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comprehensive analytical review(s) of WPs results and provide recommendations relative to technical, economic and societal issues

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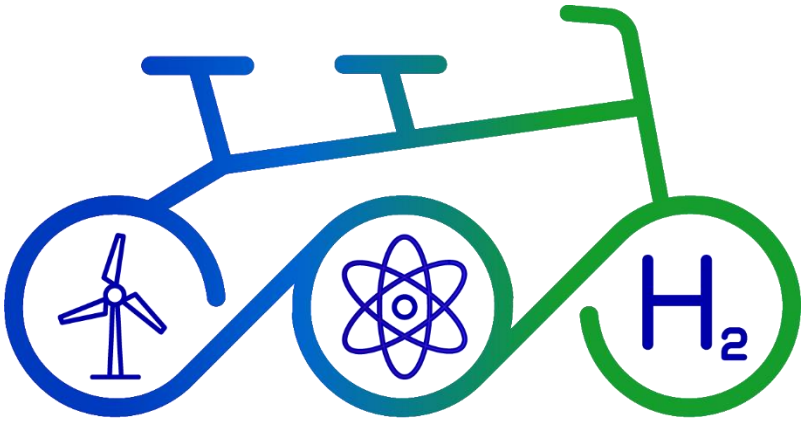

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D5.2 – Synthesis report of project results and technical recommendations

WP5 - Task 5.1

August 27, 2025 [M36]

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Abbreviations and Acronyms

Acronym	Description
AI	Artificial Intelligence
AMR	Advanced Modular Reactor
CCGT	Combined Cycle Gas Turbine
CCUS	Carbon Capture Use and Storage
E&T	Education & Training
EU	European Union
FMI	Functional Mock-up Interface
FMU	Functional Mock-up Unit
GIF	Generation IV International Forum
GIF	Generation IV International Forum
HES	Hybrid Energy System
HLO	High-Level Objective
HTSE	High Temperature Steam Electrolyzer
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
IRR	Internal Rate of Return
IT	Information Technology
IUG	Industrial User Group

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KPI	Key Performance Indicator
LCOE	Levelized Cost of Electricity
LCOH	Levelized Cost of Heat
$LCOH_2$	Levelized Cost of Hydrogen
LW-SMR	Light Water Small Modular Reactor
MILP	Mixed Integer Linear Programming
NC2I	Nuclear Cogeneration Industrial Initiative
NGO	Non-Govermental Organisation
NPHyCo	Nuclear Powered Hydrogen Cogeneration
NPV	Net Present Value
PID	Proportional-Integral-Derivative (controllers)
PIRT	Phenomena Identification and Ranking Table
SAC	Scientific Advisory Committee
SMGR	Steam Methane Gas Reforming
SMR	Small Modular Reactor
SNETP	Sustainable Nuclear Energy Technology Platform
TSO	Technical Safety Organisation
VHTR - HP - PMB	Very High Temperature Reactor - Hydrogen Production – Project Management Board
WP	Work Package

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Executive Summary

A comprehensive analytical review of the results obtained by the TANDEM Euratom project between September 2022 and August 2025 is conducted in this document. It enables to provide recommendations on technical, economic, societal and education & training challenges related to the integration of Small Modular Reactor into Hybrid Energy Systems. The project focuses on light-water technologies for a near-term deployment. However, when the results are technology-neutral, they are extended to Advanced Modular Reactors of Generation IV.

Keywords

TANDEM, SMR, Hybrid Energy System, synthesis, result review, recommendations

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1 Introduction

The TANDEM project (Small Modular ReacTor for a European sAfe aNd Decarbonised Energy Mix)[1] is a Horizon-Europe project funded under the Euratom research and training program – work program 2021-2022. The overall ambition of the project is to *promote multi-purpose Small Modular Reactors (SMRs) integrated into hybrid energy systems as reliable, resilient, and affordable clean energy options in Europe*. The project focuses primarily on light water SMR technologies for a near-term deployment in Europe by 2035, but also aims to support the deployment of Advanced Modular Reactors of Generation IV by 2050 when technology-neutral outcomes are identified.

The intrinsic key feature of the TANDEM project is the development of an integrated vision of the low-carbon energy mix on a local/regional scale (an urban area or an industrial zone). Indeed, the project considers nuclear energy as an electricity and heat source to supply industrial processes and district heating – as in other Euratom projects working on nuclear co-/poly-generation – but also studies coupling (also referred to as "hybridization") with renewables and energy carrier storage systems. The project addresses the technical feasibility (safety, operability and flexibility of the energy supply) and economic viability of such hybrid energy systems, as well as citizen engagement and E&T needs to prepare the workforce required for the development and deployment of SMRs integrated into Hybrid Energy Systems (HES). TANDEM provides methodologies and tools for the assessment of HES and has implemented them on demonstrative study cases of energy systems to be decarbonized.

In parallel, TANDEM has built an open and long-term community that will ensure expertise in the field of nuclear HES and support the wide acceptance of multipurpose SMRs and AMRs. This European community has forged close links with other international communities and industrial stakeholders, to develop new collaborations and foster exchanges in the field of nuclear cogeneration, non-electric applications of nuclear energy and nuclear HES. The discussions between TANDEM and these international communities clearly underline that nuclear cogeneration and its integration into hybrid energy systems is a matter of utmost importance.

The breakdown of the project's work packages is shown in Figure 1. The project has set up two external groups, a Scientific Advisory Committee (SAC) and an Industrial User Group (IUG), and regularly interacts with them.

[1] https://tandemproject.eu/

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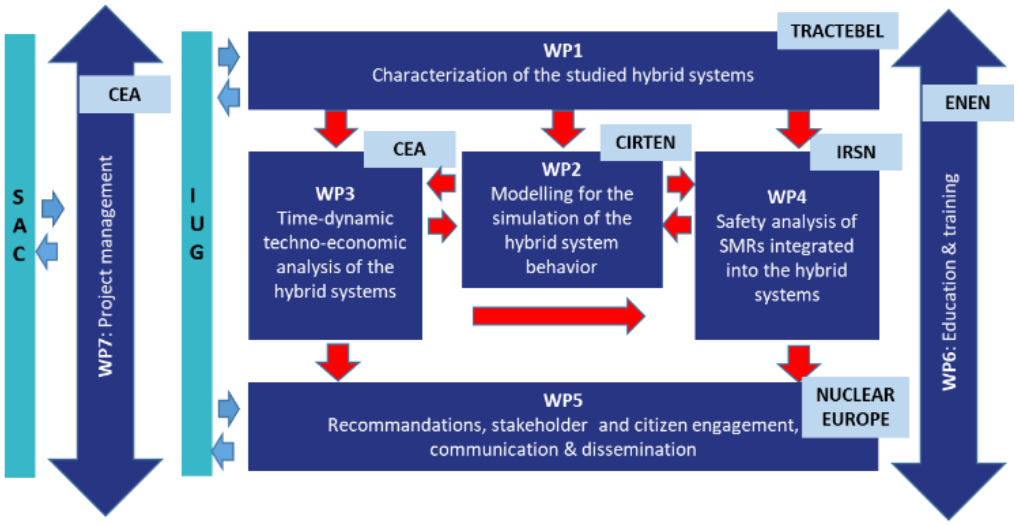

Figure 1: Work package breakdown in TANDEM.

In this report, the following sections summarize the main outcomes of the project for each project work package (WP) and provide recommendations related to technical, economic and societal issues, as well as E&T gaps, to facilitate the development and deployment of SMRs into HES.

2 WP1: characterization of the studied HES

2.1 Synthesis of the results

The main European energy policy guidelines supporting energy decarbonization, as well as the reduction of the European dependency on Russian fossil fuels after the Russian-Ukrainian conflict, rely on the European Green Deal, the Fit for 55 package, the REPowerEU plan and the Net Zero Industry Act. The potential of low-carbon energy market in EU is huge, as shown by Engie-Tractebel (TANDEM D1.1, 2022) and the European pre-partnership (SMR pre-Partnership, 2023), prefiguring the set-up of the European Industrial Alliance on SMRs. In this context, all the available low carbon-energy sources and carriers have to be implemented to achieve the energy transition.

The energy transition strategy relies heavily on substantial electrification of many sectors, replacing fossil fuels, supported by the accelerated deployment of renewable electricity generation capacity. Nuclear and renewable energies are considered as the backbone of a carbon-free European power system. However, decarbonizing only the electricity sector is not enough, representing only about one-third of the way to net-zero emissions (IEA, 2021);

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achieving net-zero emissions will require a radical transformation in the supply, conversion, and usage of energy.

The analysis of the EU low-carbon energy needs has led the TANDEM project to consider the following energy priorities: the decarbonization of low temperature heat for district heating in urban areas and the energy decarbonization for industrial zones, such as port areas, involving many energy flows (electricity, heat, hydrogen, hydrocarbons) and the supply of commodities, such as fresh water.

SMR and AMR technologies have the potential to strongly contribute to the energy decarbonization for both electric and non-electric applications. The TANDEM project focuses on the study of the integraton of SMRs into hybrid energy systems, including other energy sources, heat network and energy conversion systems, as well as energy storage systems, at a local scale. Considering that the SMR deployment may start in 2030's in EU, the TANDEM project has defined three energy scenarios for the purpose of its studies:

- A business-as-usual energy scenario in 2035: only fossil fuel plants and renewables are considered as energy sources in the hybrid energy systems,
- The start of the deployment of SMRs in 2035: fossil fuel plants are progressively replaced by SMRs. The energy sources in hybrid energy sources are composed of a mix of fossil fuel plants, SMRs and renewables,
- The achievement of the carbon-neutrality in 2050: most of fossil fuel plants are replaced by low-carbon energy sources, in particular SMRs, in the hybrid energy systems.

The state-of-the art of the development of the different technologies implementable as main HES components has been reported in (TANDEM D1.2, 2023); it stresses the main technology features, in particular their maturity level and their ability to deal with flexibility of the energy supply. This analysis has been used to choose the technologies to be incorporated in the TANDEM HES.

The Key Performance Indicators (KPI) relevant to characterize HES have been defined (TANDEM D1.3, 2023):

- For technical performance: sizing of the HES components, share of each technology in the load demands or productions (electricity, heat, H2), electricy/ heat cogeneration rate of SMRs,
- For economical viability: Net Present Value (NPV), the Levelized Cost Of Electricity (LCOE), Heat (LCOH) and Hydrogen ($LCOH_2$). Other indicators such as the Payback Period and the Internal Rate of Return (IRR) can be also considered;

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- For environmental preservation: direct and grey CO_2 emissions.

At the end, two generic HES, consistent with the the priorities of energy decarbonisation sectors and the technology choices made in TANDEM, have been configured (TANDEM D1.4, 2023): the first one is dedicated to the supply of district heating network and power grid in an urban area, and the second one is an energy hub, supplying different energy carriers and commodities in a port zone.

2.2 Recommendations

Recommendation n°1: The Balance Of Plant (BOP) – characterizing the coupling between SMRs and non-electric applications (district heat, hydrogen production, etc) requiring heat extraction from the nuclear power plant – has been designed on the basis of TANDEM partners' background, without specific optimization study in the project activities. For future projects and initiatives, it is recommended to carry out studies on the nuclear heat/electricity conversion system to optimise the BOP according to the processes implemented in the non-electric applications. Innovative conversion energy cycles for AMRs could also be investigated (beyond the Rankine cycle implemented in LW-SMRs).

Recommendation n°2: In the TANDEM project, the reference heat extration rate is 10% in the SMR secondary circuit; for specific impact studies, an extraction rate of 20% has been considered. Further studies should be carried out to determine accurately the limit of the nuclear heat extraction rate under off-design conditions, achivable without major modifications of the nuclear plant operating in heat/electricity cogeneration mode.

Recommendation n°3: The value chain of the hydrogen production (as well as the value chain of any product of the industrial applications) and potential costs due to hydrogen transportation have not been considered in the project to limit the study complexity. The value chain and additional costs should be taken into account in further studies.

3 WP2: modelling for the simulation of the HES behavior

3.1 Synthesis of the results

In the framework of the TANDEM project, a set of modelling tools has been developed with the purpose of increasing the knowledge about the dynamic behaviour and safety of hybrid energy systems. Three main results have been produced during the project. The first one is the development of an Open-Source, Modelica-based "TANDEM" model library aimed at simulating the behavior of power plants, systems and components, including SMRs. This library enables the analysis, comparison, and optimization of hybrid energy systems from a technical perspective,

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with particular focus on their performance under operational transients. The second achievement is the development of two hybrid system simulators for the district heating and energy hub cases to be employed in the techno-economics tools and safety analysis. The third result is the development of the coupling between safety codes (CATHARE3 and ATHLET) and Modelica BoP models to perform the safety analysis considering the integration of SMRs into hybrid energy system.The Modelica language was selected for this application because of its suitability to model complex engineering systems such as HES (Elmqvist et al., 1998). It is an object-oriented and equation-based modelling language, which enables the development of models that can be easily reused for a wide range of applications. This latter feature is particularly important in the framework of the TANDEM project since the independently developed models are intended to be coupled into a wide range of HES architectures. The Modelica language is non-proprietary; it can be implemented both in open-source and commercial simulation environments, such as OpenModelica and Dymola, respectively. The library is based on the version Modelica 4.0.0.

The TANDEM library have been built on well-established Modelica libraries and has not been developed entirely from scratch:

- ThermoPower (Casella & Leva, 2006) and ThermoSysPro (El Hefni & Bouskela, 2019),
- HTSE[2],
- Buildings (Wetter et al, 2014),
- WindPowerPlants (Eberhart et al, 2015).

The TANDEM library is a collection of models representing different components that can be integrated into a hybrid energy system. The first version of the library includes the following components:

- SMR: a) Nuclear Steam Supply System; b) Balance of Plant and Power Conversion System,
- Combined Cycle Gas Turbine (simplified),
- Heat pump (simplified),
- Electrical Grid,
- District Heating Network,
- Storage : a) Thermal; b) Electrical (simplified),
- Desalination (simplified),
- H_2 production: a) Low temperature electrolizer (simplified); b) High temperature steam

[2] https://github.com/CEA-Liten/HTSE

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electrolyzer.

The components labelled as “simplified” above are modelled as black boxes, providing the amount of produced energy with a certain power flow in input, for example. This choice is motivated by the nature of these components and their connection to the HES, which is mainly of a purely electrical nature.The other models in the library are physics-based and take into account heat transport phenomena, with connections to the HES that are both thermal and electrical in nature. The TANDEM library has been made publicly available in a git repository (https://gitlab.pam-retd.fr/tandem/tandem/) under the 3-clause BSD-license slightly modified. The documentation containing the Modelica model description (TANDEM/D2.3, 2024) has also been released by the project and it is also present in the library itself. A request has been submitted to the IAEA to include the TANDEM library in the ONCORE[3] initiative.

Based on this library, simulators of the two hybrid energy systems configured in TANDEM/WP1 have been developed by coupling different Modelica models of components to simulate the dynamic physical behaviour of the systems. The simulators have been included in the library itself for the v1.1 release. Illustrations of the HES performance studies in dynamics, in particular for the assessment of the system flexibility, have been provided in (TANDEM/D2.5, 2024).

In parallel, a modelling of the SMR use-case implemented in TANDEM has been developed with two reference safety codes, ATHLET (TANDEM/D2.7, 2024) and CATHARE3 (TANDEM/D2.6, 2024). The SMR use-case relies on the E-SMR academic concept, developed by the ELSMOR[4] project: the data has been open in a repository (https://etsin.fairdata.fi/dataset/00b62da2-7b96-4e70-82ef-1e8afaa0ecb1). It is a 540 MWth reactor with an integrated design. All the components of the primary circuit are modelled as 0-D or 1-D elements, as typically assumed in the nodalization of Nuclear Power Plants with such system thermal-hydraulics codes. Eight compact plate-type once-through steam generators are in the reactor pressure vessel. Six are dedicated to normal operation and two for accident conditions. They are modelled as 1-D elements coupled to the primary circuit by means of heat walls, representing the steam generator plates. Boundary conditions are provided at the steam generator inlet and outlets to impose the feedwater mass flow rate and enthalpy, and the downstream pressure, respectively. These boundary conditions are key elements to set up a coupling between the safety code models of the secondary circuit and the Modelica model of the balance of plant. This coupling between CATHARE3 and ATHLET with some components of the TANDEM Modelica-based library has been set up in the project in order to assess safety aspects arising from the hybridization of

[3] Open-source Nuclear Codes for Reactor Analysis: https://www.iaea.org/topics/nuclear-power-reactors/open-source-nuclear-code-for-reactor-analysis-oncore
[4] https://www.elsmor.eu/

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SMRs. This coupling has been achieved thanks to the Functional Mock-up Interface (FMI) standard. The standard allows encapsulating a Modelica model into a Functional Mock-up Unit (FMU) that can be easily exchanged across different simulation environments by means of predefined input and output variables

3.2 Recommendations

Recommendation n°1: In the first version of the TANDEM library, the development efforts have been put on the numerical models of some key components. Other models rely on a very simplified approach, and the models of some components even do not exist. In the future, the libray could go on evolving by:

- Improving the modelling of some components,
- Providing models for new HES components (such as the methanation plants),
- Providing models for alternative technologies (such as AMRs of Generation IV, other technologies not considered at this stage for hydrogen production and desalination).

Recommendation n°2: the HES performance studies have been provided in the project as illustrations of the tools capabilities; it could be important to extend these studies in future projects and initiatives. Besides, simulators could also be used in order to define transients of interest for safety, resulting from the SMR hybridization.

Recommendation n°3: It has been checked in the project that the HES component models developed for the TANDEM library provided realistic physical behavior. It would be necessary to implement now a rigorous Verification&Validation (V&V) process on the library to ensure the predicitivity of the separate component models collected in the TANDEM library and the simulators built with the coupling of the library models. It could also involve benchmarking activities against other international tools with similar modelling capabilities.

Recommendation n°4: the coupling implemented between the safety codes (ATHLET and CATHARE3) with Modelica models showed some convergence instability. Some improvements in the coupling strategy should be envisaged.

Recommendation n°5: Although the TANDEM library is developed in the Modelica language, careful consideration is necessary to ensure its compatibility with OpenModelica. While both Dymola and OpenModelica implement the Modelica standard, their practical behavior can differ significantly, particularly in terms of performance. These differences are especially relevant when solving complex problems, as it is the case with the HES simulator, and in the ability to compile FMU models. To achieve full compatibility, it is advisable to engage with the Open Source Modelica Consortium (OSMC) to help prioritize efforts aimed at enhancing OpenModelica's

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capabilities in handling complex systems, improving symbolic manipulation, and developing more efficient solvers. Initial discussions have already taken place with the Director of the Open Source Modelica Consortium in this regard. In parallel, further development could focus on a systematic testing effort of the TANDEM library within the OpenModelica environment.

4 WP3: time-dynamic techno-economic analysis of the HES

4.1 Synthesis of the results

Three study cases were derived from the two hybrid energy systems configured in WP1, as demonstrative practical cases to carry out studies on techno-economics and environmental impact (TANDEM/D3.1, 2023). They have been defined in the light of a specific regional context, depending on local resources, geography, industry, energy markets and policy, to perform a relevant sizing and assessment. Two study cases associated with the hybrid energy system configuration dedicated to district heating and electricity supply have been characterized in TANDEM: the Northern European case and the Central European case. The Northern European case concerns a district heating system in the metropolitan area of Helsinki (Finland), which includes the large cities of Espoo and Vantaa.

The aim of the Central European case study is to propose i) possible ways to replace a part of coal heat sources by low-emission energy sources, and ii) the assessment of a potential of hydrogen production for industrial application – establishment of a "Hydrogen valley" on a selected model case in the Moravian-Silesian region in Czech Republic. This region is highly industrialized with high CO_2 emission.
The study case for the energy hub configuration is inspired from a harbour-like infrastructure in France. In Europe, there are several examples of industrialized harbours (Rotterdam, Dunkirk, Fos-sur-Mer, etc), responsible for a high rate of CO_2 emissions and involved now in a process of decarbonization. Due to the difficulties of accessing detailed energy flow characteristics across many industrial plants in ports, it was decided to arbitrarily set an initial architecture to produce constant loads of hydrogen and electricity for the definition of the case study.

The benefit of integrating SMR in these three study cases has been analysed, starting from the current initial architecture of the study cases with fossil fuel plants and renewables (the "business-as-usual" energy scenario), and replacing progressively fossil fuel plants by low-carbon energy sources, SMRs and renewables, so as to decarbonize the system. The Backbone and PERSEE tools, respectively developed by VTT and CEA, have been implemented to analyse the three study cases (TANDEM/D3.2, 2024). They rely on an optimization process based on the optimization of an objective function (based on the costs), taking into account environmental

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constraints, to assess an optimal sizing of hybrid energy system components. Optimizations are based on calculations carried out over one year with a time step of 1h. Most of the techno-economic and environmental data used in the optimizations come from open literature (peer-reviewed papers, OECD/NEA and IAEA documents, etc.). The time series data are based on year 2019. Data for CAPital EXpenditures (CAPEX) and variable costs in the study correspond to a forecast in 2035. The time series data are based on year 2019. All the costs are expressed in $€_{2023}$.

The Northern European case was studied from the perspective of a district heating operator, investigating decarbonization in the Helsinki Metropolitan area; as a strong assumption, the study case does not take into account the services rendered to the electricity grid by SMRs or their remuneration. From the viewpoint of a district heating operator whose priority is to produce heat as a baseline, small heat only units like LDR-50 (J. Leppanen, et al., 2021) – a heat only boiler SMR producing 50 MW_{th} – allow the operator to find profitability in the context of the Helsinki area. It is supported by a high summer-to-winter variability of the heat demand in Finland and a seasonal variation of electricity prices in the Finnish market area.

For the Central European case study, the calculations have shown the potentiality to decarbonize the production of district heating, electricity and hydrogen with the use of SMRs, Low Temperature Electrolysers for hydrogen production and renewable energies (solar and wind). For the decarbonisation scenarios, the LCOE value is about 77€/MWh_e and the $LCOH_2$ is 5.4 €/kg H_2. Besides, the LCOH is about 19 €/MWh_{th}, taking into account the assumptions associated with the study. Whereas in the scenarios using fossil fuel plants, the hydrogen produced emits at least 8 times more CO_2 than the EU Taxonomy threshold, in the decarbonisation scenarios using SMRs, the required threshold for sustainable hydrogen is reached with a large margin. Demonstrative results of the Central Europe case study could be easily valorised for decarbonizing other similar territories, such as Silesian Voivodeship in Poland or Žilina self-governing region in the Slovak Republic.

For the Southern European case, the study identified a configuration with a decarbonization rate of around 80% compared to the “business-as-usual” reference scenario - which includes a Combined Cycle Gas Turbine (CCGT) and a Steam Methane Gas Reformer (SMGR) - for an extra cost of 26.1 €/MWh_e and 2.2 €/kg H_2. This configuration contains E-SMRs, High Temperature Steam Electrolysers (HTSE) and a hydrogen storage, and produce electricity, heat and low-carbon hydrogen. Furthermore, the flexibility offered by the E-SMR can be exploited to either reduce the total costs and/or the carbon emissions. A greenhouse gas cost of 100 €/ton CO_2 eq would cancel the extra cost on the LCOE whereas a greenhouse gas cost of 172 €/ton CO_2 eq would lead to the same total costs between the reference and the first configuration with E-SMRs and HTSE, thus to very similar LCOE, LCOH, $LCOH_2$. This order of magnitude for the cost of CO_2 can be considered plausible since it reached more than 100 €/ton CO_2 in February 2023.

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The analysis of these three study cases shows that SMRs can be a relevant option to decarbonize HES. Furthermore, it is important to be aware that the results obtained for the three study cases deeply rely on the assumptions taken into account and are likely to be affected by the uncertainties associated with the optimization input parameters.

To complement the studies, sensitivity analyses of the optimization results to the assumptions and uncertainties- related to economical and technological parameters – have been carried out for the Northern European case and the Southern European case. Both study cases highlight the importance of the uncertainties on economical parameters: investments, investment costs in the energy system, prices and the year of the time series chosen for the studies, can have a significant impact on the optimization results and the final techno-economics evaluation.

The Southern European case has also been the subject of additional studies on the benefit to implement complementary systems of decarbonization, such as a Carbon Capture Use and Storage (CCUS). Equipping the CCGT and the SMGR with CCUS components results in decreasing CO_2 emissions at low extra cost; however, the main disadvantage is the high carbon storage capacity required (the order of magnitude is a dozen ktons of CO_2 to be stored over the 20-year life of the project).

The physical coupling between HES components, which can exchange multiple energy carriers, results in complex interconnection and potential non-linear dynamic effects that cannot be adequately captured by MILP-based optimisation tools. Additional studies involving couplings between the techno-economics tools (Backbone and PERSEE) and the Modelica simulators have been carried out to analyse the impact of HES modelling on techno-economics optimizations over short time scales (typically one day duration, taking into account 15min time steps). The goal is to check the feasibility and accuracy of the results obtained in the MILP techno-economic and environmental studies using refined models.

Two coupling strategies have been investigated: weak and strong coupling. In the former, the optimisation model parameters are updated in an iterative process to be consistent with the operational conditions observed in the dynamic simulator. In addition, the viability of a given optimal dispatch strategy is verified a posteriori by testing the optimised setpoints with the dynamic simulator. Conversely, the strong coupling approach allows system dynamics to be better taken into account in the optimization, with the states of the optimization models being iteratively updated according to feedback from the dynamic simulator; this can have significant impact on the techno-economic and environmental results. The reader can find further details in (TANDEM/D3.4, 2025).

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4.2 Recommendations

Recommendation n°1: These studies demonstrate that the SMRs integration into HES to produce heat, electricity and hydrogen could be economically viable. Now it is required to accelerate the studies of nuclear HES to turn the integration of SMRs in HES into reality. New projects and initiatives at the European level are to be launched to carry on the developments and studies intiated by the TANDEM project on nuclear cogeneration and the integration of SMRs into HES. It concerns different topics: techno-economics, but also safety, technical performances and citizen engagement.

Recommendation n°2: TANDEM has explored demonstrative study cases. In future projects and other initiatives, it will be required to demonstrate on a more complex real European *industrial* case that a safe and cost-effective implementation of SMRs and AMRs integrated in a HES is a realistic and smart low-carbon energy solution. To this end, it will be necessary to share data with industrial partners in order to specify the industrial study case to be decarbonized, including the production of heat, electricity, fresh water and hydrogen.

Recommendation n°3: The TANDEM studies show that the assessment of economical Key Performance Indicators (KPIs) for HES integrating SMRs can be strongly impacted by the assumptions and uncertainties associated with economical and technological input parameters. It is mandatory to keep aware of this, and therefore to perform impact studies and assess the uncertainties affected the KPIs in optimization studies. Robust optimization under uncertainties should also be developed.

Recommendation n°4: To give greater credibility to the optimization results, the predictivity of the tools should be assessed by defining numerical benchmarks and carrying out cross-comparisons of results.

Recommendation n°5: The techno-economics studies focus on the integration of light-water SMRs for a short-term deployment. Further studies should also investigate the integration of AMRs, for a longer-term deployment; indeed, AMRs economical characteristics can be significantly different from light-water SMRs.

Recommendation n°6: . The KPIs studied in WP3 mainly focus on economical indicators (total cost, NPV, IRR, Levelized Cost). Further studies should promote the use of other non-economical indicators such as CO_2 intensity, reliability and resilience of energy systems, security of the energy supply, safety related indicators, etc.

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Recommendation n°7: A realistic comparison of KPIs associated with energy produced from carbon-based and clean energy systems cannot be established without the implementation of CO_2 taxes.

Recommendation n°8: The results performed in TANDEM highlight the necessity for tighter integration between the techno-economic optimization tool and the dynamic model when dealing with components whose dynamics significantly influence system operation. Physical effects such as thermal inertia, fluid travel time between the Balance of Plant and heat application may introduce pronounced non-linearities. Future modeling developments should focus, on one hand, on optimizing the coupling between the optimization tools and the Modelica-based dynamic simulators, both in terms of computational efficiency—for example, through the use of surrogate or reduced-order models—and in terms of incorporating advanced features. These features include the influence of operator decisions (e.g., by integrating control strategies, maintenance scheduling, and fuel optimization logics) as well as improving the treatment of predictive horizons (e.g., through dynamic adjustment of the MILP models during the optimization process).

Recommendation n°9: The studies perfomed in TANDEM did not focus on the electrical grid equilibrium: the services rendered by the SMR to the national electricity grid was not considered (Northern European Case) and the SMRs was operated at constant full power with the grid equilibrium guaranteed by assumption either by the CCGT or the national grid (Sourthern European Case). Flexibility solutions (thermal energy storage, batteries, SMR load following) should be considered in future studies to have more realistic conditions and evaluate the value added by such solutions.

5 WP4: safety analysis of SMRs integrated into the HES

5.1 Synthesis of the results

The use of nuclear power plants for cogeneration has been effective for many years in several countries, mainly for desalination and district heating applications, in addition to the supply of electricity. These configurations have often been seen as the juxtaposition of two industrial processes with a customer-supplier relationship and a small number of interfaces. The risks associated with one process are often envisaged independently from the other process, considering the other process as a potential external hazard.

Considerable work has been made in the frame of the European Nuclear Cogeneration Industrial Initiative (NC2I), as a pillar of the Sustainable Nuclear Energy Technology Platform (SNETP), for

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(very) high temperature reactors ((V)HTR); the related Euratom projects (EUROPAIRS, NC2I-R and GEMINI+) provided useful general safety considerations for nuclear co-/poly-generation (TANDEM/D4.1, 2023).

When SMRs are integrated into a hybrid energy system, the interfaces between the nuclear reactor and non nuclear components of the hybrid energy system are multiple and more dynamic (than in the case of the juxtaposition of two industrial processes), which requires the development of additional specific guidelines (TANDEM/D4.2, 2023). In addition to the safety approach implemented to take into account the specific features of SMRs in conventional use and specific external hazards due to the proximity (/possible co-location) of the various system components, the fundamental principles of safety remain the basis for investigating the possible disturbances that will be caused by the integration of SMRs into a hybrid energy system and then lead to consider "hybridization transients". Assessing the safety of a SMR integrated in a hybrid energy system requires a comprehensive methodology that considers various aspects of nuclear safety. The proposed methodology to assess the safety of such a system is based on the IAEA guide SSG2- rev 1 and can be split into several phases:

(a) Detail precisely the design and operational characteristics of the SMR and the full energy system.

(b) Perform two separate safety analyses, one for the nuclear power plant and one for the industrial plant or the electrical grid by considering each installation as potential source of external hazards on the other; and then for the full hybrid energy system in interaction with the nuclear island, with the SMR operating in cogeneration mode.

(c) Identify sources of risk and sensitive system components.

(d) Identify operational conditions which could be affected by the coupling between the SMR and the rest of the energy system, with potentially the definition of new transients.

(e) Perform safety studies taking into account c) and d).

There is no specificity of SMRs with respect to large nuclear power plants in terms of safety definition and classification. Considering the latest WENRA RHWG document (WENRA RHWG, 2021) dealing with the specificity of SMRs, there are still the three main categories, namely normal operation (DBC-1), control of abnormal operation and failure (DBC-2), control of accident and prevention of escalation to severe accidents (DBC 3/4, Design Extension Conditions called DEC).
The last category (DEC) is not considered here, considering that specific studies are already carried for the nuclear plant itself, and should cover the hybridization configurations.

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The extension of the deterministic safety analysis therefore consists in identifying the event initiators specific to the hybridization combining the SMR reactor and its balance of plant. Several transients, related to Design Basis Conditions (DBC) from 1 to 3, have been identified as relevant for analyzing the impact of hybridization on nuclear reactor behaviour:

- A sudden increase of decrease of the heat demand by the end-users,
- A sudden rejection of the electricity demand,
- A loss of the external electrical load leading to a long term loss of offsite power.

To carry out the transient analysis, the modelling of the Nuclear Steam Supply System (NSSS) developed with the CATHARE3 and ATHLET in TANDEM/WP2 has been coupled to a Modelica-based dynamic modelling of the BOP taken from the TANDEM library. The BOP includes a cogeneration line to supply heat to produce electricity and to supply heat to downstream applications

A Python supervisor script is used to implement the coupling between the NSSS, the BOP and a set of Proportional-Integral-Derivative (PID) controllers simulating the action of the automatic control systems on the power plant. All the PID controllers have been implemented in the Python language. The algorithm is explicit, corresponding to one-way coupling for each time step.

The detailed analysis of the hybridization transients, directly linked to a variation of the electricity or heat loads, simulated with the CATHARE3-based and ATHLET-based coupling are available in (TANDEM/D4.3, 2025) and (TANDEM/D4.4, 2025). From these analyses, it is concluded that cogeneration is not expected to adversely affect the severity of the DBC-1 to 3 transients simulated in the framework of the TANDEM project; however, it may play a role in their prevention.

Indeed, cogeneration can reduce the risk of failing a load rejection procedure leading to house load operation. Such a failure may lead to a loss of offsite power scenario, which is a design basis transient that can also evolve into a DBC-3 transients if it lasts for several hours; the actual impact of cogeneration in preventing the loss of offsite power depends on the initiating event that causes the load rejection.

5.2 Recommendations

Recommendation n°1: The deterministic safety analysis of SMR hybridization carried out in TANDEM points out that there does not seem to have major safety challenge to overcome for nuclear HES safety. A best estimate approach for transient simulation has been adopted in order to study the impact of hybrizidation. Studies show that hybridization is not detrimental to nuclear safety, and can even have beneficial effects.

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However, additional work on safety should be carried out on the elaboration of generic Phenomena Identification and Ranking Tables (PIRTs) for the safety impact analysis of the coupling between nuclear and a large panel of industrial technologies (SMRs/AMRs with hydrogen production plants, refineries, district heating networks, desalination plants, etc). Using PIRTs, it will be possible to draw conclusions on safety transient frequencies.

Recommendation n°2: Complementary deterministic studies of safety transients (e.g. to show the impact of the coupling between a SMR and a thermal energy storage system) could be conducted in future projects and initiatives.

Recommendation n°3: Even if no design study has been carried out for the BOP, it is important to stress that an intermediate heat exchanger should be implemented in the BOP between the extraction line of heat from the secondary circuit and the circuit of industrial non-nuclear applications (e.g. HTSE) to avoid the contamination of industrial processes by radioactivitive isotopes.

Recommendation n°4: Principles for establishing a common regulatory framework between nuclear safety regulators and industrial risk regulators do not exist today and need to be discussed and set up.

6 WP5: recommendations, stakeholder and citizen engagement, communication and dissemination

6.1 Synthesis of the results

Stakeholder and citizen engagement

An important aspect of the TANDEM project is timely and relevant outreach to stakeholders. That is why a Stakeholder Engagement Plan (TANDEM/D5.3, 2023) has been developed in the framework of the project. The goal of this plan is to map and identify the various stakeholders to whom this project could be of potential interest. Each stakeholder is then grouped according to his/her needs and messages of relevance for that particular stakeholder are identified.

Four citizen events supported by the TANDEM project (TANDEM/D5.8, 2025) were organized between 2024 and 2025 in collaboration with context-specific organizations. The first workshop was co-organized in Finland by VTT, the city of Kuopio and Kuopion Energia. SMRs are being considered as a future option for district heating in Kuopio which located in the Finnish Lakeland and is the regional capital of North Savo with a population of approximately 126,000 residents.

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Kuopion Energia is a local energy company committed to developing cleaner energy production and ensuring reliable electricity and district heating services for the residents of Kuopio. Thus the organization of a citizen event in this framework for residents of Kuopio seemed to be very meaningful. Most of the ~70 participants were middle-aged and men. Although the majority of respondents had a positive attitude towards the introduction of SMRs, the attitudes towards SMRs were strongly influenced by gender: women were more opposed than men to the use of SMRs. Gender could be a statistically highly significant explanatory factor and the strongest indicator behind SMR safety. The second workshop was co-organized in Finland by VTT and women's associations, i.e. the National Council of Women of Finland and Women in Nuclear Finland. Following the first workshop, the workshop objectives were to gain a better understanding of women's specific needs and concerns, to provide fact-based information on the use of nuclear power and its boundary conditions, and to promote joint learning through open and polyphonic discussion, especially focused on SMRs. The event brought together around 30 female participants.

The third workshop was organized in the Czech Republic, as an open workshop ”SMR – future energy sources˝ within the Nuclear Days 2024 event[5]. The University of West Bohemia in Plzeň, supported by the Czech Ministry of Industry and Trade, the Plzeň region, utilities, the power industry, and UJV Řež, organized a fully open event/workshop for citizens on the deployment of SMRs in the Czech Republic. The event brought together around 70 participants of various ages and genders including seniors (Association of Nuclear Veterans[6]) as a specific part of public in the Czech Republic.

The last workshop was organized in Belgium by nucleareurope. The workshop aimed to facilitate peer-to-peer learning and the exchange of best practices among participants regarding stakeholder engagement strategies. It identified key challenges and opportunities for effective stakeholder engagement within the context of nuclear research and SMRs. Additionally, the workshop aimed to develop actionable policy recommendations to enhance stakeholder engagement processes. The event brought together 27 participants from various sectors and countries in Europe and beyond. The analysis of the workshop process and results has enabled to provide practical insights and findings to industry and public organizations.

TANDEM Industrial User Group

The project has set up an Industrial User Group (IUG) to engage in a constructive dialogue about:

- The technological feasibility of the hybrid systems incorporating SMRs,

[5] https://www.jadernedny.cz/en
[6] Nuclear Veterans

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- The different energy markets and their particularities,
- Regulatory, societal and economic issues related to implementation of such systems.

The TANDEM IUG is composed of 14 members: Vattenfall (Sweden), NUWARD™ (France), GENVIA (France), COGEN Europe (Europe), Euromines (Europe), Eurometaux (Europe), IFIEC (Europe), Febeliec (Belgium), INERIS (France), Enel (Italy), Edison (Italy), Optit (Italy), KGHM (Poland) and EPRI (USA).

Three dedicated meetings with the IUG members were organized:

- on March 29, 2023,

- on April 5, 2024,

- on January 29, 2025.

Besides, the IUG members were systematically invited to attend the annual meetings of project review and the events organized by the project (webinars, E&T workshops, TANDEM final conference, etc).

The IUG showed to be a good communication forum between the project and the representatives of key industry sector for the potential deployment of SMRs technologies. (TANDEM/D5.5, 2025) compiles the synthesis of the interactions between the IUG and the TANDEM project during these meetings.

Dissemination & Communication

The results produced by the project require consideration for their suitability and usability by various stakeholder groups. Hence, tailored messages have been prepared for different stakeholder groups. This report presents a comprehensive analytical review of WPs results and provides recommendations on technical, economic, societal and training issues. In addition, policy briefs (TANDEM/D5.2, 2025) have also been prepared and delivered to support the development of nuclear hybrid energy systems. They deal with different aspects: finance & economics, stakeholder engagement & public acceptance, regulatory framework and skills The target audience is policy makers at all levels (EU, national, regional and local).

A final conference was organized in Brussels on July 2. It was an open international workshop designed to share the main outomes of TANDEM and to engage a constructive dialogue with EU & national policy makers, nuclear regulatory community, sectorial associations on energy, energy intensive-industry stakeholders, R&D communities and NGOs.

TANDEM developed different channels to communicate through :

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- the social media LinkedIn: https://www.linkedin.com/company/tandem-project-eu/
- the TANDEM website: https://tandemproject.eu/
- international well-known conferences and peer-reviewed journals
- events organized by TANDEM and other Euratom projects which TANDEM collaborates with.

All the technical deliverables published by the TANDEM projects are public and are on the TANDEM website. The project prepared 7 papers for conferences and published 3 papers in peer-reviewed journals (+2 under review) over the three years of the project. The list of the papers is given in Appendix A.

The TANDEM consortium has forged close links with other international communities. The TANDEM project has given presentations during numerous cross-cutting events, such as:

- A joint workshop with the ELSMOR Euratom project (organization at the latter's initiative) in Brussels, in December 2022
- A consortium meeting of the GEMINI 4.0 Euratom project– online, in November 2023
- The ENLIT Europe 2023 conference in Paris (EU Projects Zone)
- A joint meeting GIF/NEANH Task Force – GIF/VHTR HP PMB – IEA-H2 TCP/Task 44 – IAEA – OECD/NEA, hosted by the Idaho National Laboratory, in Idaho Falls, USA, in January 2024
- The SNEPT forum in May 2023 and April 2024
- A meeting of Working Group on Hydrogen Value Chains (H2-VAL) at OECD/NEA – online, June 2024
- A Technical Meeting on Recent Developments in Cogeneration Processes in Member States, organized by IAEA, online in October 2024
- The international workshop on SMR Safety for a Sustainable Short-term Deployment, organized by the SASPAM-SA Euratom project, in Fontenay-aux-Roses, France, in October 2024
- The final conference of the NPHyCo Euratom project – online, in February 2025
- The 5th SNETP project portfolio webinar on the TANDEM, SANE and EASI-SMR projects

A special issue has been launched in the Elsevier peer-reviewed journal **«** Sustainable Energy Technologies and Assessments »; it is entitled « *Beyond conventional use of nuclear for new energy needs* **»**. The special issue aims to foster publications of the results obtained in the project, within the framework of the project, with a view to extending publication opportunities to the entire international scientific community working on new uses for nuclear energy. The team of

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guests editors is composed of members of the Scientific Advisory Commitee and the TANDEM coordinator. Submission of articles is open from mid-2024 until the end of the project.

6.2 Recommendations

Recommendation n°1: The IUG proved to be a good communication forum with industry and energy stakeholders representatives about nuclear technologies integration in HES and it is recommended to sustain the IUG principles beyond the end of the project. However, an appropriate framework remains to be defined and perhaps the implementation could take place in the framework of the European Industrial Alliance on Small Modular Reactors

Recommendation n°2: The organization of dedicated workshops about SMR licensing with TSOs and nuclear safety authorities is required to encourage harmonization and to accelerate SMR emergence for industrial applications.

Recommendation n°3: It would be beneficial to establish contacts with investors to check whether the techno economic information produced in the simulations is appropriate for producing business plans and applications for financing. The results of the HES simulations using the TANDEM tools will be science based, they will be justifiable and they can be helpful to support nuclear technologies in investment roadmaps.

Recommendation n°4: Citizen engagement is very important to support nuclear technologies integration in HES. It is recommended to involve industry and energy stakeholders representatives for the assessment of citizen engagement during workshops as they usually deploy effective means of communicating their needs in terms of energy decarbonisation.

Recommendation n°5: Stakeholder and citizen engagement requires a long term effort. It is recommended to share feedback and to implement an iterative process ensuring that each event is better than the last one, ultimately fostering a more informed and engaged community.

Recommendation n°6: Consideration should be given to involving retired nuclear technology experts in the public awareness and information process, drawing on their knowledge and enthusiasm for nuclear energy.

Recommendation n°7: Preparing a joint analysis and communication of the policy recommendations with project representatives from GEMINI 4.0/ NPHyCo/ TANDEM should be discussed because this communication may be more impactful.

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7 WP6: education & training

7.1 Synthesis of the results

An E&T gap analysis in the domain of safety of SMRs and hybrid energy systems has been carried out in the framework of TANDEM (TANDEM/D6.1, 2023). Work began by drawing up and sending out a specific questionnaire to assess the skills required in this domain. A total of 12 people answered the survey questions relating to SMRs and E&T needs.

Following this questionnaire, an analysis of the education and training offers available today was carried out. The E&T curricula of various European universities were analyzed and compared. The analysis revealed that while engineering programmes (e.g. Bachelor level courses) address the integration of nuclear power plants into the energy system, many of these courses are taught by non-nuclear professors. There is therefore a risk that these courses will fail to take account of the latest developments in the potential of SMRs, in particular the additional benefits that these technologies can bring in terms of heat, hydrogen, etc. In addition, there is currently no master's program devoted specifically to SMRs and AMRs.

Given the changing landscape, students should benefit from education and training courses that offer a broader vision of what the future hybrid energy system will look like. This will give them a better understanding of the various aspects that go beyond purely nuclear topics, including the supply of electricity and heat for hydrogen production, district heating, seawater desalination, etc. In this way, students will acquire the broader knowledge and skills required by the industry.

Interdisciplinary collaboration is strongly encouraged so that experts from different fields can better understand the potential of a hybrid energy system. This could already be envisaged at university level, for example, by encouraging students studying different but related fields to work together on projects dedicated to the development of a low-carbon energy system.

Based on this E&T gap analysis, a series of actions (TANDEM/D6.2, 2023) was designed in the framework of the TANDEM project: an international summer school, two technical workshops and six webinars. The actions were specifically conceived for MSc and PhD students, PostDocs, young and experienced researchers and engineers that were interested in deepening their knowledge on the potential role that nuclear hybrid energy systems – integrating SMRs - plays in the ongoing energy transition.

Six webinars were organized in the framework of the TANDEM project. Some were jointly organized with the ENEN2+ Euratom project. The titles of the webinars were the following:

- “Nuclear Desalination”, in November 2023,

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- "Nuclear Batteries, a New Way in Energy", in December 2023,
- "What must be known when using system codes for reactor design and safety analysis", in April 2024,
- "Economy of Scale vs. Multiples: Bottom-up Cost Estimation of Nuclear Reactors", in April 2024,
- "Technoeconomic Modeling & Simulation of Integrated Energy Systems: Overview of the Framework for Optimization of ResourCes and Economics (FORCE) Tool Suite", in June 2024,
- "Non-electric applications of nuclear energy", in June 2024.

All the webinars were recorded and their records are available at the following address: http://nucleare.ing.unipi.it/it/webinars/webinars-2023-2024

The one-week summer school was organized in Lecco, Italy, in June 2024. Three Learning Objectives (LO) were defined for the school:

- LO1: to provide participants with an extensive overview of the advantages and challenges of nuclear reactor concepts producing commodities beyond power supply;
- LO2: to train students in the use of tools and methodologies essential for designing and simulating the operation of nuclear hybrid energy systems;
- LO3: to equip attendees with the quantitative skills necessary for assessing the impact of these systems within different contexts, ranging from a local scale to the global decarbonization of the energy system.

The two technical workshops were organized in the framework of the TANDEM project. The topics of the workshops were:

- Non-electric applications of SMRs, hybrid energy systems and their components, organized in Saint Paul-les-Durance, France, in September 2024,
- Modelling and optimization tools to assess hybrid energy systems integrating nuclear reactors, organized in Pisa, Italy, in February 2025.

The E&T materials for the summer school and the two technical workshops are available at the following address: https://enen.eu/index.php/portfolio/tandem-project/

Once the summer university and the two workshops were completed, a survey form was sent out to participants for their feedback, enabling the project to draw up a summary of the results and impact of these events (TANDEM/D6.3, 2025). Strategic recommendations of future E&T

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planning in the field of safety of SMRs and hybrid energy systems have also been delivered at the end of the project (TANDEM/D6.4, 2025).

7.2 Recommendations

Recommendation n°1: Dedicated SMR and Hybrid System Educational Curricula need to be developed to prepare the workforce required for the development and deployment of SMRs. In particular, it should build on the launch of new EU-supported Master and Specializing Masters programmes focused on SMRs, non-electric applications of nuclear and hybrid energy systems, and promoting interdisciplinary collaboration between engineering, environmental science, IT faculties and soft-skills focused faculties.

Recommendation n°2: It is also required to enhance soft skills (e.g., communication, adaptability, teamwork, analytical thinking and stakeholder engagement) and project-based learning in E&T programmes to facilitate the development and deployment of SMRs.

Recommendation n°3: Recent steep development of the IT and AI domain created numerous opportunities for synergies between engineering skills, tools and the computer-based solutions. In this regard, it is very important to develop real time/real process simulators or virtual reality platforms for experiential learning, which means that is necessary to expand access to IT-supported training.

Recommendation n°4: Foster EU-Wide Coordination and Recognition is also recommended. It relies on the following various aspects:

- Establishing an EU SMR Safety E&T Network/Initiative under Euratom. Having a network which is supported by European Institutions would give Europeans the chance to have a coordinated answer to the growing need of specialists;
- Creating a certification system for SMR/hybrid system skills, ensuring mutual recognition across Member States;
- Harmonizing quality assurance protocols for SMR-related E&T modules. This would be supporting various institutions who wish to provide a recognized educational process across EU countries.

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8 WP7: project management

8.1 Synthesis of the results

The interactions between the Scientific Advisory Committee and the TANDEM project were arranged within the framework of WP7. The other WP7 actvities mainly concern the day-to-day management of the project.

The SAC was composed during the setup of the project; Shannon-Bragg-Sitton (Idaho National Laboratory, USA), Alina Constantin replaced from March 2024, by Molly-Kate Gavello (IAEA, Austria), Michael Fütterer (EC-JRC, Netherlands) and Koroush Shirvan (Massachusets Institute of Technology, USA) accepted to join the group.

The expectations of the TANDEM project from the SAC were to:

- provide feedback and recommendations on the results, scientific choices and directions of the project;
- support interactions with other European and international initiatives which the SAC members are involved in and which are related to the activities of the project.

Twenty-four recommendations (TANDEM/D7.5, 2025) issued from the SAC were fully implementd by the project, and four additional ones partially implemented, with the objectives:

- To make the results understandable, reusable and « expandable »,
- To clarify or better justify the assumptions associated with the TANDEM studies,
- To strengthen the project impact,
- To connect the project to stakeholders not initially targeted by the project or to other international initiatives.

Seventeen recommendations have not been implemented by the project, mainly because they require either too much technical effort or are beyond the scope (/work program) of the project, without an associated funding from the European Commission.

The recommendations have been expressed during specific meetings:

- a first dedicated meeting with the SAC members was organized remotely on 8 March 2023,
- the SAC members were invited to attend the full annual project reviews in person (with a possibilibility of remote attendance as well):
  - ✓ in Milan (Italy) on 5 + 6 October 2023
  - ✓ in Brussels (Belgium) on 29+30 October 2024,
  - ✓ in Brussels (Belgium) on 3 July 2025,

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A dedicated session with the SAC members and the TANDEM management team was organized at the end of the project review.

Most of the recommendations have been expressed between the start and mid-term of the project.

8.2 Recommendations

Recommendation n°1: The SAC recommendations that have been partially implemented and not implemented in TANDEM should be analyzed in the light of the text of the next Euratom call, as they provide ideas for potential new project proposals.

9 Conclusion and outlook

The TANDEM project is considered as successful as all the work programme initially set up in the proposal has been achieved. It enabled to reach the High-Level Objectives (HLO) associated with the project:

- HLO1: Assess the safety compliance of SMRs to be integrated in the future European energy mix;
- HLO2: Provide guidance in a deployment perspective for future integration of SMRs and AMRs into well-balanced hybrid energy systems;
- HLO3: Foster enabling environment for development of hybrid energy systems based on SMRs and AMRs.

A review paper on the TANDEM project has been prepared for publication in a peer-reviewed journal. It includes many of the results mentioned in this deliveable.

Finally, the project prepared a letter summarizing potential areas of work for new projects and initiatives. This letter was shared with representatives of the European Commission and the secretariat of the European Industrial Alliance on SMRs in early 2025. A copy of the letter is available in Appendix B.

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Bibliography

(Casella & Leva, 2006) F. Casella, A. Leva, Modelling of thermo-hydraulic power generation processes using Modelica, Mathematical and Computer Modelling of Dynamical Systems, 12, 19–33 (2006). https://doi.org/10.1080/13873950500071082

(Eberhart et al, 2015) Eberhart, T. Shan Chung, A. Haumer, C. Kral, Open Source Library for the Simulation of Wind Power Plants, Proc. Int. Modelica Conf., Versailles, France (2015)

(El Hefni & Bouskela, 2019) B. El Hefni, D. Bouskela, Modeling and Simulation of Thermal Power Plants with ThermoSysPro: A Theoretical Introduction and a Practical Guide, Springer International Publishing, (2019) https://doi.org/10.1007/978-3-030-05105-1

(Elmqvist, 1998) H. Elmqvist, S.E. Mattsson, M. Otter, Modelica — An International Effort To Design An Object-Oriented Modeling Language, Proc. Int. Conf. SCSC'98, Reno, Nevada, USA (1998) , https://doi.org/10.1016/S1474-6670(17)43628-7

(IEA, 2021) Energy technology perspectives 2020, revised version, February 2021

(J. Leppanen, et al., 2021) A Finnish District Heating Reactor: Neutronics Design and Fuel Cycle Simulations, Proc. Int. Conf. on Nuclear Engineering, ICONE-28, 85246, p. V001T04A009. American Society of Mechanical Engineers.

(SMR pre-Partnership, 2023) European SMR pre-Partnership Reports, Workstream A – Market Analysis, available at https://snetp.eu/wp-content/uploads/2023/07/European-SMR-pre-Partnership-WS1_MarketAnalysis_FinalReport-3July2023.pdf

(TANDEM/D1.1, 2023) A. Goicea, Analysis of the key features of the future European energy market and associated regional/ national landsacpes, Deliverable 1.1.

(TANDEM/D1.2, 2023) A. De Angelis et al, Description and techno-economic characterization of the hybrid system components, Deliverable 1.2.

(TANDEM/D1.3, 2023) M. Minchole et al, Description of techo-economic assessment of energy policies and relations among hybrid energy systems, Deliverable 1.3.

(TANDEM/D1.4, 2023) K. Värri et al, Description of selected study cases for safety, techno-economic analysis and optimisation, Deliverable 1.4.

Funded by the European Union

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(TANDEM/D2.3, 2024) G. Simonini et al, Modelica models description for the "TANDEM" library development, Deliverable 2.3.

(TANDEM/D2.5, 2024) C. Martos Nogales and G. Masotti, Hybrid system simulator description, Deliverable 2.5.

(TANDEM/D2.6, 2024) C. Lombardo et al, CATHARE SMR model description, Deliverable 2.6.

(TANDEM/D2.7, 2024) S. Buchholtz et al,CATHARE SMR model description, Deliverable 2.7.

(TANDEM/D3.1, 2023) S. Crevon et al, Definition of case studies for techno-economic analyses including some environmental aspects, Deliverable 3.1.

(TANDEM/D3.2, 2024) G. Lavialle, S. Crevon et al, Presentation of dynamic techno-economic analysis for each study case, Deliverable 3.2.

(TANDEM/D3.3, 2024) J.P. Ikonen et al, Sensitivity of the hybrid system techno-economics analysis to uncertain key parameters, Deliverable 3.3.

(TANDEM/D3.4, 2025) G. Masotti et al, Assessment of the control and flexibility constraints on system components by the hybrid system simulator coupled wth an optimizer, Deliverable 3.4.

(TANDEM/D3.5, 2025) C. Martos Nogales et al, Technical study of optimized architectures with ECOSIMPRO for the three case studies, Deliverable 3.5.

(TANDEM/D4.1, 2023) A. Pucciarelli et al, Status report on safety analysis in Europe from the operational flexibility and cogeneration viewpoint, Deliverable 4.1.

(TANDEM/D4.2, 2023) J. Miss et al, Identification of potentially impacted safety margins and methodology for safety analysis of a SMR integrated in a hybrid system, Deliverable 4.2.

(TANDEM/D4.3, 2025), S. Buchholz, A. De Angelis, Report of operational transient safety case studies for a SMR with cogeneration Deliverable 4.3.

(TANDEM/D4.4, 2025) P. Olita et al, Report of operational Design Basis Accident case studies for a SMR with cogeneration, Deliverable 4.4.

(TANDEM/D4.5, 2025) N. Rodionov et al, Summary report on safety case studies for a SMR with cogeneration, Deliverable 4.5.

(TANDEM/D5.1, 2025) J. Johson et al, Policy briefs, Deliverable 5.1.

Funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Atomic Energy Community ('EC-Euratom'). Neither the European Union nor the granting authority can be held responsible for them.

(TANDEM/D5.3, 2023) J. Johnson, Stakeholder Engagement Plan, Deliverable 5.3.

(TANDEM/D5.4, 2025) J. Johnson, Summary Analysis of Stakeholder Engagement, Deliverable 5.4.

(TANDEM/D5.5, 2025) C. Schneidesch et al, Summary of the recommendations of the Industrial User Group, Deliverable 5.5.

(TANDEM/D5.8, 2025) N. Wessberg et al, Citizen Engagement Report, Deliverable 5.8.

(TANDEM/D6.1, 2023) J. Johnson, G. Pavel, E&T gap analysis in the domain of safety of SMRs and hybrid energy systems, Deliverable 6.1.

(TANDEM/D6.2, 2023) A. Pucciarelli et al, Design of E&T actions on safety of SMRs and hybrid system applications, Deliverable 6.2.

(TANDEM/D6.3, 2025) S. Lorenzi et al, Outcomes and impact for the students at the International School, Workshops, and other E&T events of the TANDEM Project, Deliverable 6.3.

(TANDEM/D6.4, 2025) G. Pavel, Strategic recommendations of future E&T planning in the field of safety of SMRs and hybrid energy systems, Deliverable 6.4.

(TANDEM/D7.5, 2025) C. Vaglio-Gaudard et al, Final SAC recommendations report, Deliverable 7.5.

(C. Vaglio-Gaudard, 2025) C. Vaglio-Gaudard et al, The Euratom TANDEM project to pave the way of nuclear SMR integration into hydrid energy systems contributing to net-zero emissions, submitted to Sustainable Energy Technologies and Assessment.

(WENRA RHWG, 2021) WENRA RHWG, *Applicability of the safety objectives to SMRs*, report, 2021.

(Wetter et al, 2014) Wetter, M., Zuo, W., Nouidui, T. S., & Pang, X. (2014). Modelica Buildings library. *Journal of Building Performance Simulation*, *7*(4), 253–270. https://doi.org/10.1080/19401493.2013.765506

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10 Appendix A

C. Vaglio-Gaudard et al, “The TANDEM Euratom project: context, objectives and workplan”, Proc. Int. Conf. ICAPP 2023, Gyeongju, South Korea, 2023.

C. Vaglio-Gaudard et al, “The TANDEM Euratom project: context, objectives and workplan”, Nuclear Engineering and Technology, 993-1001, 2024.

A. De Angelis et al, “Technology review and safety assessment of nuclear-renewable hybrid energy systems with light-water small modular reactors”, Proc. Int. Conf. ICONE31 Prague, Czech Republic, 2024.

G.C. Masotti et al, “Dynamic modelling and optimisation of a Small Modular Reactor for electricity production and district heating in the Helsinki region”, Proc. Int. Conf. ICAPP 2024, Las Vegas, Nevada, USA, 2024.

G.C. Masotti et al, “Simulation of flexible small modular reactor operation with a thermal energy storage system”, Proc. Int. IAEA Conf. on Small Modular Reactor and their applications, Vienna, Austria, 2024.

G. Simonini et al, “Integrating Small Modular Reactors into hybrid energy systems: the TANDEM Modelica library”, Proc. Int. Conf. on Small Modular Reactors and their applications, IAEA, Vienna, Austria, 2024.

C. Vaglio-Gaudard et al, “The TANDEM Euratom project to study the integration of SMRs into low-carbon hybrid energy systems: progress status at mid-term”, Proc. Int. IAEA Conf. on Small Modular Reactor and their applications, Vienna, Austria, 2024.

C. Serin, M. Glückler, M. Pasquet, C. Vaglio-Gaudard, “Outcomes of three Euratom projects on cogeneration of electricity, heat and hydrogen”, EPJ. Nuclear Sci. Technol., 11, 12 (2025).

C. Vaglio-Gaudard et al, “The Euratom TANDEM project to pave the way of nuclear SMR integration into hydrid energy systems contributing to net-zero emissions”, submitted to Sustainable Energy Technologies and Assessment.

G. Masotti, S. Crevon, S. Lorenzi, M. Ricotti, “Optimising a Nuclear Hybrid Energy System’s dispatch strategy: coupling dynamic and techno-economic optimisation tools”, Proc. Int. Conf. on Advances in Nuclear Power Plants (ICAPP), Antibes, France (2025).

Funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Atomic Energy Community ('EC-Euratom'). Neither the European Union nor the granting authority can be held responsible for them.

J.P. Ikonen, T. Lindroos, P. Hiltunen, “Feasibility of small modular reactors for decarbonizing district heating systems: a case study of the Helsinki metropolitan area”, Nuclear Engineering and Design, 442, 114262, 2025.

G. Masotti et al, “Modelling nuclear hybrid energy systems: objectives, architecture, and applications of the TANDEM Modelica library”, submitted to Sustainable Energy Technologies and Assessments.

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11 Appendix B

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January 8th, 2025.

From Members of the TANDEM management team, SNETP board and SNETP/NUGENIA/TA6 lead:

- Claire Vaglio-Gaudard, Eric Hanus, Stéphanie Crevon (CEA)
- Christophe Schneidesch (Engie-Tractebel)
- Marco Ricotti (CIRTEN & POLIMI), Stefano Lorenzi (POLIMI)
- Andrei Goicea and Jessica Johnson (Nucleareurope)

Feedback from the TANDEM project for the next calls of Euratom and Horizon-Europe programs

To: Mr Angelgiorgio Iorizzo, Project Officer at the European Commission

For information:
The Secretariat of the European Industrial Alliance on SMRs

Dear Mr Iorizzo,

Dear Members of the Secretariat of the European Industrial Alliance on SMRs,

The three-year TANDEM Euratom project will come to an end in August 2025, and we are now starting taking stock of the project. The overall ambition of TANDEM[1] ("Small Modular ReacTor for a European sAfe aNd Decarbonized Energy Mix") is to *promote multi-purpose Small Modular Reactors (SMRs) integrated into hybrid energy systems as reliable, resilient, and affordable clean energy options in Europe*. The project focuses primarily on light water SMR technologies for near-term deployment in Europe by 2035, but also aims to support the deployment of Advanced Modular Reactors of Generation IV by 2050 when technology-neutral outcomes are identified.

The **intrinsic key feature of the TANDEM project** is the development of an integrated vision of the low-carbon energy mix on a local/regional scale (a urban area or an industrial area). Indeed, the project considers nuclear energy as an electricity and heat source to supply industrial processes and district heating – as in other Euratom projects working on nuclear co-/poly-generation – but also studies coupling (also referred to as "hybridization") with renewables and energy carrier storage systems. The project is addressing the **technical**

[1] https://tandemproject.eu/

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feasibility (safety, operability and flexibility of the energy supply) and economic viability of such hybrid energy systems, as well as **citizen engagement** regarding their deployment.

The project provides methodologies and tools for the technical assessment of Hybrid Energy Systems (HES) and implements them on demonstrative case studies of energy systems to be decarbonized. By mid-2025, as expected, the project will release policy briefs and technical guidelines supporting the safe and cost-effective deployment of SMRs/ AMRs in urban or industrial areas consistent with the future European low-carbon energy mix in Europe.

In parallel, TANDEM has built an **open and long-term community** that will ensure expertise in the field of nuclear HES and support the wide acceptance of multipurpose SMRs and AMRs. This European community has forged **close links with other international communities**, such as the Idaho National Laboratory (INL)[2], the Nuclear Power Technology Development Section of the International Energy Atomic Agency (IAEA) and industrial stakeholders, to develop new collaborations and foster exchanges in the field of nuclear cogeneration, non-electric applications of nuclear energy and nuclear HES.

The discussions between TANDEM and these international communities clearly underline that nuclear cogeneration and its integration into hybrid energy systems is an issue of utmost importance. TANDEM paves the way for the credibility of hybrid energy system integrating SMRs and AMRs on a local scale. Given the urgency of achieving net-zero targets and answering new energy challenges driven by the international geopolitical context, ***it is now time to turn the integration of SMRs and AMRs in hybrid energy systems into reality***, *while ensuring the competitiveness of the technologies implemented in HES and speeding up their deployment through digitalization*. Achieving this goal requires to tackle several R&D and technical issues, enabling for fostering cross-sectorial collaborations between nuclear and renewable communities. As the following topics are oriented towards the nuclear community, and more broadly, the low-carbon energy community, it would be a great opportunity if they could be addressed in both the upcoming Euratom and Horizon-Europe calls for tenders:

1. **Definition and study of low-carbon energy solutions integrating SMRs and AMRs for the decarbonizaton of a real industrial energy hub in EU**: TANDEM has explored demonstrative study cases. It is now required to demonstrate on a more complex real European industrial case that a safe and cost-effective implementation of SMRs and AMRs integrated in a HES is a realistic and smart low-carbon energy solution. To this end, it will be necessary to share data with industrial partners in order to specify the industrial study case to be decarbonized, including the production of heat, electricity, fresh water and hydrogen. Then the sizing of HES as low-carbon energy solutions will be carried out using appropriate tools and methodologies, based on simulation tools and optimization algorithms, such as those developed and/or implemented in TANDEM. To give greater credibility to these results, the predictivity of these tools and

[2] Which Integrated Energy System (IES) program is a pioneer in the analyses of integrated energy systems and the study methodologies developed in this framework

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methodologies will be assessed by defining numerical benchmarks and carrying out cross-comparisons of results.
On the basis of the adaptation and formalization of existing methodologies for other technologies, a generic methodology will be developed to perform a comprehensive assessment of low-carbon solutions/ HES incorporating SMRs/AMRs; it will enable to compare not only economic parameters (e.g. identification of the lowest costs for energy production with the most competitive technologies) between various low-carbon solutions, but also technical performances (e.g. flexibility of energy production), energy security / sovereignty, sustainability (e.g. resources of critical materials), resilience to climate change (e.g. storms), environmental impact, etc. Implementation of the methodology will be illustrated on the study case;

2. **Safety demonstration and regulatory framework for HES integrating SMRs / AMRs:** guidelines to assess safety of HES integrating AMRs/SMRs need to be developed on lessons learnt from TANDEM (and other EU projects) and on the elaboration of generic Phenomena Identification and Ranking Tables (PIRTs) for the safety impact analysis of the coupling between nuclear and different industrial technologies (SMRs/AMRs with hydrogen production plants, refineries, district heating networks, desalination plants, etc). Using PIRTs, it will be possible to draw conclusions on safety transient frequencies. By the way, deterministic studies of safety transients will be performed complementing TANDEM analyses.
   It is also proposed to assess the Emergency Planning Zone (EPZ) of SMR and AMR designs and the safety distances associated with risk management of the industrial facilities that will be part of the HES corresponding to the energy hub. An implementation map for the SMRs/AMRs integrated into the HES, taking into account these safety constraints, will be drawn up. Expert discussions are underway on codes and standards for hydrogen risk assessment; it will be necessary to critically review and propose improvements to the methodologies implemented for hydrogen risk-related safety distances in the study case.
   Moreover, principles for establishing a common regulatory framework between nuclear safety regulators and industrial risk regulators also need to be discussed;

3. **Design development of the SMR/AMR Balance of Plant (BoP)**: the design of the BoP characterizing the coupling between SMRs / AMRs and industrial processes and energy storage systems need to be subject to both safety and technical guidelines. Emphasis will be placed on the design of the heat conversion system with a Rankine cycle to be developed to ensure SMR/AMR cogeneration operation and the industrial process optimization. Studies will be carried out to determine the limit of the heat extraction rate under off-design conditions, in heat/electricity cogeneration mode, without major modifications of the nuclear plant.
   The simulation of SMRs and AMRs integrated into HES requires holistic modelling of the nuclear island, including the Rankine cycle, both in modelica-based simulators and

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in system thermal-hydraulics codes. An analysis of the state-of-the-art of Rankine cycle models and available experimental data for model validation will be carried out; it will stress the lack of experimental data. Solutions will be developed to fill this gap (design of a new lab experiment or collection of industrial data from the industrial PWR fleet in EU);

4. **Development of the first HES modular demonstrator in EU:** reflection on this topic is still ongoing, and some aspects of the demonstrator's technical feasibility (notably the time constants for component control) have not yet been thoroughly analyzed. Today we envisage a demonstrator that will rely on a high-speed connection by optic fibre between energies sources (SMR and renewables), potentially coupled with energy storage systems, located in a research centre, and with an industrial application on a technology-designer's or R&D site. Some components of the HES demonstrator will be real (e.g. renewables and the industrial application which could be a High Temperature Steam Electrolyser, whose energy source inputs will be emulated), others will be numerical simulators (e.g. SMR). The various components will be controlled through a Supervisory Control And Data Acquisition (SCADA) system. The demonstrator will be modular and will let the possible to be coupled with other numerical or real components (in particular other industrial processes) in the future.
   The development of this demonstrator will be an important step to make nuclear HES real for energy-intensive industrials involved in energy transition; the demonstrator will be developed as an advanced demonstration lab enabling for tests of decarbonisation solutions.
   The demonstrator will also make it possible to study safety transients occurring in HES and to serve as benchmark for other HES simulators (e.g. simulators based on simplified physical models and developed with the TANDEM modelica-based library).

All the R&D activities proposed above will provide credible arguments for consideration of nuclear in the broader low-carbon energy community and represent an excellent opportunity to complement the work of different TWGs of the European Industrial Alliance on SMRs. The analysis presented here comes from the critical review of the TANDEM outcomes, technical discussions within the Consortium, as well as feedback from the TANDEM Scientific Advisory Committee and the TANDEM Industrial User Group. All the proposed technical axes seem to be of particular relevance for the Euratom research and training program. However, technical axes n°1, 3 & 4 could also be of great interest for the Horizon-Europe program (Pillar II), by proposing an integrated vision of the future low-carbon energy mix in industrial areas, studying the BoP design and developing a HES demonstrator. So a funding request to both programs might be considered.

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Having said that, we remain at your disposal to initiate the discussions with the relevant TWGs of the Alliance and to explore these different axes and how to implement them in future European funded projects.

Sincerely,

On behalf of all the co-authors of the letter:

Claire Vaglio Gaudard
Coordinator of the TANDEM Euratom project

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