cases for the SMR integration into the future energy mix. The description serves as a foundation for further analysis in different phases of the TANDEM project. The selected configurations include a hybrid energy system designed for district heating and power supply, as well as an energy hub configuration.

Three different configurations cover the heat and electricity supply in district heating scenarios for a typical large urban area. For the 2035 timeframe, SMRs were not incorporated in the low SMR deployment scenario, while in the high scenario, a single SMR plant replaced a single CCGT unit. Furthermore, in the high scenario for the year 2050, the entire heat demand was met by SMR CHPs and SMR HOBs alongside the utilisation of heat pumps. Similarly, in the energy hub scenario, one CCGT/CHP power/heat unit was replaced by one SMR in 2035, and in 2050, two CCGT/CHPs power/heat units were substituted by two SMRs. In a corresponding manner, the utilisation of SMRs serves as a replacement for fossil-based fuels.

The configurations selected in Task 1.4 will be addressed during the modelling phase of the HES within WP2. Some of the assumptions and recommendations presented in this document may change as the project progresses. As additional analyses and studies will be conducted, refinements and adjustments may be necessary to ensure the relevance of the results in the context of the TANDEM project.

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Bibliography

Goicea, A., et al, (2023) “Analysis of the key features of the future EU energy market and associated regional/ national landscapes”. TANDEM deliverable 1.1, 1.2.2023. Available: http://tandemproject.eu/wp-content/uploads/2023/02/D1_1_Analysis_of_the_key_features_of_the_future_EU_energy_market_and_associated_regional__national_landscapes_V1_V1.pdf

De Angelis, A., et al., (2023) “Description and techno-economic characterization of the hybrid system components”. TANDEM deliverable 1.2, 19.4.2023. Available: http://tandemproject.eu/wp-content/uploads/2023/04/D1_2_description_and_techno_economic_characterization_of_the_hybrid_system_components_v1_quality_3_V1.pdf

Minchole, M., et al., (2023) “Description of techno-economic assessment of energy policies and relations among hybrid energy systems”. TANDEM deliverable 1.3, 4.5.2023. Available: http://tandemproject.eu/wp-content/uploads/2023/04/D1_3_Description_of_techno_economic_assessment_of_energy_policies_and_relations_among_hybrid_energy_systems_V1.pdf

Communication from the commission to the European parliament, the European council, the council, the European economic and social committee and the committee of the regions REPowerEU Plan. (2022). COM(2022) 230 final. Brussels, 18.5.2022. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2022:230:FIN

Finnish Energy, (2022). “Energy Year 2022 - District Heating”. 26.01.2022. Available: https://energia.fi/files/5695/Energy_Year_2022_DistrictHeating.pdf

ELSMOR (Towards European Licensing of Small Modular Reactors) Official Website. Available: http://www.elsmor.eu/

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