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Definition of case studies for techno-economic analyses including some environmental aspects

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Summary

All participants contribute to the characterization of the ?techno-economics? case studies associated with the hybrid systems considered in TANDEM in a specific location and context in Europe (Nordic countries, Central and Southern Europe).

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WP3 - Task 3.1

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Abbreviations and Acronyms

Acronym	Description
ATR	AutoThermal Reforming
BESS	Battery Electric Storage Systems
CAPEX	CAPital EXpenditures
CCGT	Combined Cycle Gas Turbine
CCS	Carbon Capture Storage
CHP	Combined Heat and Power
CR	Czech Republic
DC	District Cooling
DH	District Heating
DHN	District Heating Network
DHC	District Heating and Cooling
EU	European Union
FMU	Fonctional Mock-up Unit
GAMS	General Algebraic Modeling System
HES	Hybrid Energy System
HOB-SMR	Heat Only Boiler – Small Modular Reactor
HP	Heat Pump
HTSE	High Temperature Steam Electrolysis
IRES	Integrated Renewable Energy System
LTE	Low Temperature Electrolysis
LW-SMR	Light Water Small Modular Reactor
MILP	Mixed Integer Linear Programming
MPC	Model Predictive Control
MSR	Moravian-Silesian Region
N/A	Not Applicable
N.C.	Not Communicated
NGCC	Natural Gas Combined Cycle
NHES	Nuclear Hybrid Energy System
NPV	Net Present Value

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Acronym	Description
OPEX	OPerational EXpenditures
PEM	Proton Exchange Membrane
PV	PhotoVoltaic
SMGR	Steam Methane Gas Reforming
SMR	Small Modular Reactor
SNG	Substitute Natural Gas
SOEC	Solid Oxide Electrolyzer Cell
TFE	Twenty-Foot Equivalent
VRE	Variable Renewable Energy
WP	Work Package
WWHP	Waste Water Heat Pump

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Executive Summary

This report, Deliverable 3.1 (D3.1), is a vital component of the TANDEM (Small Modular ReacTor for a European sAfe aNd Decarbonized Energy Mix) project, funded by the Euratom programme. It aims to provide a detailed description of three case studies conducted as part of Work Package (WP) 3, focusing on Nuclear Hybrid Energy Systems (NHES) integration in different regions of Europe. The case studies explore NHES potential in supplying district heating networks and power grids in Northern and Central Europe, as well as generating heat and power while producing valuable commodities like hydrogen in Southern Europe. This report serves as a foundation for subsequent techno-economic and environmental assessments, supporting the evaluation of NHES operability, profitability, and environmental impact in the context of the TANDEM project's goals.

The research and analysis conducted for this report, Deliverable 3.1 (D3.1), involved a comprehensive and systematic approach to gather and present information on the three case studies exploring NHES integration into Hybrid Energy Systems (HES) across different regions of Europe.

The methods employed to conduct this study included a combination of literature review, data collection, and expert input. A thorough literature review was carried out to gather existing information and insights on NHES, HES, and relevant energy infrastructure in Northern, Central, and Southern Europe. This process involved sourcing scientific papers, reports, and industry publications to establish a strong foundation of knowledge on the subject matter.

Furthermore, relevant data sources were identified and utilized to gather specific information for each case study. This included data on energy consumption patterns, current energy infrastructure, greenhouse gas emissions, and other relevant factors. Throughout these case studies, the characteristics and potential of the PERSEE and Backbone tools played a central role. Although the tools have not been used yet, this report successfully presents the inputs and information that will be fed into these tools during Task 3.2. The techno-economic and environmental assessments to be conducted in Task 3.2 will further evaluate the feasibility and viability of implementing NHES in each region.

The main findings and outcomes of the report, Deliverable 3.1 (D3.1), on the three case studies exploring NHES integration in different European regions are as follows:

- Northern European Case Study:

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The Northern European case focuses on utilizing NHES to supply both district heating networks and power grids in the region. The case study showcases the integration of Small Modular Nuclear Reactors (SMR) with renewable energy sources, such as wind and solar, to enhance the overall energy mix and reduce greenhouse gas emissions.

The Backbone tool is utilized for techno-economic and environmental assessments, enabling the evaluation of NHES operability, profitability, and environmental impact in this context.

- Southern European Case Study:

In the Southern European case, the NHES configuration is inspired by industrialized harbors aiming to decarbonize and transition towards clean energy. Industrial ports like Rotterdam and Dunkirk serve as examples, implementing strategies for reducing CO_2 emissions through hydrogen production, renewable energy integration, and waste recovery.

The PERSEE tool is employed for techno-economic and environmental assessments, providing insights into NHES profitability and environmental benefits in the region.

- Central European Case Study:

The Central European case focuses on integrating NHES into the district heating networks of the Moravian-Silesian Region (MSR) of the Czech Republic. By replacing existing coal heat sources with low-emission SMR sources, the region aims to significantly reduce polluting emissions.

The PERSEE tool is used for techno-economic and environmental assessments, facilitating the evaluation of NHES profitability and operational feasibility in this region.

Overall, the report provides in-depth descriptions of each case study, highlighting their unique contexts, objectives, and challenges. The use of specialized tools, such as Backbone and PERSEE, offers valuable insights into the techno-economic and environmental aspects of NHES integration, enabling informed decision-making for achieving a safe and decarbonized energy mix in Europe.

Keywords

SMR, LW-SMR, HOB-SMR, Nuclear energy, Hybrid Energy Systems, District heating, Power supply, Energy Hub, Techno-economic and environmental study, Case study

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1 Introduction

The TANDEM (Small Modular ReacTor for a European sAfe aNd Decarbonized Energy Mix) project, funded by the Euratom programme, aims to facilitate the integration of Small Modular Nuclear Reactors (SMRs) into Hybrid Energy Systems (HES) with a focus on nuclear safety assessments, techno-economic and environmental profitability, and operation feasibility. In pursuit of this goal, the project will develop essential tools, including an open-source MODELICA library and methodologies, to be applied in two configurations across three case studies. These configurations are designed to supply district heating networks and power grids in Northern and Central Europe and to generate heat and power while producing valuable commodities in an energy hub, particularly hydrogen, in Southern Europe.

As part of Work Package (WP) 3, the TANDEM project delves into the operability, profitability, and environmental impact of Nuclear Hybrid Energy Systems (NHES) through dynamic techno-economic and environmental assessments. To carry out these crucial studies, appropriate tools will be employed, and special emphasis will be placed on sharing the methodology of such assessments. For the Northern Europe case, the Backbone tool will be utilized to conduct the techno-economic and environmental study, while the PERSEE tool will be deployed for the Southern and Central Europe cases. Additionally, the operation of the system will be analyzed using the ECOSIMPRO tool or through a coupling between the PERSEE tool and the MODELICA open-source library, developed in WP2.

Task 3.1 within the TANDEM project is dedicated to providing detailed descriptions of the three case studies. Building on the groundwork laid in WP1, this task aims to provide essential information to enable the execution and analysis of techno-economic and environmental assessments in Task 3.2. By thoroughly examining the unique characteristics of each case study, this deliverable (D3.1) serves as a crucial precursor to the subsequent assessments that will shed light on the feasibility and viability of implementing NHES in diverse European regions.

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2 Methodology of techno-economic and environmental study

As the usage of electricity in the transportation sector and for heating and cooling continues to grow, energy systems are becoming more integrated. Additionally, there is a rapid increase in the share of Variable Renewable Energy (VRE) in the power sector. These developments necessitate the representation of multiple energy sectors in numerical models and the consideration of high temporal and spatial resolution. Moreover, it is crucial to take into account for short-term and long-term uncertainties associated with large volumes of VRE. While several modeling approaches exist for each of these aspects individually, only a few have successfully addressed both simultaneously. This is primarily due to two reasons: (1) the need to concurrently consider both aspects has only recently become pressing for many systems, and (2) computational limitations have made it challenging to do so for larger systems. However, despite increasing computational power, it remains impossible to include every detail. Consequently, a modeling framework that aims to capture multiple energy systems comprehensively needs to make appropriate compromises. We argue that the nature of these compromises depends on the specific task and that the best compromises are often not known in advance. Therefore, it would be valuable to have a highly adaptable methodology capable of accommodating such needs. The following sections introduce the frameworks Backbone and PERSEE used for modeling energy systems.

2.1 The Backbone tool

Backbone is a versatile framework for modeling energy systems that can be effectively employed to construct models for analyzing the design and operation of energy systems, encompassing investment planning and scheduling perspectives. It incorporates a wide array of features and constraints, including stochastic parameters, various reserve products, energy storage units, controlled and uncontrolled energy transfers, and notably, multiple energy sectors. The formulation of this framework is rooted in mixed-integer programming and encompasses unit commitment decisions for power plants and other energy conversion facilities. It can accurately model both large-scale systems at a high level and smaller-scale systems with intricate details. The open-source Backbone modeling tool has been developed utilizing the General Algebraic Modeling System (GAMS). To showcase its capabilities, an example of a power system is presented, demonstrating that Backbone produces results comparable to a commercial tool. However, the adaptability of Backbone goes beyond this, enabling the creation and solving of energy systems models with relative ease for various purposes, thereby enhancing the existing methodologies available.

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Backbone achieves adaptability in multiple dimensions through its framework structure, which defines the model based on parameter settings and input data rather than rigid structures. For instance, the duration of a time period in the model can be easily modified by adjusting a single parameter, as long as the underlying data has sufficient resolution. This also means that the same framework can define multiple models from the same data, such as an investment model and a scheduling model. To avoid excessive complexity in the formulation, Backbone defines sets and equations in a manner that allows them to serve multiple purposes. As a result, the modeling framework remains relatively concise, with the intricacies residing in the input data.

The litterature contains numerous descriptions of energy systems models, including those capable of considering multiple energy sectors. These tools include e.g. MARKAL/TIMES, MESSAGE, PRIMES and SMART models which all are used to model energy systems and concentrate in various phenomena. However, they all have their shortcomings some with for example applying the demand dynamics and the variability of renewable energy sources and others with validation in the usage at high temporal or spatial resolution or with stochastic inputs. The methodologies of interest should be able to represent large-scale systems rather than focusing solely on local phenomena. They should also accommodate high temporal or spatial resolutions and stochastic phenomena. Additionally, it is important that investment planning solutions can be evaluated by conducting operational optimizations for optimized portfolios.

Backbone surpasses the existing methodologies by offering adaptability and the ability to address both investment planning and operational optimization. With the appropriate base data, Backbone users can construct different levels of abstraction that facilitate solving planning and operational problems at suitable scales and speeds with relatively minimal effort. Given the significance of open models and software in energy research, one advantage of Backbone is the freely available implementation in the GAMS language [1].

2.1.1 How does it work?

2.1.1.1 Structure of Energy Networks within Backbone

Backbone energy networks and their constituent elements are represented through grids, nodes, lines, and units. Nodes and lines adhere to the fundamental concepts of graph theory, specifically vertices and arcs. Grids are utilized to distinguish and separate various energy networks, while units serve to classify the functionalities within the nodes. By employing a network structure consisting of nodes and lines, it becomes possible to incorporate bottlenecks and losses within the grids. An illustration of the network structure is depicted in Figure 1.

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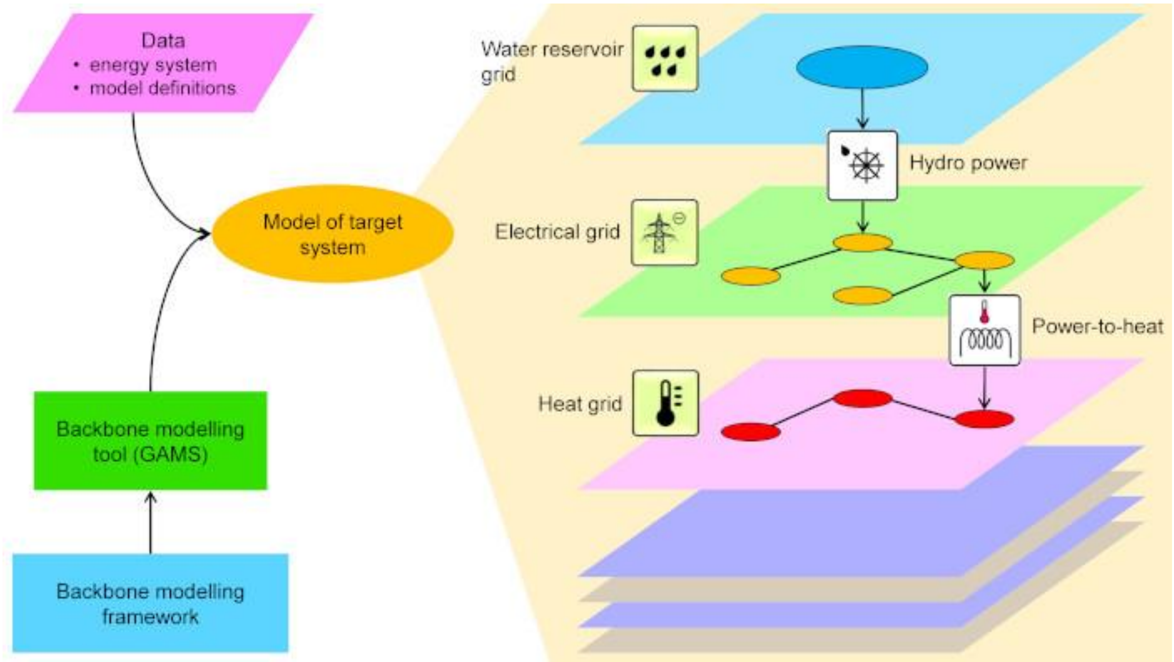

Figure 1: Energy network structure within Backbone

The structure of the network is characterized by three layers, each representing distinct grids. The nodes, depicted as circles on the layers, signify important points within the network. The lines connecting the nodes symbolize the connections.

2.1.1.2 Grids

Grids are collections of nodes that share a common form of energy or another quantity, such as electricity, heat or water. They provide structure to the model and allow for the grouping of results. Direct transfer and diffusion of energy between nodes in different grids are generally not allowed due to the incompatibility of the exchanged quantities. Instead, the controlled transfer of energy between grids is referred to "conversion" and is facilitated by units capable of performing conversions, as explained in Section 2.1.1.5. Also uncontrolled energy leakage called diffusion between grids is currently supported in Backboneand actively used in the building-level models constructed with Backbone.

2.1.1.3 Nodes

Nodes are integral components of the network within Backbone, playing a crucial role in the model structure. Each defined node enforces energy balance. In addition to their unique names, nodes possess various properties, including but not limited to:

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- State: This property represents the energy content, temperature, or a similar quantity associated with the node. A node can either have a single state, such as for energy storage, or no state at all.
- Spill capability: Nodes can be configured to allow energy spillover, enabling the transfer of excess energy outside the model boundaries.
- Contain units: While units represent distinct entities, each unit must be connected to at least one node within the network structure.
- Reserve requirements: Similar to enforcing energy balance, reserve requirements can be imposed on the nodal level, particularly for power systems. Other grid types may not have direct relevance to reserve requirements.

Different boundary conditions can be applied to node properties listed above, ranging from simple absolute upper and lower bounds to more flexible bounds that allow violations at the cost of defined penalties. These bounds can be invariant or follow predetermined time series. It is also possible to constrain the state of a node relative to another node's state.

2.1.1.4 Lines

Lines represent connections between two nodes within the model. They possess the following properties:

- Transfer: Nodes can be linked to other nodes within the same grid through controlled transfers, which can be either uni- or bi-directional. The transfer capabilities of nodes can be restricted using various parameters.
- Diffusion: Nodes can be interconnected within the same grid through diffusion coefficients, leading to uncontrolled energy leakage from one node to another based on their respective states. While diffusion coefficients can be technically defined for nodes without states, they will have no effect (nodes without states contain zero energy). Diffusion can be asymmetric, resulting in a unidirectional and uncontrolled flow of energy from one node to another.

2.1.1.5 Units

While nodes handle the flow of energy within different grids, they lack the ability to generate, consume, and convert energy between grids. Units fill this role and can function in various ways based on the input data parameters. The key properties of units are briefly explained below:

Energy production and consumption: A unit can either produce energy at a node or consume it.

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- Energy production is often defined to increase fuel consumption (which incurs a cost) or has limited production capacities based on time series data (e.g., solar, wind, hydro).
- Energy consumption in units is treated as "negative production." In the case of typical units, e.g. Natural Gas Combined Cycle (NGCC) plant, this equals fuel consumption, but the approach allows also modelling energy sinks, such as demand reduction technologies.
- Units provide more detailed parameters for defining energy production and consumption compared to nodes.

Energy conversion between grids: Units are the only means of transferring energy (referred to as conversion) between nodes in different grids.

- This functionality allows a unit to be connected to multiple nodes, and energy production and consumption variables in each node are linked according to specified conversion rules and constraints.

2.1.1.6 Resulting Spatial Structure

The specific spatial structure can be freely defined by determining appropriately the number of nodes and lines. Different levels of detail can be assigned to different grids and their associated nodes. While spatial aggregation is not currently automated, it can be achieved by defining multiple parallel datasets for the same geographic area and establishing scenarios that utilize those separate datasets.

2.1.2 Temporal Structure

Time is divided into sequential blocks, each with its own temporal resolution, as depicted in Figure 2. The user defines the resolution of the underlying data by specifying the duration of a single time step. Each block requires an interval duration, measured in time steps, along with the last time step of the block. Prior to solving, the model calculates averages for time series parameters when an interval aggregates multiple time steps. The variable temporal resolution can be creatively utilized to reduce computational requirements, similar to the approach described in the work of Bakirtzis et al in 2014 [2].

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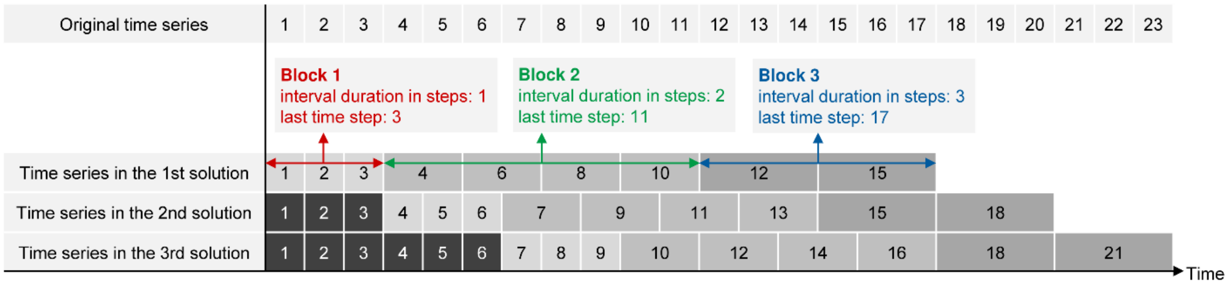

Figure 2: Temporal structure. Decisions in the intervals shown with a black background have been realized already in the previous solutions

2.1.3 Model Formulation

The model formulation encompasses the objective function and constraints related to energy balance, unit operation, transfers, system operation, and portfolio design. The formulation draws inspiration from power system production cost models but has been generalized to accommodate the modeling of other energy vectors. The formulas used for the optimizer can be found from [3].

Backbone employs two methods to represent stochastic behavior. The first method involves utilizing a forecast tree that can branch out from a selected time step. A central forecast can be used to extend the horizon beyond the stochastic tree. In this approach, forecast branches are connected back to the central forecast after the final time step in the stochastic tree.

The second method for representing stochastic quantities involves selecting representative periods from the time series. These samples can be combined in different ways, either as parallel alternatives (e.g., different inflow years for water value calculation) or as sequential or circular time lines (e.g., for investment decisions using representative periods). Operational decisions are generally independent for each sample, but inter-sample constraints can be created for node states, ensuring storage state continuity, for example.

It is advised against using forecasts and samples simultaneously without careful consideration. Forecasts are suitable for short-term unit commitment and economic dispatch modeling, typically covering hours to days. On the other hand, samples are valuable for optimizing investment decisions or long-term storage scheduling, usually spanning months to years. This includes scenarios involving the potential divestment of old or non-operational units. Figure 3 provides an illustration of the multi-forecast and multi-sample structures.

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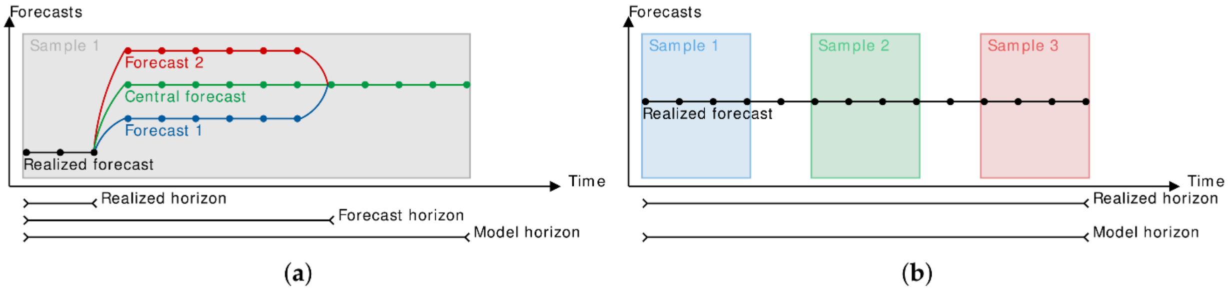

Figure 3: Stochastic structures: (a) a multi-forecast structure used by the scheduling model and (b) a multi-sample structure used by the investment model

2.1.4 Ancillary Services and Policy Constraints

The model considers frequency-related reserves as the primary ancillary service category. The input data allows defining any number of reserve types, each including up and down directions. Reserve requirements can be defined through various alternatives, including a constant requirement, a time series, dependency on the forecasted production of specific units (typically VRE), or on a unit (or combination) providing the largest output.

Each unit includes parameters that describe its capability to provide reserves for each reserve category. Units with a variable representing their online status must be online to provide reserves. However, units without an online status variable can also be defined to provide reserves. Additionally, it is possible to define a reserve transfer capability for individual lines, allowing a unit connected to one node to provide reserves to another node.

Each reserve category has a gate closure time, indicating the number of time steps ahead at which reserve allocation decisions must be made. The allocation frequency, duration of reserve allocation periods, and the ability to release specific reserve categories for realized time intervals can also be defined.

Furthermore, the model can accommodate other limitations and requirements, such as a capacity margin, maximum instantaneous share of specific energy production types, minimum number of online units, maximum permitted volume of emissions over a given period, annual energy production by certain unit types, and more.

2.2 The PERSEE tool

2.2.1 An optimization modelling tool

PERSEE stands for “oPtimizER for System Energy managEment”. It is a modelling software dedicated to techno-economic and environmental assessment of several designs of energy systems at local, industrial and territorial scales, while optimizing their operating costs. It allows to optimize both the sizing of the system and the operation. It is based on the Mixed Integer Linear Programming (MILP) formalism.

It has been developed since 2018 on the basis of past experiences from Odyssey [4] and PEGASE platform [5]. A literature survey [6] has confirmed the relevancy of MILP formalism to deal with such problems of production unit commitment, storage sizing and management to meet energy or mass demand profiles while integrating non controllable renewable or fatal energy sources.

PERSEE provides a graphical user interface that allows the user to model the system by assembling MILP model contributions from a C++ library, to build a time-dependent optimization problem solved by one of the solvers available in PERSEE through a multi-MILP-solver interface (OSI opensource, Cplex, Gurobi…)

2.2.2 How does it work?

Global MILP optimization problem will result from assembly of several MILP subproblems describing constraints and objective contributions of components from an existing library or from user defined dynamic libraries. The components can be connected to each other by bus components to perform mass or energy balances, or impose system constraints. Thus, this assembly will build the optimization problem that is composed of an objective function on time horizon and contraints of technical, economic and environmental types. In general, the Net Present Value (NPV) is used as objective function. It accounts for CAPital EXpanditure (Capex), OPerational EXpanditure (Opex), replacement costs, purchase and sales expanditures as well as possible carbon mission penalties. It becomes an operating cost function when no investment is considered. The variables of the problem are mainly instantaneous energy and mass flows consumed and produced by the system to meet user load profiles, and if needed, storage or production maximum capacities. The constraints on the variables express the way they are linked together to take into account for example conversion efficiencies between input and output of a process, instantaneous mass and energy balances or to represent operation limits such as ramp-up ramp-down speed limitations, or time to pass from cold-standby to full production for heat generators. This assembly results in a dynamic optimization problem over one or several years (levelized on the project lifetime) with a user defined timestep.

The user has to define the relevant energy carriers of electricity, heat or material (gas, fuel, biomass). Using the models available in PERSEE, the user describes the way energy is used and carried by the system, from energy sources (renewable energies, generators, etc…) or grids, to load profiles, through storages and convertors to pass from one carrier form to another while respecting energy and masss balance. As mentioned above, Persee provides models to ensure energy or mass balance, including carbon emission limitations etc.

Following up survey [6], PERSEE models have been written to be compliant with several time discretizations (constant timestep, variable timestep condensed typical periods).

Figure 4 shows how an architecture scheme composed of different energy sources (wind turbines and electrical grid) and an electrolyzer for hydrogen production used to feed loads can be translated into MILP modeling in PERSEE.

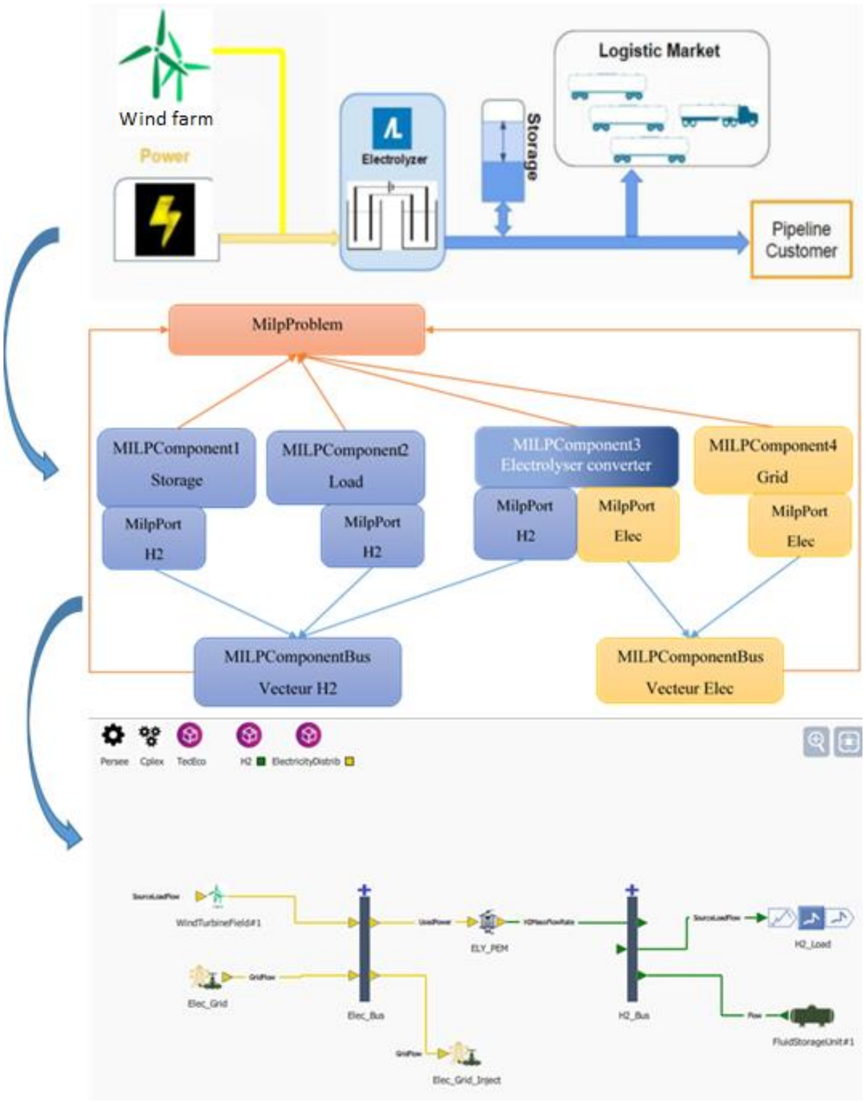

Figure 4: From architecture scheme to PERSEE model

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2.2.3 What are the outputs?

Once the simulation has been executed, PERSEE gives the optimal values for optimization variables, generally component sizing and the optimal operating of the system that maximize or minimize the objective function, generally that maximize the NPV.

The results can be analyzed in a dedicated window of PERSEE that allows the user to plot variables. The user can also plot easily pie chart, bar graph or Sankey diagram.

Furthermore, there is a file containing usefull information exported automatically at the end of the resolution. Thus, the user can easily access to global indicators such as the value of the objective function (generally the one of NPV), the total CAPEX, the value of environmental penalty if any and to component indicators such as their contribution to the objective function, their nominal power, their use, etc.

Finally, it is possible to perform sensitivity studies or parametric studies by coupling PERSEE either with Python either with URANIE (a platform of uncertainty treatment developped by CEA) [7]. It allows the user to investigate if a parameter has a significant impact on the objective function. Owing to that, it is also possible to build Pareto fronts, for example the levelized total cost of the system compared to CO_2 emissions that can be obtained by executing several simulations with a different constraint on CO_2 emissions.

2.2.4 Coupling PERSEE and PEGASE

PERSEE can also be used to operate real-time systems or simulators when it is used as a module of PEGASE platform. This co-simulation platform is also developed by CEA. It allows to build a sequence of modules that are executed one after the other and that exchange their data through a data exchange area.

In WP3, a coupling between PEGASE and PERSEE will be used to check the sizing obtained in T3.2 by operating refined models under 24h horizon foreseen hypothesis. In such coupling, PERSEE sends setpoints to Functional Mock-up Unit (FMU) exported from MODELICA models for example. Then, once the models have been executed, they send their final state and PERSEE can use it to perform a new optimization. This principle is represented in Figure 5.

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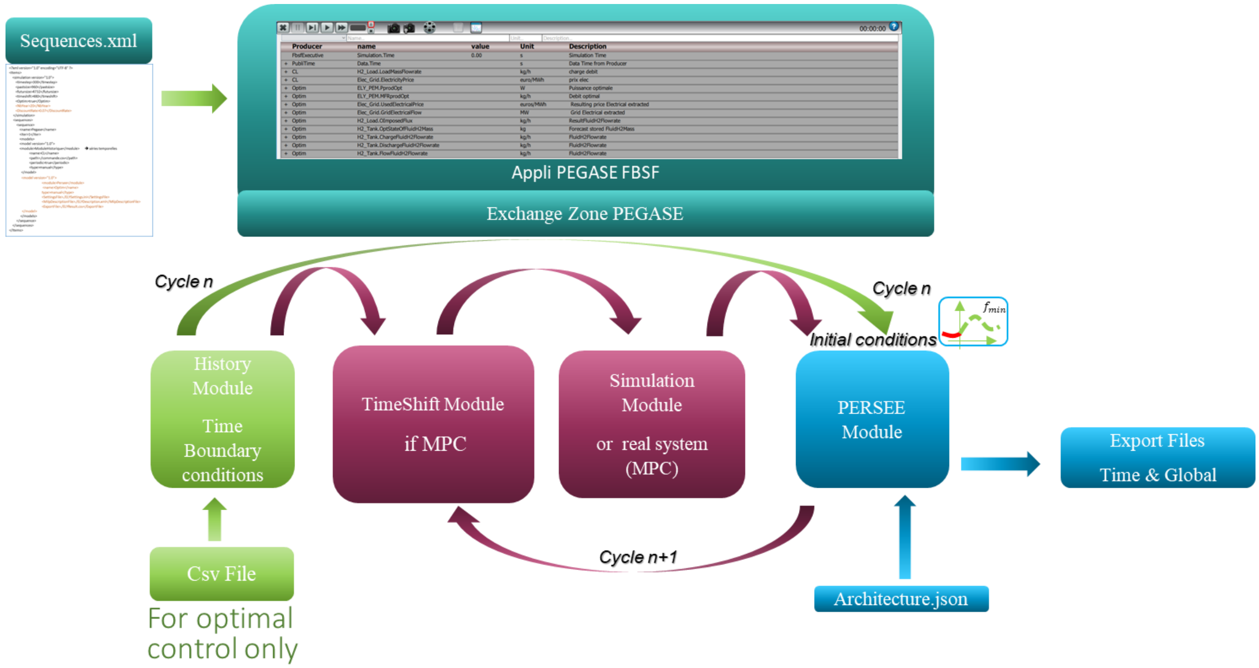

Figure 5: Functional diagram of PEGASE/PERSEE coupling

In [8], PERSEE has been used in stand-alone mode to compare the robustness of the optimal choice of technologies for two smart energy systems architectures at district level, illustrated by a case study representative of a newly built district in Grenoble, France. The electricity-driven architecture relies on the national electric grid, decentralized photovoltaic panels and decentralized heat pumps for heat production building by building. The alternative architecture consists of a district heating network with multiple sources and equipment for centralized production of heat. Those are a gas boiler plant, a biomass-driven cogeneration plant, a solar thermal collector field, and a geothermal heat pumping plant (grid-driven or photovoltaics-driven). Electric and heat storages are considered in both architectures. The sizing and operation of both architectures are optimized thanks to PERSEE, through a multi-objective approach (total project cost versus carbon dioxide emissions). Both architectures are compared at nominal scenario and at sensitivity scenarios. It is concluded that the electricity-driven architecture is less robust, especially to uncertainties in space heating demands (+150%/-30% impact on costs) and in heat pump performance (+35%/-15% in costs). Meanwhile, the multisource architecture is less sensitive to space heating demands (+110%/-30%) and has negligible sensitivity to the rest of parameters except photovoltaic panels efficiency (+14%/-7%).

Thus, in [9], the multisource architecture has been used in a co-simulation study. The co-simulation platform PEGASE runs the grid control and the detailed physical models developed using MODELICA (heat system) and Simulink (electric system). A Model Predictive Control (MPC)

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based on sliding time window MILP optimisations manages the flexibility of the multi energy system and ensures the balance between production and consumption. The objective of the optimizations is to minimise CO_2 equivalent emission costs and operational costs of each component, including the purchase of gas, biomass and electricity. A parametric study on the coupling strength between the electric and the heat system is performed by modifying the price of the electricity purchased from the national grid. Multiple scenarios with different thermoelectric coupling strength are analysed to show the dependency of the energy mix on the coupling strength. With increasing coupling, photovoltaic self-consumption increases and heat generation gradually shifts from the heat pump to the biomass cogeneration and to the gas boiler. This study also demonstrates how couplings between PEGASE and PERSEE enable easy implementation of optimal control on co-simulations of multi energy detailed physical models.

3 Detailed description of the case studies

This paragraph aims to present the three case studies that will be analysed within WP3. Each partner responsible for a case study explains the context, describes the case study and in particular its main assumptions and its methodology.

As a reminder, the three case studies are:

- Northern European case: a DH test case architecture based on Helsinki DH network with 4 main heating zones, handled by VTT,
- Central European case: a DH test case architecture based on Moravian-Silesiant region, handled by UJV,
- Southern European case: an energy hub test case based on a virtual industrial harbor inspired from Dunkirk harbour data that aims to provide electricity, heat and hydrogen owing to a coupling with a HTSE, handled by CEA.

3.1 Description of each case study

3.1.1 Northern European case

3.1.1.1 Context

In order to meet the commitments outlined in the Paris Climate Agreement [10], Finland must undergo significant decarbonization across various sectors. According to data from the National Inventory Report [11], energy-related greenhouse gas emissions accounted for 72% (39Mt CO_2 eq.) of the total emissions (53 Mt CO_2 eq.) in 2019. Furthermore, 42% (16Mt CO_2 eq.) of the energy-related emissions were attributed to the energy industries, specifically the production of district heating, electricity, and industrial process heat. Our study focuses on the decarbonization of the district heating system in the metropolitan area of Helsinki, the capital of Finland, which includes the large cities of Espoo (population of 293,000) and Vantaa (population of 237,000). It is important to note that each city has separate companies responsible for district heating production: Helen Ltd. in Helsinki, Fortum Ltd. in Espoo, and Vantaa Energia Ltd. in Vantaa. The district heating networks of Espoo and Vantaa are connected to the Helsinki district heating network with limited transfer capacity. Currently, the district heating supply in Helsinki and Espoo relies on natural gas and coal-fired units, although the use of heat pumps and biomass is increasing. In Vantaa, municipal waste plays a significant role in energy production. The specific characteristics of district heating supply and demand in these metropolitan cities are described in detail in the model and scenario description of this study.

The decarbonization ambitions for Helsinki are outlined in the Carbon Neutral Action Plan [12], which includes the development program of Helen Ltd. The current objective of Helen Ltd. is to comply with the national coal ban in the energy sector starting from 2030 [13]. To identify the most feasible measures for this transition, the city of Helsinki organized an international competition called the Helsinki Energy Challenge [14], which presented a wide range of solutions involving heat pumps and heat storage. The importance and potential of distribution temperatures within the district heating network were also recognized. Additionally, decarbonization efforts in the city of Espoo are being implemented through the Espoo Clean Heat project by Fortum Ltd., which aims to phase out coal use in Espoo's district heating production by 2025 and prioritize biomass utilization, waste water, and data center-based heat pumps [15]. Finally, the city of Vantaa has outlined an action plan with a goal of achieving carbon neutrality by 2030. According to the plan, the Vantaa district heating system would combine waste incineration with biomass combustion, waste heat utilization, and geothermal heat pumps. Overall, the entire metropolitan energy goals present an interesting foundation for analyzing decarbonization measures of district heating systems.

The diagram in Figure 6 illustrates the arrangement of conversion units and energy flows within the model. To maintain clarity, Figure 6 is a slightly simplified illustration of the main calculation model. Regarding TANDEM, the main energy vectors of the model are electricity and heat. In addition, the model covers cooling, hydrogen, and fossil fuels, such as gas and coal. Electricity generation options include Combined Cycle Gas Turbine (CCGT), Combined Heat and Power (CHP) plants, gas engines or turbines, solar Photovoltaic (PV), and wind turbines. Short-term energy storage is facilitated by heat storages and Battery Electric Storage Systems (BESS). District heating production can be achieved through CHP plants, gas and electric boilers, and various types of heat pumps.

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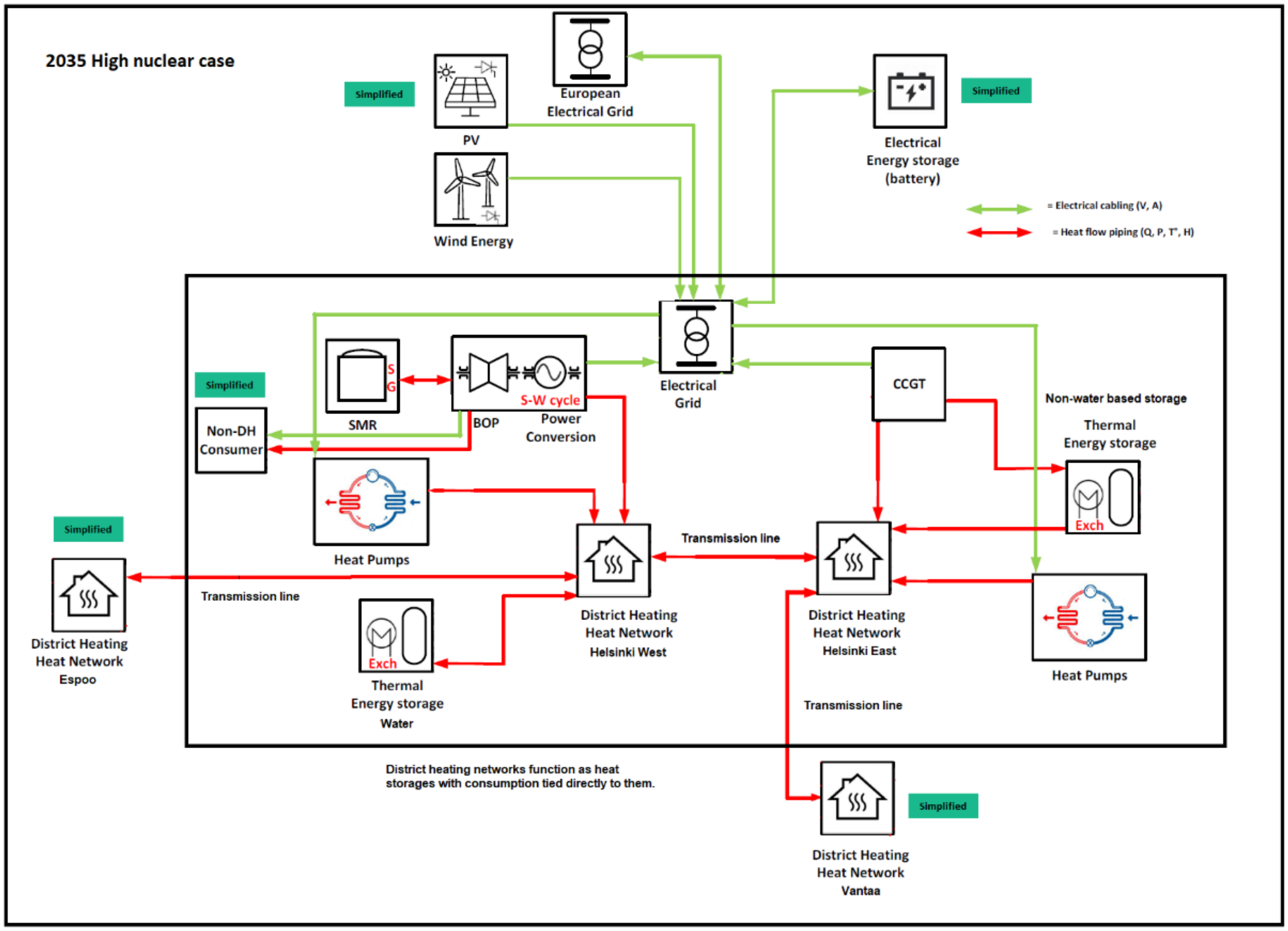

Figure 6: District Heating System configuration as described in the TANDEM/deliverable D1.4

Backbone models are relatively easily adjustable and it is possible to study also hydrogen and methanation scenarios. They might be relevant for the project as Helsinki is considering a construction of large H_2 facility as their production generate heat that can be used in the district heating grid. Hydrogen is produced via electrolysis and can be exported, injected directly into the gas grid, or stored for later use in a methanation plant. CO_2 required for methanation is captured either from CHP flue gases at a post-combustion capture plant or directly from the ambient air. Methanation generates Substitute Natural Gas (SNG) as a replacement for fossil natural gas.

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3.1.1.2 Case study description

To achieve decarbonization in the District Heating and Cooling (DHC) system of the Helsinki metropolitan area, it is necessary to invest in new energy technologies and approaches that replace fossil fuel-based District Heating (DH) production. In this regard, following scenarios are compared

Main scenarios

- No additional investments
- Heat Only Boiler Small Modular nuclear Reactors (HOB-SMR)
- Combined heat and power SMRs (CHP-SMR)
- Combination of HOB-SMR and CHP-SMR

Additional scenarios

- District heating Heat Pumps (HP) from low-quality heat sources
- Biomass HOBs
- Optionally H_2 scenario where hydrogen would be exported and side-product heat used in district heating

An investment analysis based on an optimization model is employed to assess the assumed 2035 and 2050 situations. The assessment focuses on evaluating the new capacity, costs, and emisssions associated with each scenario. Sensitivity analysis considering different assumptions regarding the existing DHC system, investment costs, and electricity prices will be performed.

Figure 7 illustrates all the scenarios which will be studied (main ones and additional ones) at the same time. The default model consists of a range of units and grid configuration presented in Figure 6. In addition to the the default model, we add alternative production technologies in each scenario and compare the results.

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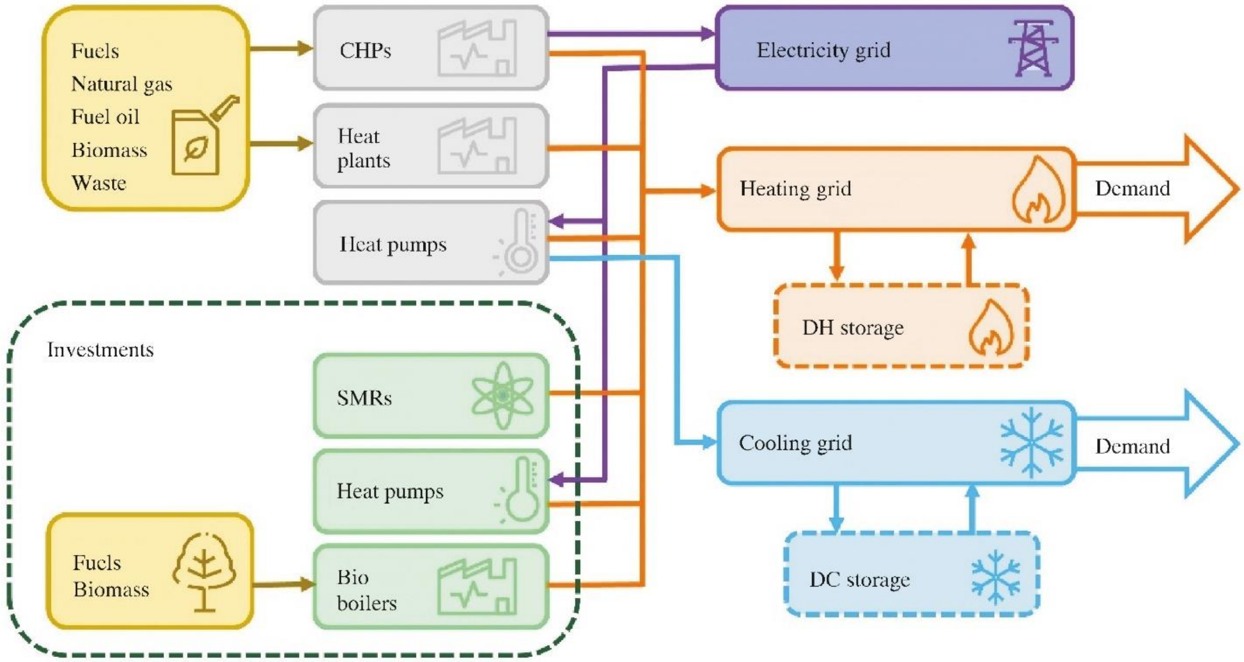

Figure 7: The simplified illustration of the modelled technology options in different scenarios. Modelled alternative additional production technologies (SMR, HP, biomass) are added to the modelled system in the studied scenarios.

The implementation of the energy system model for the Helsinki metropolitan DHC system involves integrating the DH and District Cooling (DC) production and storage structure into the Backbone model framework. The fundamental structure of the DH system is depicted in Figure 7; however, it should be noted that this illustration does not illustrate the division of the DH system into model regions, which include the DH grids of Helsinki 1, Helsinki 2, Espoo, Vantaa, and their interconnections. Additionally, the DH system is interconnected with the national electricity grid to facilitate the supply of electricity to heat pumps and enable the sale of electricity generated by CHP units to the Nordic electricity market.

District cooling can be obtained from heat pumps, compression chillers, or free cooling utilizing seawater. Moreover, heating and cooling are byproducts of the power-to-gas process. The district heating and cooling networks are localized within the city, while electricity and natural gas can be imported from or exported to national transmission grids.

The suitable rooftop area for solar PV installations in Espoo covers a total of 4.7km^2 [16]. To account for module spacing and obstacles, an availability factor of 60% was applied to this figure [17]. Using a DC power density of 170W/m^2, the total potential for solar PV was determined to be 480MW. Ground-mounted PV was not considered due to competition for land use and the high cost of land. Onshore wind power potential was also considered negligible due to high population density. However, coastal regions in Finland generally offer good potential for offshore wind. Therefore, offshore wind power was included in the case study without a specific capacity upper limit. Temporal profiles for solar PV and wind power in Espoo were extracted from Renewables Ninja platform using weather data from the year 2011 [18]. The year 2011 was selected because the heat demand, as measured by heating degree days, was slightly below the long-term average. It also encompassed cold periods necessary for realistic system design. Additionally, it is worth noting that the annual wind and solar power production were close to the average level.

Direct demand profiles for electricity, district heating, and cooling were not readily available for Espoo. Therefore, a linear model was fitted to data published for a similar-sized Finnish city [19] in order to estimate these demand profiles. The explanatory variables in the model included the type of day (weekday/weekend), hour of the day, and ambient temperature. This model was then used to forecast the demand for Espoo by scaling the total demand to historical values from 2018 [20]. The annual cooling demand was estimated based on [21].

Certain conversion units were assumed to be existing legacy units within the model. These units included a CCGT, a CHP plant with a capacity of 220MWe, gas boilers, and a Waste Water Heat Pump (WWHP). These types of plants are currently present in Espoo. However, new investments in these units were not permitted due to economic considerations for the CHP plant. The gas boilers were assumed to provide district heating reserve capacity during contingencies, and thus their capacity was not limited. The WWHP capacity (70MWth) was determined based on the available waste water and cooling demand. Additionally, a small biogas engine with a capacity of 15MWe was also included in the model.

3.1.2 Southern European case

3.1.2.1 Context

The Southern European case corresponds to the energy hub configuration. As defined in TANDEM/deliverable D1.4 [22], the energy hub configuration is inspired from harbour-like infrastructure.

In Europe, there are several examples of industrialized harbours, responsible of a high share of CO_2 emissions and involved now in a processus of decarbonation.

The port of Rotterdam is the first European port for Twenty-Foot Equivalent (TFE) criteria with 14.5 TFE in 2020 and it is responsible for about 20% of the national CO_2 emissions of the Netherlands (it was responsible for 22.5 Mton of CO_2 emission in 2020 as shown in Figure 8).

Since 2016, the port of Rotterdam has started to build a decarbonation strategy that resulted in the 2019 Rotterdam Climate Agreement. This document, written by Rotterdammers, gathers almost fifty climate deals to accelerate the reduction of greenhouse gases and stimulate a CO_2-free economy for the whole Rotterdam city including its port and its industries.

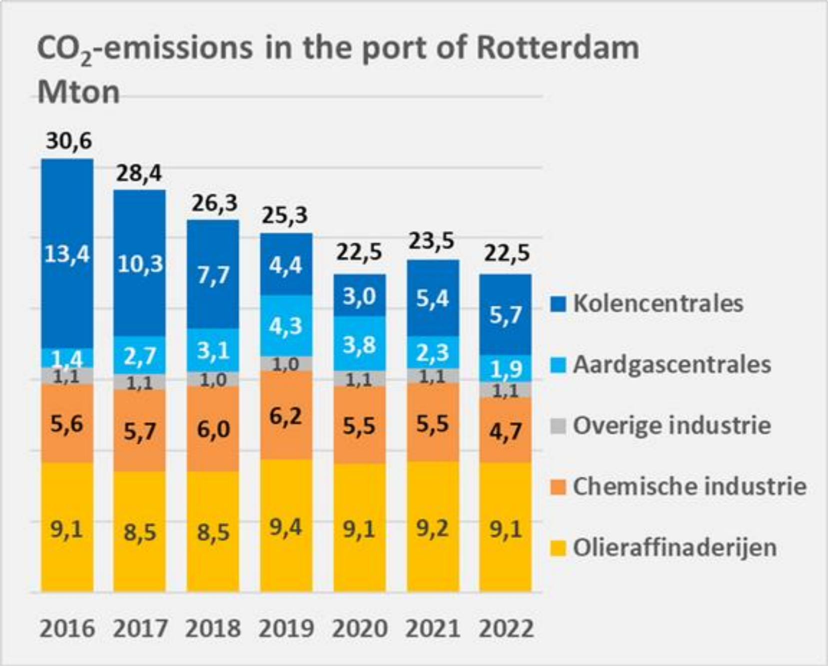

Figure 8: Evolution of CO_2 emissions in the port of Rotterdam [23]

The port of Dunkirk in France is another example of harbour involved in a decarbonation process. It contributes to 21% of the French CO_2 emissions due to the industrial sector. It has been selected in the ZIBAC national call for projects launched by ADEME [24] to promote the development of low carbon industrial areas. The port of Dunkirk has been involved in the energy transition for years and in 2018, the "Toile énergétique®" of this region has been released [25]. This "Toile énergétique®" is a representation of the energy ecosystem of the territory. It makes it possible to identify the resources and energies imported, produced, transformed and exchanged inside this territory and with other territories. Owing to this representation, it is possible to have an idea of the energy fluxes of the port of Dunkirk.

Like the other large industrialized harbours, the port of Dunkirk is composed of various complex energy fluxes. There are several energy producers including a nuclear power plant, a CCGT, waste recovery plant, wind farms and several energy consumers including a district heating and a lot of industrial end users in different sectors like steel industry (ArcelorMittal, Ascométal, Ferroglobe, …) and chemical industry (Rio Tinto Minerals, Versalis…). There are several projects ongoing to

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increase the share of renewable energy of this territory: an offshore wind farm of 600 MW, 40 MW of PV field.

Furthermore, like in other large industrialized harbours, Dunkirk bets on hydrogen through a project with H2V called H2V59 that aims to produce 42 ktons of H_2 per year by 2029 owing to 300 MW of installed electrolyser capacity [26]. **The port of Rotterdam** has also chosen to produce hydrogen with, initially, blue hydrogen (produced either by Steam Methane Gas Reforming (SMGR) or Auto Thermal Reforming (ATR) with Carbon Capture and Storage (CCS)), that will be replaced by green hydrogen with the development of renewable energies. The objective of the port of Rotterdam is to obtain an hydrogen production of 700 ktons per year [27].

Besides, **the industrialized harbour of Fos-sur-Mer**, located in Southern France, is worth mentioning here through two examples of hydrogen projects: H2VFos that aims to produce 84 ktons/per by 2031 owing to 600MW of electrolyser capacity installed and Masshylia that should feed the biorefinery of Total-Energies with 5 tons/day of green hydrogen owing to PV. Today, hydrogen produced locally as a byproduct of refineries and petrochemical industries or from SMGR or from brine electrolysis, is consumed locally for refineries, bio-refineries, chemical industries, process heat production mixed with natural gas. Finally, a project of hydrogen corridor H2MED would make it possible to transport hydrogen produced in Portugal and Spain from Barcelona to Germany through the port of Fos-sur-Mer/Marseille.

All these examples confirm that **industrialized harbours are relevant and interesting areas to study NHES**. In such environment, SMR can be coupled with hydrogen production and/or with heat network supplying other process in addition to other energy sources such as PV fields or wind farms and CCGT in an energy hub. As it is quite difficult to obtain realistic timeseries for an industrialized harbour (there are few detailed open data) and as this case study has a strong methodological interest, it has been decided to study a virtual harbour located in Southern Europe designed from the architecture that was released in TANDEM/deliverable D1.4 and that is presented in Figure 9.

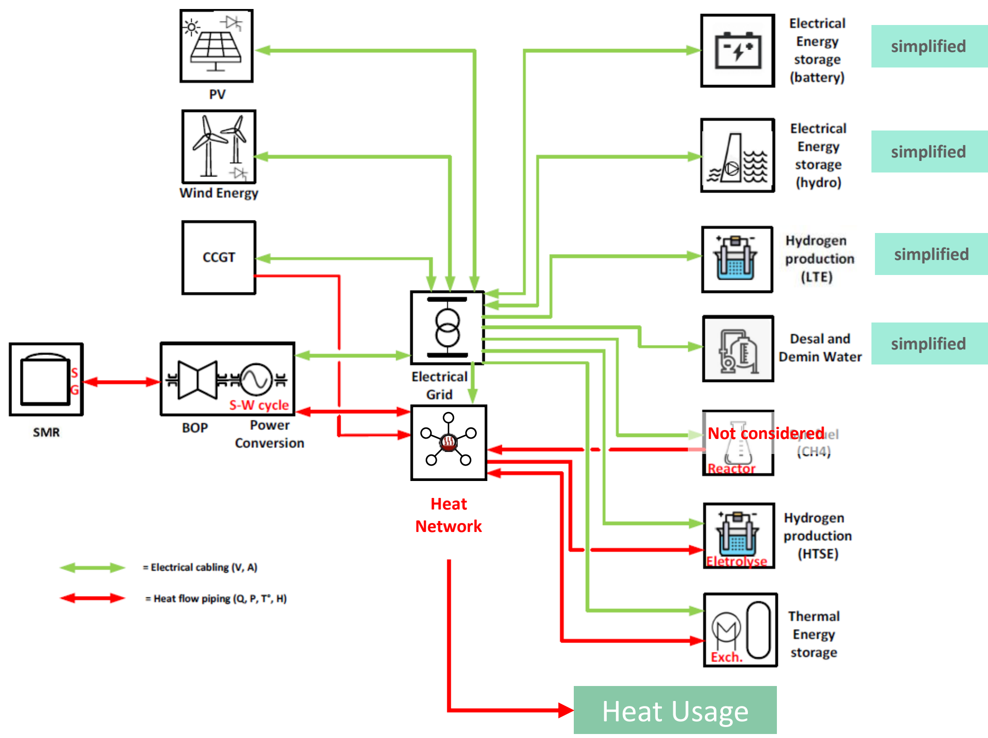

Figure 9: Architecture of the HES study case (TANDEM/deliverable D1.4)

From TANDEM/deliverable D1.4 and from the context described previously, a reference case and variants will be built. WP1 has defined three scenarios that will be derived into variants:

- 2035 low SMR deployment in which there will be no SMR integrated in the HES.
- 2035 high SMR deployment in which there will be 1 SMR integrated in the HES.
- 2050 high SMR deployment in which there will be 2 SMR integrated in the HES.

3.1.2.2 Case study description

- Objectives & methodology

The main objective is to investigate the techno-economic and environmental profitability of such NHES through two main steps.

First step : the sizing fo the system:

As seen, in the architecture from TANDEM/deliverable D1.4, some components need to be sized. The number of SMR and of CCGT will be fixed depending on the scenario. Realistic data will be used for the sizing of these components. Nevertheless, the HTSE needs to be sized as well as the thermal energy storage and the hydrogen storage.

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The first step of the study will lead to obtain the optimal architecture and its optimal sizing. In this first step, only sizing constraints will be taken into account and *the study will be conducted over one year with a time step of one hour*. PERSEE will have a perfect knowledge of the inputs data for the whole year. The case study will be built in PERSEE in such a way that PERSEE will be able to choose the best option among the proposed ones. For example, two technologies for hydrogen production – Solid Oxide Electrolyzer Cell (SOEC) for HTSE and Proton Exchange Membrane (PEM) for LTE - will be in competition and PERSEE will size these two components. In the same way, PERSEE makes it possible to study different configurations and a particular attention will be paid to the thermal supply of HTSE: the heat can be picked directly from the SMR, it can be taken from a specific heat network (the baseline consideration in TANDEM) but else provided with heaterstick.

Second step : Validation of the architecture and analysis of the system operation and flexibility

In the second step, the study will be refined. *The study will be again conducted over one year with a time step of one hour* but *PERSEE will not have a perfect knowledge of the inputs data for the whole year but only for the next week*. *Rolling horizon will be used* to have a more realistic approach. Additionally, models could be refined if it is relevant to reach the objective of this second step that is to validate the obtained architecture and the operation of the different components. This step is mandatory to consolidate the techno-economic and environmental analysis of such NHES.

Finally, in this second step, a study of the flexibility offered by such NHES will be conducted as it is also a main objective of the TANDEM project. The coupling between SMR, renewable energies and HTSE offers several possibilities for flexibility: for example, the flexibility could come from HTSE and energy storages while SMR would operate in base-load mode.

- Case study description

The case study for the Southern European case is a **virtual** harbour located in Southern Europe and inspired from real data of Dunkirk port. In the reference case, the location will be Fos-sur-Mer in France. Another location can be studied in a sensitivity study, for example Algeciras in Spain. The Figure 10 gives an overview of the energy card of Dunkirk harbour. It is a very simplied view from an energy flux map built by AGUR [25] where only hydrogen, electricity and heat vectors are represented and only few industrial sites are shown.

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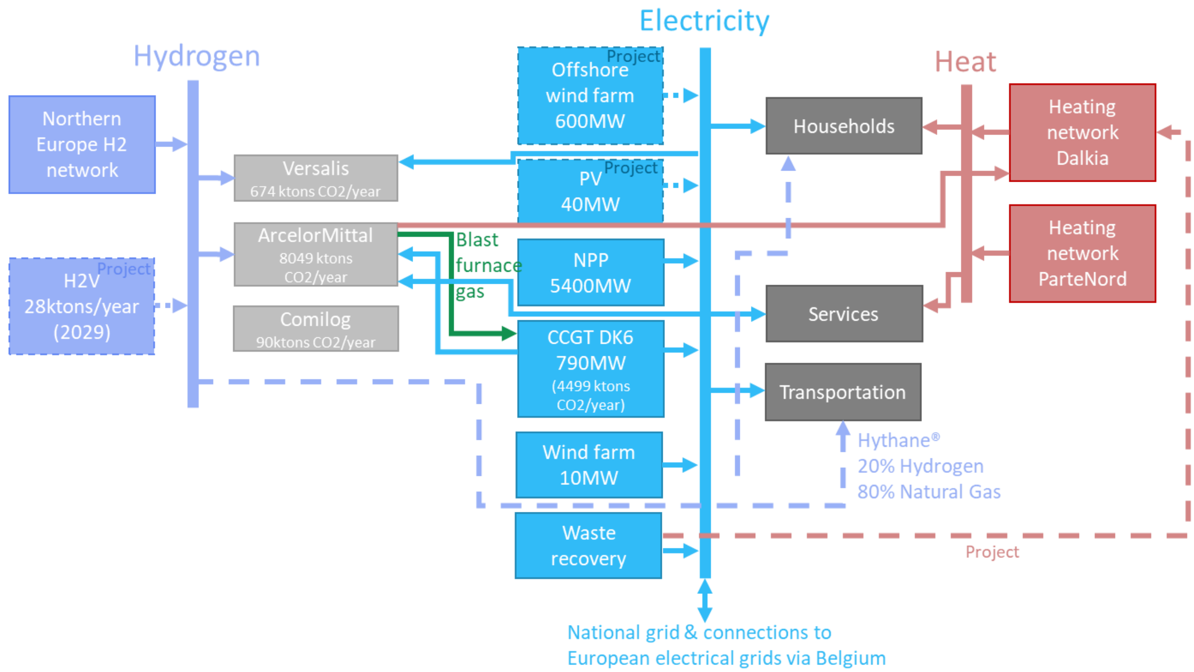

Figure 10: Energy card of Dunkirk

As described in Figure 9 from TANDEM/deliverable D1.4, the architecture will be composed of several energy sources that will be modelled in PERSEE, the modeling envisaged is shown in Figure 11.

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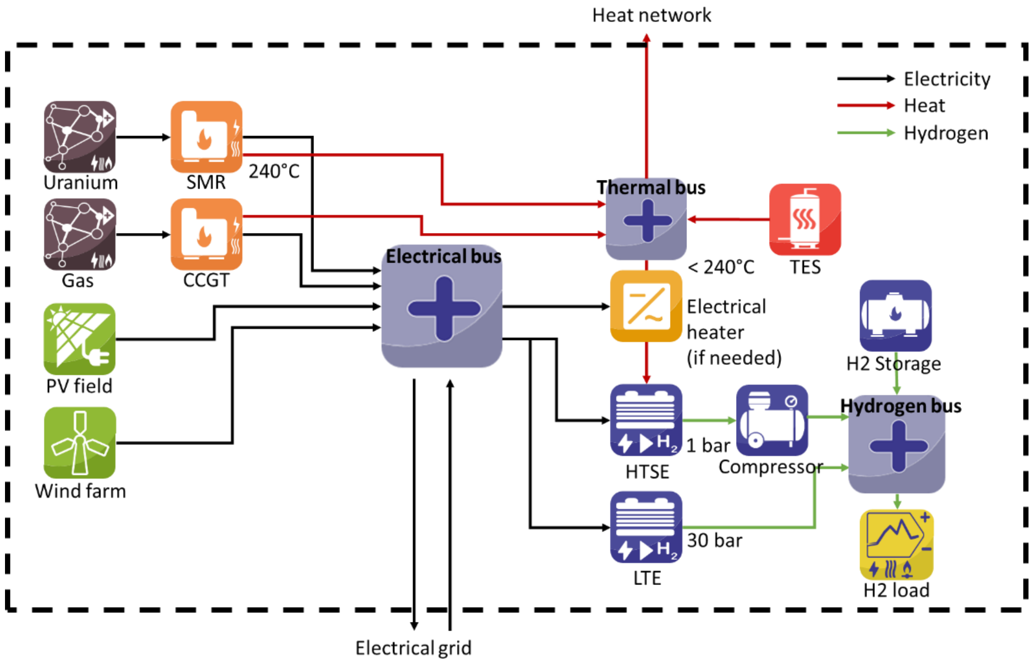

Figure 11: Scheme of the model envisaged

Detailed tables with techno-economic and environmental parameters can be found in paragraph 3.2 for the main components whereas a short description of them is given in the paragraph below.

- SMR

The SMR considered in this study is the E-SMR from ELSMOR project. The characteristics of one unit are 540MWth and 170MWe. The reference design is composed of two units in such a way that the whole system can deliver 340MWe. This design can be used to deliver both heat and electricity. Heat availablable for coupling would have a temperature level between 150°C and 250°C and up to 20% of the thermal power could be used with a small decrease of the electricity capacity.

- CCGT/CHP

The CCGT considered in this study will be inspired from real data. For example, the one of Dunkirk, named, DK6, was commissioned in 2005 for a total cost of 450M€$_{2005}$. It is operated by Engie and it recovers steelmaking gases from Sollac factory. The global efficiency is 50% and it has a power generation capacity of 790MWe. This CCGT produces only electricity.

In our modelling, the CCGT will produce both heat and electricity.

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- Renewable energies

A PV field and an offshore wind farm will be considered. PVGis [28] will be used to estimate the potential of a PV field located at Fos-sur-Mer. Owing to PVGis, a timeseries of electricity production for a 1MWpeak PV field at Fos-sur-Mer will be generated. In the same way, renewables ninja [29] will be used to estimate the potential of an offshore wind farm.

There could be an interest to study two different locations as depending on the location, the profiles for PV and offshore wind farm can be very different as well as the existing potential for PV and offshore wind farm.

Figure 12 gives the electricity production for a 1MWpeak PV plant located at Fos-sur-Mer (on the left) and at Dunkirk (on the right) fo year 2019. These curves were generated using PVGis for monocrystalline technology, two-axis tracker and 14% of system losses.

Figure 13 gives the electricity production for a 1MWpeak floating offshore wind turbine located at Fos-sur-Mer (on the left) and at Dunkirk (on the right) fo year 2019. These curves were generated using Renewable Ninja for one “Vestas V164 9.5kW” wind turbine. Floating offshore wind turbine was selected due to the fact that this technology is the most suitable for the Mediterranean Sea.

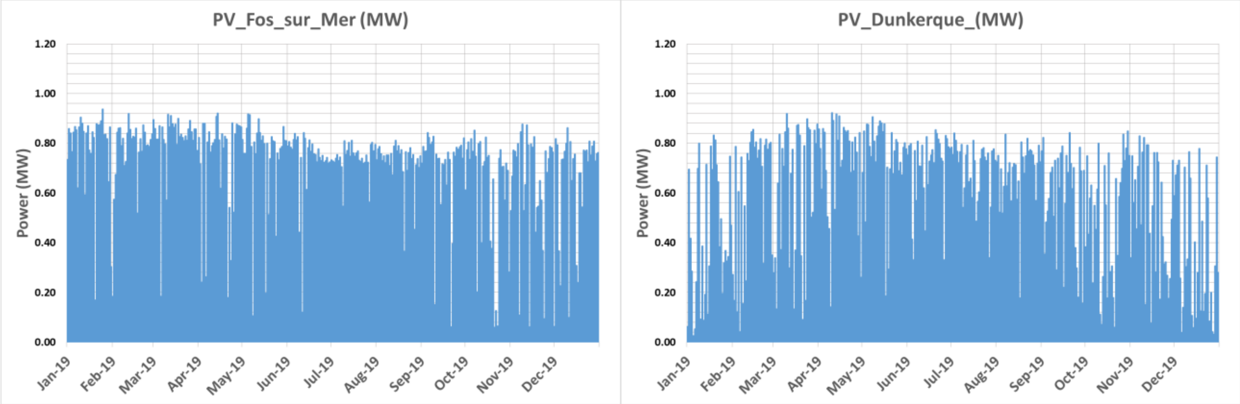

Figure 12: Electricity production for a 1 MWpeak PV plant at Fos-sur-Mer and at Dunkirk

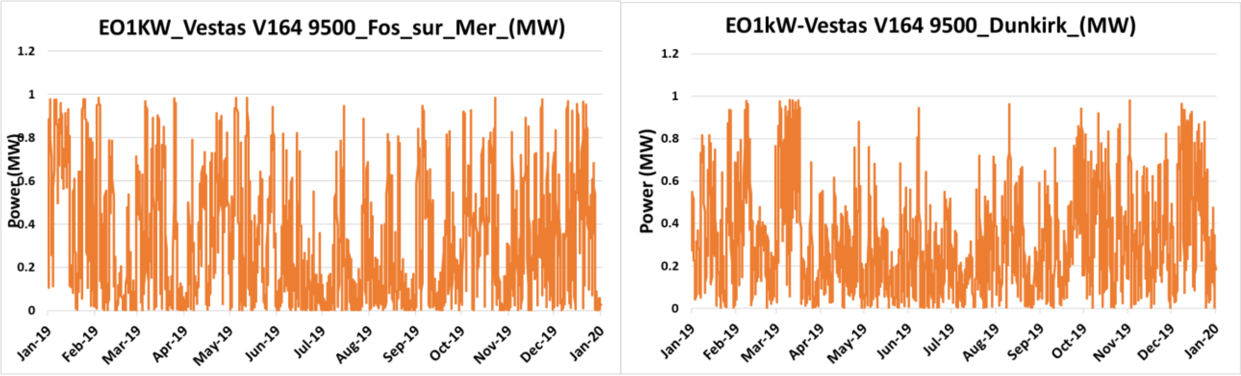

Figure 13: Electricity production for a 1 MWpeak floating offshore wind turbine at Fos-sur-Mer and at Dunkirk

In the PERSEE modelling, theses unit profiles are used as input data and the sizing process will optimize the number of units within the limit of the potential of the chosen location.

Two local projects can be worth being mentionned: TotalEnergies inaugurated the largest French PV field with trackers in La Feuillane near Fos-sur-Mer. This 33MWpeak PV field is made up of 80,000 PV modules installed on 49 hectares. Regarding wind farms, there is an ongoing project for floating offshore wind farms on the French Mediterranean coast. It would consist of two farms of 250MW each, but the location is still under study near Le Barcarès, located 150km away from Fos-sur-Mer. However, a demonstration farm of 25MW involving three turbines is currently in construction near Fos-sur-Mer.

The NHES will be used to feed several uses through different energy vectors. In PERSEE, only electricity, heat and hydrogen vectors will be considered. The uses must be characterized.

- Electricity

RTE estimated that the Dunkirk harbour will need 3500MW additional electricity in 2030 due to decarbonation and 4500MW in 2040 [30]. Additionally to industry decarbonation, this electricity could be used to produce hydrogen or to develop cold ironing. Owing to this process, electrical power can be provided to ships at berth allowing them to turned off their auxiliary engines reducing ship's emissions. Dunkirk harbour has already a cold ironing process of 8 MW.

The NHES studied in this case study will be connected to the national electrical grid with the possibility to consider some constraints. For example, the NHES should have to deliver a constant amount of electricity to the national electrical grid.

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Futhermore, with regard to the cost of electricity, as a first approach, historical electricity prices for the years 2019 and 2022 could be used. These two years correspond respectively to a classic year and a disrupted year. Figure 14 shows the historical electricity prices over these two years in France and Spain.

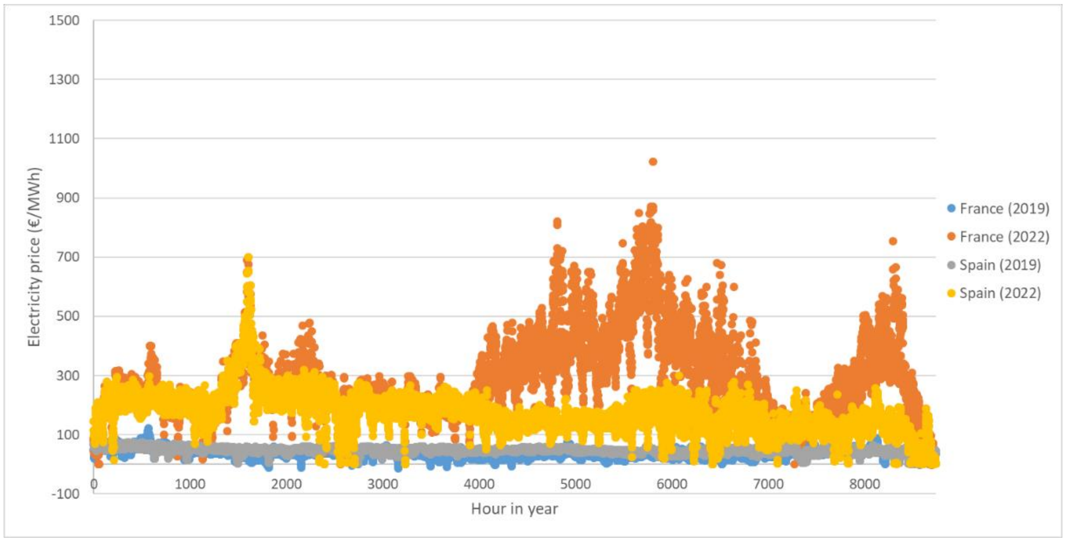

Figure 14: Evolution of electricity prices in France and in Spain for years 2019 and 2022

- Hydrogen

As previously mentioned, several harbours bet on hydrogen to decarbonize industrial sectors. The precise load profile is not known but the quantities needed are very large. Besides, there will be several end-users for hydrogen as, in addition to industry, there will be transportation, sector for which hydrogen can be used either as fuel itself or combined to provide synthetic fuels.

This is why, in this study, we will consider a given and annual hydrogen load. The final usages are not modelled and no assumption is taken regarding this point. Thus the load profile will be constant over the year and an hydrogen storage will be modeled to give flexibility to this chain. The proposed architectures and systems calculated by PERSEE will be compared through technical, economic and environemental results acccording to this annual load. A particular attention will be paid to the origin of electricity used to produce hydrogen and to the amount of CO_2 released to produce hydrogen.

- Heat

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The heat load will not be considered in this case study as this aspect is already handled in the Northern European case an in the Central Europe case. Heat excess will be injected into the heat network under specific constraints.

3.1.3 Central European case

3.1.3.1 Context

On April 12, 2023, the government of the Czech Republic (CR) approved the starting points for update of the State Energy Policy of the CR and related strategic documents, which is a guide for the preparation of relevant strategic documents. Strategic goals relevant for TANDEM project were defined as follows:

- Reduce greenhouse gas emissions to a level that corresponds to the goals of the Fit for 55 package and achieve climate neutrality in the Czech Republic by 2050 and permanently reduce emissions of pollutants in accordance with the National Emission Reduction Program.
- Reduce the share of fossil fuels in primary energy consumption to 50% by 2030 and 0% by 2050 and completely phase out the use of coal for electricity and heat generation by 2033.
- Reach the share of RES at the final level corresponding to the EU target by 2030 and further increase this share by 2050 in line with the achievement of climate neutrality.

The CR is facing the soon coal mines either shut down or depletion. The SMR technology could be an alternative (arising among other alternatives) as a possible replacement for the existing fossil energy sources. SMR units can make a significant contribution to greenhouse emissions reduction and together with Renewbles could be one of the tools to achieve the requirements of National Energy and Climate Plan of the CR [31].

The possibility of reusing existing coal-fired sites for SMR deployment brings a number of advantages:

- Land acquisition: Avoiding land acquisition for the SMR plant is a great economic advantage, SMR can be constructed on or near the site of retired coal plant.
- Existing water source, rail and road connectivity.
- Trained human resources within commuting distance: It is possible to redirect workers from the retired fossil fuel industry to the nuclear industry.
- Supply chains are similar for coal and nuclear plants: economic transition for local companies is possible as well as job preservation.
- Continuation of power production for local customer.

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- Suitability for existing grid connections and heat networks: SMRs are similar to typical coal fired plants, therefore they are suitable for existing grid connections and heat networks.
- Some systems can be repurposed: These include plant make-up water and water storage systems, cooling towers, compressed air systems, chemical stores, technical gases storage system, wastewater treatment systems and mobile lifting equipment.

For these reasons, the first consideration for SMR in the CR should be as an alternative to coal-fired sources.

- Scenarios of decarbonization of district heating network in the CR using SMR

The following model scenario illustrates the possible contribution of SMR to the decarbonization of the District Heating Networks (DHN) in the Czech Republic, primarily by replacing existing coal sources. The scenario is of a working nature for the purposes of the TANDEM project and do not have the ambition to define real future plans for the construction of nuclear energy sources in the Czech Republic, they only illustrate the possibilities of future development for the purposes of the DHNs.

The aim of the Central European case is to propose a way to replace a part of coal heat sources in the Moravian-Silesian Region (MSR) of the CR with low-emission SMR sources and thus decisively reduce polluting emissions in MSR. This region was selected because it is located very near to the Polish and Slovakia border and therefore appropriately represents the area of central Europe.

- Moravian-Silesian Region – current situation

MSR is a highly industrialized region with a large share of CO_2 production in the CR. The most significant polluters are mainly large stationary sources e.g. iron and steel works (Třinec, Vítkovice and Ostrava), power plants (Dětmarovice and Třebovice) and heating plants (Karviná). The supply of heat to the population and industry comes mainly from fossil fuels, and therefore it is a significant contributor to emissions. In the whole MSR, more than 214,000 flats are supplied with heat from district heating. There are 1238.9 km of heating networks, of which:

- 137.9 km for steam distribution (max. 240°C, max. 1.8 MPa),
- 429.5 km for hot water (max. 180°C, max. 2.5 MPa),
- 671.5 km for warm water (max. 110°C, max. 1.6 MPa).

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There are 243 plants licensed to produce heat energy, which are grouped into 57 DHNs. Many of these DHNs are very small and therefore unsuitable for SMR. Only 15 DHNs supply heat to more than 10 000 inhabitants.

3.1.3.2 Case study description

The Central European case focusing on the analysis of LW-SMR integration within a configuration of HES incorporating district heating networks and a power grid. The scenarios cover timeframes for 2035 and 2050, with the 2035 timeframe considering the low and high SMR deployment scenarios and 2050 only the high scenario.

This research is focused on the analysis of the possibilities of the SMRs projects in MSR as the sources intended to replace the existing energy sources based on the coal burning mainly used for the district heating. The study case will be modelled in PERSEE with the focus on:

- determination of the optimal architecture,
- determination of the proper size of certain components,
- finding a suitable configuration for DHNs interconnection,
- assessment of the techno-economic aspects, and operational feasibility.

A LW-SMR with power output of 540 MWt/170 MWe (E-SMR concept) was selected for TANDEM project. The size of SMR component is unnecessarily large for most heat networks in Moravian-Silesian region. The most optimal solution for Central European case study is to interconnect several heat networks as shown on the map (Figure 15). It is recommended to interconnect DHN Bohumín/Orlová and DHN Havířov/Karviná and supply these connected systems with heat from SMR deployed in Dětmarovice site. The total annual supply of heat from SMR will be 3260 TJ. The values of potential heat supply and current installed power of CHPs within modelled area are summarized inTable 1.

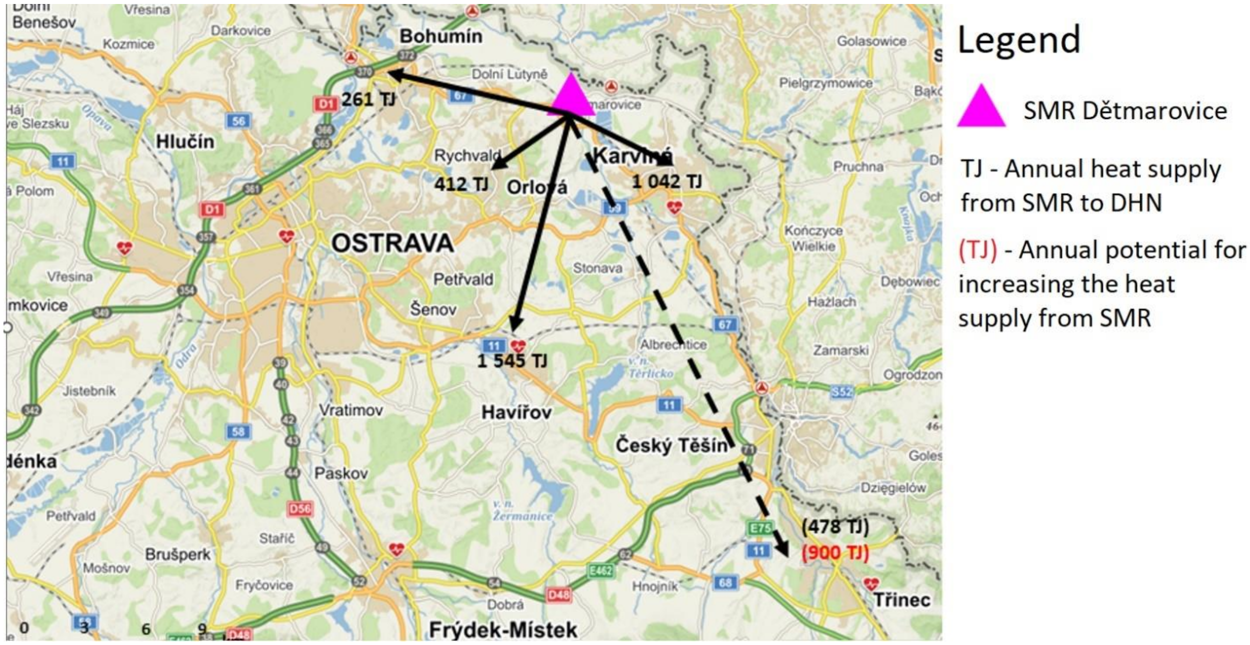

Figure 15: Possible interconnection of several DHNs for Dětmarovice SMR

<table>
<tr><th rowspan="2">DHN</th><th rowspan="2">CHP</th><th rowspan="2">Thermal power / electrical power [MWt / MWe]</th><th colspan="2">Annual heat supply [GJ]</th><th rowspan="2">Possible heat supply from SMR [TJ]</th></tr>
<tr><th>Residential sector</th><th>Non-manufacturing sector</th></tr>
<tr><td rowspan="2">Karviná and Havířov</td><td>Karviná Heating Plant</td><td>248.0 / 54.9</td><td rowspan="2">2 031 834</td><td rowspan="2">455 628</td><td rowspan="4">3260</td></tr>
<tr><td>ČSA Heating Plant</td><td>171.0 / 24.0</td></tr>
<tr><td>Orlová</td><td rowspan="2">Dětmarovice Power Plant</td><td rowspan="2">2073.7 / 800</td><td>344 200</td><td>51 630</td></tr>
<tr><td>Bohumín</td><td>228 080</td><td>22 808</td></tr>
</table>

Table 1: Potential heat supply and current installed power of CHPs

The mainreasons, why Dětmarovice site was selected for TANDEM project:

- Three coal-fired sources will be replaced to meet the requirements of National Emission Reduction Program,
- It is one of the potential sites for the SMR deployment in the CR.

The architecture of the study case will be composed of energy sources based on the National Energy and Climate Plan:

- PV field,

- Wind plants,
- CHP,
- SMR,
- Heat pumps (in small scale or not considered),
- Heat only boilers (may not be considered).

These energy sources will be used to produce heat and electricity to supply several end-users.

In 2035, the low SMR deployment scenario does not include SMRs; power and heat are produced by a mix of Integrated Renewable Energy System (IRES) and CHPs. The high scenario for 2035 will include a single SMR module replacing whole Dětmarovice Power Plant. This will result in a significant decrease in electricity production. One SMR module will be primarily used to saturate the heat demand for interconnected DHNs. The architectures of low and high scenario for 2035 are shown on Figure 16 and Figure 17.

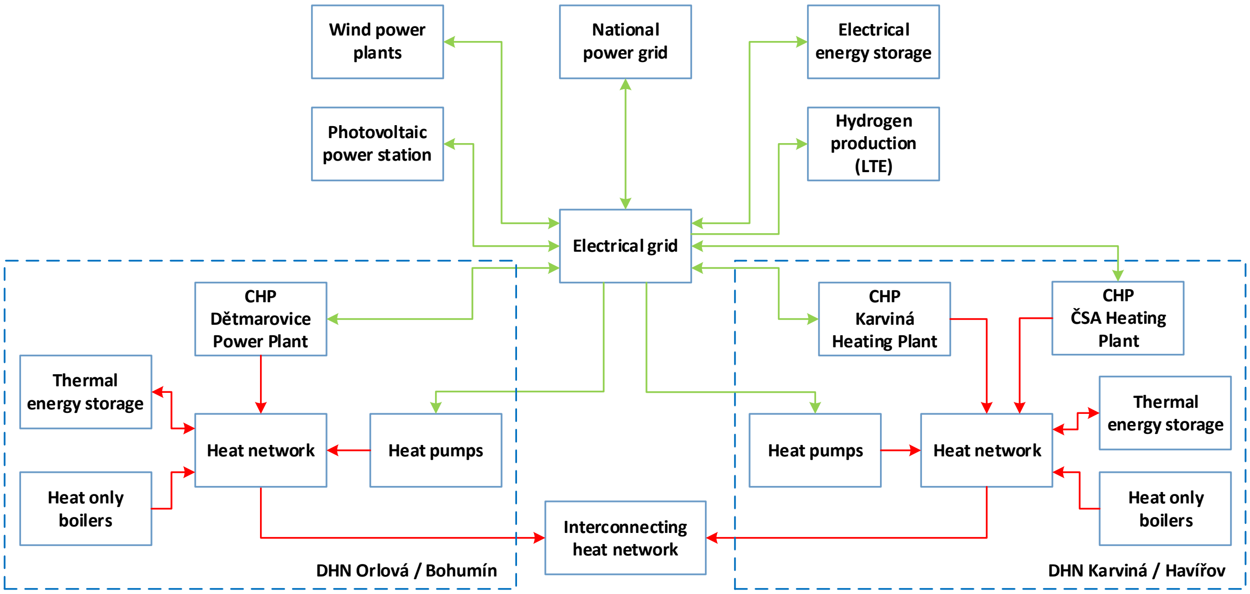

Figure 16: District Heating Low Scenario - 2035

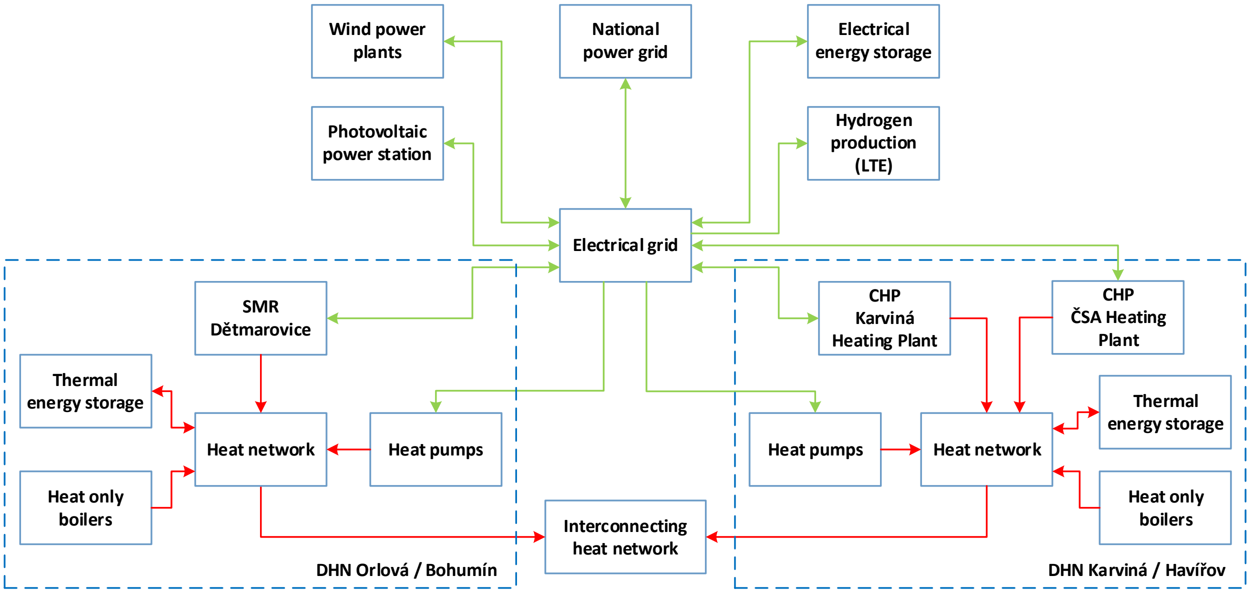

Figure 17: District Heating High Scenario – 2035

For 2050, in the high SMR deployment scenario, four SMRs replace all the CHP plants. All SMR units will be sited in Dětmarovice. This step will result in an optimal power replacement for coal resources (Figure 18).

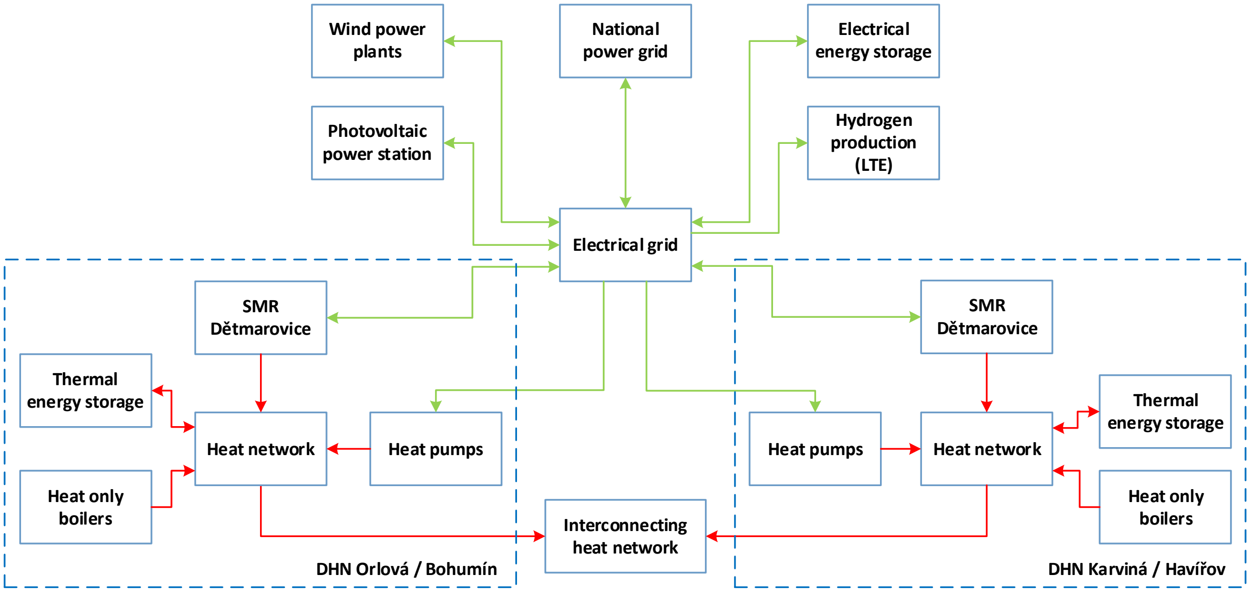

Figure 18: District Heating High Scenario - 2050

3.2 Techno-economic and environmental parameters

The tables below give an overview of the technical, economic and environmental parameters that will be needed to build the study cases in the Backbone and PERSEE tools. When values or ranges of values are available and public, they are provided in the tables.

3.2.1 SMR

Table 2, Table 3 and Table 4 give respectively the technical, economic and environmental parameters for the SMR considered in the case studies. The CHP-SMR that will be considered is a SMR based on the design developed in the ELSMOR Euratom project (E-SMR concept) [32]. Besides, VTT will consider a HOB-SMR based on LDR-50 design for comparison. The values given in the tables, especially economic and environmental values are based on TANDEM/deliverable D1.3 [34].

3.2.1.1 Technical parameters

Parameter name	Unit	Value TANDEM	Value LDR-50
Thermal power capacity	MWth	540	50
Net Electrical power capacity	MWe	170	0
Load following range	%	[20 - 100]	N.C.
Speed of load following	%Pn/min	5	N.C.
Effective heat recovery capacity[1]	%	[10 - 20]	N/A
Temperature of heat recovery (for coupling)	°C	>200	[130 – 155]
Pressure of heat recovery	MPa	~1	[0.5 – 0.8]
Efficiency for electricity production	%	~33	N/A
Ratio heat/electricity	%	Variable	N/A
In-House plant consumption	MWe	~10	N.C.
Fuel material	-	UO_2	UO_2
Enrichment	%	5	2.5

Table 2: Overview of the technical parameters of the SMR

3.2.1.2 Economic parameters

Parameter name	Unit	Value TANDEM	Value LDR-50

[1] It corresponds to the ratio of the SMR thermal power associated with heat supply

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Design lifetime	years	60	N.C.
Capacity factor	%	92	N.C.
CAPEX	€/MW	5710000	N.C.
OPEX	%/CAPEX	N.C.	N.C.
Installation factor	%	N.C.	N.C.
Combustible cost	€/MWh	7	N.C.
Variable cost	€/MWh produced	23	N.C.

Table 3: Overview of the economic parameters of the SMR

3.2.1.3 Environmental parameters

Parameter name	Unit	Value TANDEM	Value LDR-50
CO_2 content (/ kWh_e)	g CO_2/kWh_e produced	[4-6]	N/A
CO_2 content (/ kWh_{th})	g CO_2/kWh_{th} produced	[1-2]	N.C.

Table 4: Overview of the environmental parameters of the SMR

3.2.2 CCGT/CHP

Table 5, Table 6 and Table 7 give respectively the technical, economic and environmental parameters for a CCGT or a CHP that could be considered in the case studies. Values are given for information.

3.2.2.1 Technical parameters

Parameter name	Unit	CEA Value	VTT Value	UJV Value
Thermal power capacity	MWth	N/A	N. C.	830
Electrical power capacity	MWe	350	N. C.	330
Load following range	%	[15-100]	[15-100]	[40-100]
Speed of load following	%/min	[5-15]	[5-15]	2
Starting time	hour	0.4	0.5	[1.66-5]
Efficiency for heat production	%	N/A	[50-100]	90
Efficiency for electricity production	%	53	[0-55]	40
Ratio heat/electricity	%	N/A	Variable	Variable
In-House plant consumption	MWe	N.C.	N.C.	4%
Level of output temperature	°C	N.C.	N.C.	530
Fuel material	-	Gas	Gas / Syngas	Coal

Table 5: Overview of the technical parameters of the CCGT/CHP

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3.2.2.2 Economic parameters

Parameter name	Unit	CEA Value	VTT Value	UJV Value
Design lifetime	years	30	30	40
Capacity factor	%	~85	Result of optimization	[41-64]
CAPEX	€/kW	[800 - 1000]	[800-1000]	N.C.
OPEX	%/CAPEX	N.C.	1	N.C.
Installation factor	%	N.C.	N.C.	N.C.
Combustible cost	€/MWh produced	Timeseries	[30-60]	N.C.
Starting cost	€/starting	0.05	N.C.	N.C.
Variable cost	€/MWh produced	5.6	N.C.	N.C.

Table 6: Overview of the economic parameters of the CCGT/CHP

3.2.2.3 Environmental parameters

Parameter name	Unit	CEA Value [33]	VTT Value	UJV Value
Fuel material	-	Gas	Gas / Syngas	Coal / Lignite
CO_2 content	g CO_2/kWh produced	[410-650]	450	[900-1000]

Table 7: Overview of the environmental parameters of the CCGT/CHP

3.2.3 HTSE

Table 8, Table 9 and Table 10 give respectively the technical, economic and environmental parameters for the HTSE considered in the case studies. Values are for 2030, they come from TANDEM/deliverable D1.3 [34] where the values for 2050 are also described.

3.2.3.1 Technical parameters

Parameter name	Unit	Value
Minimal power	%Nominal power	[50-93]
Nominal power	MW	[0.001-2.6]
Electrical consumption	kWh/kg H_2 produced	[37-43]
Heat consumption	kWhth/kg H_2 produced	[8-12]
Water consumption	kg H2O/kg H_2 produced	[14.5-18]
Stack degradation	%/1000h	N.C.
Operating temperature	°C	[700-900]
Operating pressure	MPa	0.1

Table 8: Overview of the technical parameters of the HTSE

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3.2.3.2 Economic parameters

Parameter name	Unit	Value
Design lifetime	years	[15-30]
Capacity factor	%	N.C.
CAPEX	€/MW	[645-1725]
OPEX	%/CAPEX	2.5
Stack lifetime (replacement)	hours	[40000-60000]
Replacement cost	€/kW	[125-378]

Table 9: Overview of the economic parameters of the HTSE

3.2.3.3 Environmental parameters

Parameter name	Unit	Value
CO_2 content	g CO_2/kWh produced	N.C.
Grey CO_2 content	tons CO2/MW	310

Table 10: Overview of the environmental parameters of the HTSE

3.2.4 TES

Table 11, Table 12 and Table 13 give respectively the technical, economic and environmental parameters for the TES that could be considered in the case studies. The technology selected for the storage of thermal energy is a sensible heat storage system and employing thermal oil as a sensible medium. The values are based on PEPS5 study [35].

3.2.4.1 Technical parameters

Parameter name	Unit	Value [35]
Storage capacity	MWhth	[0.5-10]
Tank size	m^3	[10-3500]
Energy density	kWhth/m^3	[540-60]
Efficiency	%	[90-95]
Minimal SOC	%	0
Self discharge	%/day	[0.7-1.3]
Operating temperature	°C	[200-350]
Charge power	MWth	[1-30]

Table 11: Overview of the technical parameters of the TES

3.2.4.2 Economic parameters

Parameter name	Unit	Value [35]
Design lifetime	years	20

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Capacity factor	%	0.99
CAPEX	€/kWhth	[10-60]
CAPEX	€/kWth	[80-150]
OPEX	€/kWhth/year	0.69
OPEX	€/kWth/year	0.84
OPEX	%/CAPEX	1 & > 1
Replacement cost (oil cycle)	% of volume based on 100 cycles/year	[1-2]

Table 12: Overview of the economic parameters of the TES

3.2.4.3 Environmental parameters

Parameter name	Unit	Value [35]
CO_2 content	g CO_2/kWh produced	N.C.

Table 13: Overview of the enviromenal parameters of the TES

4 Conclusion

In conclusion, this report has provided a detailed description of the three case studies conducted in the context of Task 3.1 within the TANDEM project. These case studies focused on exploring the potential of NHES in three distinct European regions: Northern European, Southern European, and Central European.

The Northern European case study centers on the metropolitan area of Helsinki, Finland, with a specific focus on decarbonizing the district heating system. The study will examine two investment paths, namely the utilization of district heating heat pumps from low-quality heat sources and the implementation of HOB-SMR. These paths will be assessed for their effectiveness in achieving the ambitious carbon-neutral objectives of the region.

Moving to the Southern European case study, the investigation revolved around industrialized harbors, such as the port of Dunkirk in France and the port of Rotterdam in the Netherlands. These harbors are key players in decarbonization efforts and provided a suitable context to explore the integration of renewable energy sources, hydrogen production, and heat networks in an energy hub as part of NHES configurations.

The Central European case study focused on the Moravian-Silesian Region of the Czech Republic, a highly industrialized area with significant CO_2 production. The challenge here is to find viable alternatives to replace existing coal heat sources and reduce polluting emissions. The study will

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explore the possibilities of utilizing LW-SMR as potential replacements for the district heating networks of the region.

Throughout these case studies, the characteristics and potential of the PERSEE and Backbone tools played a central role. Although the tools have not been used yet in the TANDEM project, this report successfully presents the inputs and information that will be fed into these tools during Task 3.2. The techno-economic and environmental assessments to be conducted in Task 3.2 will further evaluate the feasibility and viability of implementing NHES in each region.

In summary, these case studies have shed light on the potential of Nuclear Hybrid Energy Systems in diverse European regions, paving the way for more detailed analyses in Task 3.2. By exploring the integration of nuclear power with renewables and other energy components, the TANDEM project takes a significant stride towards shaping cleaner, more resilient, and sustainable energy systems for the future.

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