The TANDEM Euratom project: context, objectives and workplan

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Abstract – The TANDEM project is a European Commission initiative funded under the EURATOM program. The project started on September 2022 and has a duration of 36 months. TANDEM stands for Small Modular ReacTor for a European sAfe aNd Decarbonized Energy Mix. Small Modular Reactors (SMRs) can be hybridized with other energy sources, storage systems and energy conversion applications to provide electricity, heat and hydrogen. Hybrid energy systems have the potential to strongly contribute to the energy decarbonization targeting carbon-neutrality in Europe by 2050. However, the integration of nuclear reactors, particularly SMRs, in hybrid energy systems is a new R&D topic to be investigated. In this context, the TANDEM project aims to develop assessments and tools to facilitate the safe and efficient integration of SMRs into low-carbon hybrid energy systems. An open-source "TANDEM" model library of hybrid system components will be developed in Modelica language to build a hybrid system simulator which, by coupling, will extend the capabilities of existing tools implemented in the project. The project proposes to specifically address the safety issues of SMRs related to their integration into hybrid energy systems, involving specific interactions between SMRs and the rest of the hybrid systems; new initiating events may have to be considered in the safety approach.

TANDEM will focus on two main study cases corresponding to hybrid system configurations covering the main trends of the European energy policy and market evolution at 2035's horizon: a district heating network and power supply in an urban area, and an energy hub serving energy conversion systems, including hydrogen production, in a regional perspective. TANDEM will provide assessments on SMR safety, hybrid system operationality and techno-economics. Societal considerations will also be encased by analyzing the European citizen engagement regarding SMR technology safety.

The work will result in technical, economic and societal recommendations and policy briefs on the safety of SMRs and their integration into hybrid energy systems for industry, R&D teams, TSOs, regulators, NGOs and policy makers. The TANDEM consortium will involve 18 partners from 8 European countries (Belgium, Czech Republic, Finland, France, Germany, Italy, Spain, Ukraine).

The TANDEM project has the ambition to become a pioneer initiative in Europe in gathering efforts and expertise around development of SMRs integration into hybrid systems. The dissemination and the exploitation of the project outcomes as well as the proposed Education&Training activities shall serve as a basis for a number of new R&D and innovation projects addressing the safety issues of SMRs and their integration into hybrid systems.

Keywords: SMR, hybrid energy systems, Euratom project, safety, techno-economics

I. INTRODUCTION

In 2022, global carbon dioxide emissions from fossil fuel combustion was expected to grow by about 1% [1]. It corresponds to a small increase regarding the 6% jump in 2021, which resulted from the rapid global recovery from the economic crisis triggered by the pandemic.

A major effort to develop and deploy clean energy technologies worldwide is urgently needed to meet international energy and climate goals defined in the Paris Agreement. Transitioning just the power sector to clean energy would get the world only one-third of the way to net-zero emissions [2]; achieving net-zero emissions will require a radical transformation in the supply, conversion and usage of energy. Every low carbon energy source for power production will be necessary to cope with the net-zero scenario, along with all low carbon energy carriers such as hydrogen, carbon capture utilization, storage or low-carbon heat generation. The clean energy transition will have to address at the same time the decarbonisation of transportation, industry, and thermal energy used for domestic purpose.

Europe consumes about half of its energy for heating purposes[1]. European total gross production of derived heat in 2021 was 599 TWh. The highest share of heat[2] was produced from natural gas and manufactured gases (38.2 %), followed by renewable energies (31.6 %) and solid fossil fuels (19.6 %).

The European Union (EU) aims to be climate-neutral by 2050 – an economy with net-zero greenhouse gas emissions. In order to reach it, more ambitious targets were recently set for 2030: the reduction of greenhouse gas emissions to at least 55% below 1990 levels. In this context, nuclear energy has, jointly with renewable energy, a major role to play in the European clean energy transition, considering these two energy sources as the “backbone” of the future carbon-free European power system [3]. Nuclear power plants have been historically designed and well optimized for the generation of electricity that is the most universal vector for energy worldwide but may provide other products and services in the next decades. The idea of using nuclear energy for non-power applications is not new [4]; since the 1950’s, nuclear power has been used as a heat source for seawater desalination (e.g. in Kazakhstan and Japan) [5] and district heating (e.g. in Switzerland, Russia and China).

The race for the development of advanced light-water Small Modular Reactors (SMRs) has started and today, no less than 70 concepts are under development covering a wide range of technology approaches and maturity levels [6]; first construction projects have already been launched. SMRs offer many advantages, such as relatively small physical footprints, reduced capital investment, ability to be sited in locations not possible for larger nuclear plants, and provisions for incremental power additions. The main multipurpose European SMR concepts are the UK SMR (United Kingdom) and NUWARD^{TM} (France). A Finnish concept, the LDR-50 [7], is exclusively dedicated to district heating or desalination. Various international SMR concepts are multipurpose reactors designed for power and non-power applications: for instance, NuScale (USA), ACP100 (China) or SMART (Korea). In non-power applications, thermal energy produced by SMRs can be used for heating or conversion through industrial processes (hydrogen production, seawater desalination, feedstock, list not exhaustive).

Versatile SMRs for power and non-power applications may be well suited to operate flexibly in *tandem* with storage systems and other energy sources, in particular variable renewable energy sources. Thus SMRs can be hybridized with other energy sources, storage systems and energy conversion applications; they are integrated into hybrid energy systems. In this case, SMRs can operate in cogeneration mode or for a dedicated application.

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[1] https://heatroadmap.eu/

[2] https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Electricity_and_heat_statistics#Production_of_electricity

These opportunities represented by the SMR technologies have the potential to strongly contribute to the European and worldwide energy decarbonization if successfully implemented. However, the integration of nuclear reactors, and in particular SMRs, into hybrid energy systems is a new R&D topic to investigate for safety, design, flexibility, societal acceptance, etc.

In this context, the TANDEM project proposes to address most specifically the SMR safety issues related to the SMR integration into hybrid energy systems. Considering a near-term deployment in Europe at 2035's horizon, the project is mainly focused on light-water technologies for SMRs. However, the project aims also at providing perspectives, whenever possible, for the integration of Advanced Modular Reactors (AMRs) into hybrid energy systems at 2050's horizon, in the Generation-IV framework.

II. GENERAL OVERVIEW OF THE PROJECT

The TANDEM project is a European Commission initiative funded under the Euratom Research and Training Programme. It is related to the topic on safety of advanced and innovative nuclear designs and fuels (NRT01-02) in the Work Programme 2021-2022. The project started on September 2022 and has a duration of 36 months.

The TANDEM consortium is composed of universities, research institutes, Technical Safety Organizations (TSO), industrials and engineering organizations. The project is coordinated by the French Alternative Energies and Atomic Energy Commission (CEA) and involves 17 other partners from eight European countries:

- *Belgium:* EC-JRC, ENEN, Nucleareurope, Tractebel-Engie,
- *Czech Republic:* UJV,
- *Finland:* VTT, Fortum,
- *France:* EDF, IRSN,
- *Germany*: GRS,
- *Italy:* CIRTEN (POLIMI, UNIPI), Ansaldo Nucleare, ENEA,
- *Spain*: Empresarios Agrupados,
- *Ukraine:* Energorisk.

As shown in Fig. 1, the TANDEM project is organized into five Work Packages (WPs) to accomplish the four different project phases presented in Section III.

To have additional information on the project and get informed about the technical progress of the project, the reader can browse the TANDEM website (https://tandemproject.eu/) and follow the project on LinkedIn (https://www.linkedin.com/company/tandem-project-eu/).

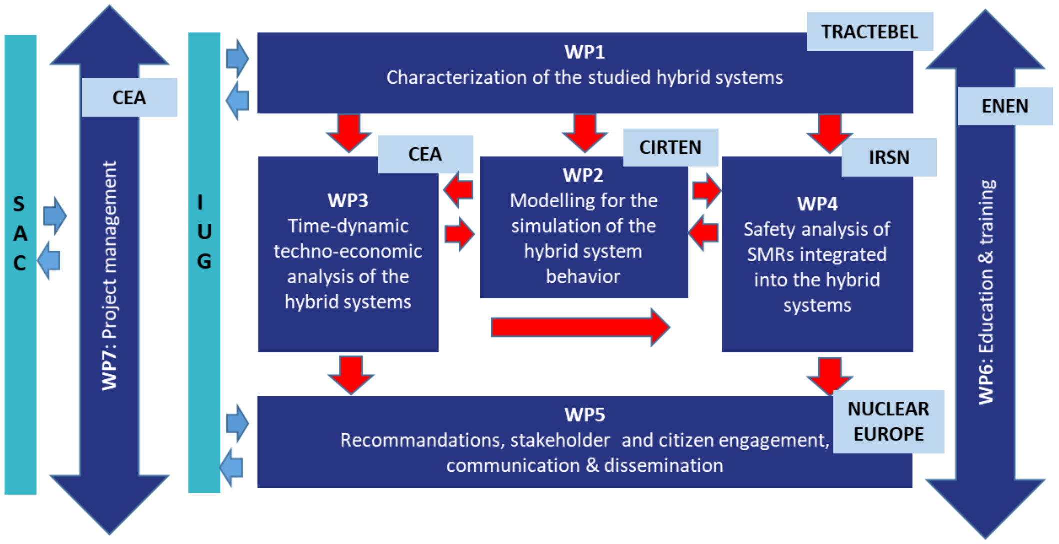

Fig. 1. Work package breakdown in TANDEM (the organization leading each WP is indicated in a light-blue box).

II. AMBITION OF THE PROJECT

II.A. General Ambition

SMRs are nuclear reactors with a power output between 100 and 1000 MWth that incorporate by design higher modularisation and standardisation, bringing the idea of economies of series. They provide a new approach to the nuclear power plant design, featuring a compact size allowing for in-factory assembly and transport on-site. A smaller size of the reactor offers interesting safety features, notably in terms of residual heat removal and size of containment structure. Thus, SMRs are expected to be easier to build and to operate.

There is currently a hard competition on the development for possible deployment between different SMR concepts worldwide. As examples but not exhaustively, ACP100 is under construction in China, NuScale obtained NRC design certification for 50 MWe units in the USA, NUWARD^{TM} project will be in the basic design phase in France in 2023. Even though the SMR market is still ahead of us, some clear market opportunities have been identified on the short term in the general EU policy perspective: replacing aging fossil power plants, offering small sized reactors on electrical grids that are not robust enough to cope with large reactors, proposing SMRs with limited investment to international nuclear newcomers.

The TANDEM general ambition is to *promote SMRs integrated into hybrid energy systems as reliable, resilient, and affordable clean energy options in Europe*. The TANDEM framework considers hybrid energy systems derived from realistic energy scenarios consistent with the European policy and energy market evolution at horizon 2035's. The project will provide tangible outcomes to raise awareness of the different stakeholder groups on the interest of hybrid systems incorporating SMRs.

II.B. Beyond the State-of-the-Art

The utilization of SMRs in hybrid energy systems, ensuring electricity, heat or hydrogen production to support a wide array of energy demands has just started to be investigated in Europe. The feasibility of the SMR integration into such systems has not been demonstrated yet in particular considering the safety perspective. The TANDEM project will gather the initiatives in Europe on this new R&D topic.

The technical and economic feasibility of SMRs integration into hybrid systems rely on three main topics addressed by the TANDEM project:

- The safety of SMRs integrated into a hybrid system: the safety assessment of SMRs integrated into hybrid systems requires an extension of the current safety approach implemented for operating nuclear power plants. Indeed, it is necessary to consider the possible impact on SMR safety of both, the other non-nuclear systems (in particular energy conversion applications, such as hydrogen production plants) and the balancing of the energy network/ grid. In particular, the hybrid system may impose additional safety design requirements deriving from additional postulated initiating events, either affecting specific Structures, Systems and Components interfacing the SMR with the storage/end-user, or induced by the storage/end-user itself and potentially affecting the SMR;
- The flexibility of the SMR energy production (and more generally the operationality of hybrid systems) to deal with renewable intermittency, grid stability and resilience and variability of the energy demand (household electricity demand, heat demand by industrial end-users, etc.). The current power ramp speed that the most modern reactor designs can manage is limited to 5% nominal power/min, considering fuel safety limitations. If a higher power ramp speed is required (20% nominal power/min), only fossil-fired plants, such as gas turbine, can be activated today; however, these systems will no longer be allowed to be integrated in the future carbon-free mix. The TANDEM project will have to demonstrate that the SMRs through heat and electricity production can manage the flexibility of the energy production in the hybrid system taking into account economic and environmental constraints for the sizing optimization of the hybrid system components;
- The SMR economic viability: hybrid systems integrating SMRs will be achievable from a techno-economic viewpoint if the hybrid systems and the way to operate them are economically competitive within the broader energy market, including electricity, hydrogen and heat markets.

The feasibility of the hybrid systems is not only technical and economical but also societal. That is why the citizen engagement will be also analysed in TANDEM: a hybrid system incorporating SMRs will be achievable only if the European citizens trust the SMR technology and its safety, for power and non-power application, in particular targeted for domestic use (hydrogen use for transport, district heating for the buildings, etc).

To perform the feasibility studies, the TANDEM project will develop a tool to model the hybrid systems integrating SMRs, and will extend the capabilities of existing nuclear safety and techno-economics tools. No computational tool dedicated to the hybrid energy system simulation is available among the consortium partners. However, the studies of SMRs integrated into hybrid systems require computational tools able to model holistically the hybrid system behaviour for both technical and economical assessments. Firstly, TANDEM will develop a set of numerical models, called the "TANDEM" library, for the simulation of the hybrid system components, with the Modelica[3] language [8]. This latter is a non-proprietary, object-oriented, equation-based language to conveniently model complex physical systems.

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[3] http://www.modelica.org

The coupling of the models included in the TANDEM library, according to the hybrid system architectures, will allow for the elaboration of a numerical hybrid system simulator. The investigation of the safety modelling strategy (see next section) for SMR safety assessment will require to take into account the physical coupling between SMRs and the rest of the hybrid system in the simulation. That is why a numerical coupling will be developed between reference nuclear safety codes and the hybrid system simulator during the project. Besides, in order to assess the hybrid system operationality (in particular the management of the energy production flexibility) by existing techno-economics tools, more detailed numerical models are required to simulate the hybrid system control: TANDEM will elaborate a coupling between the numerical hybrid simulator and the techno-economics tools already developed by consortium partners. Fig. 2 shows the synthesis of the simulation strategy implemented in TANDEM.

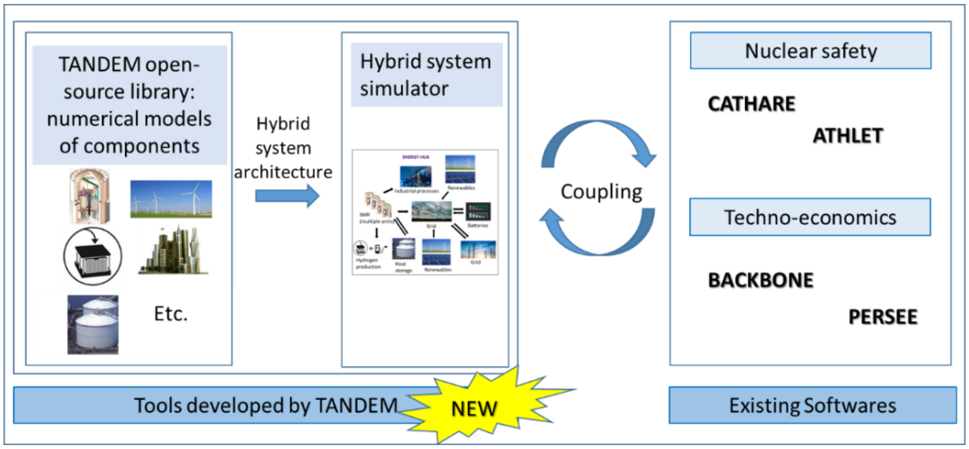

Fig. 2. Modelling and simulation strategy proposed by the TANDEM project.

III. OVERALL METHODOLOGY IMPLEMENTED IN THE PROJECT

The following general definitions are given below to clarify the methodology description:

- *an energy scenario*: it defines the energy framework as it could result from market and policy evolution for different regions in Europe at one given date;
- *a hybrid system configuration*: it is the hybrid system architecture resulting from the practical implementation of an energy scenario;
- *an energy study case*: it is the whole characterization of a hybrid system configuration from the technological and techno-economic viewpoint. Specifications can be derived from this characterization;
- *a case study*: it is related to the implementation of a study case in a specific European regional and market context.

The overall methodology relies on 4 phases that are strongly interrelated; these phases are briefly described below.

PHASE 1: Identification of hybrid system to study

The project first phase achieved in WP1 is dedicated to the identification of two energy study cases that will be the inputs of the other phases for hybrid system modelling (see PHASE 2) and assessment of SMR safety and hybrid system techno-economics and operationality (see PHASE 3). In each energy study case, a hybrid system that will combine nuclear power generated by one or several SMR units with other energy sources and with downstream application systems will be configured.

The energy decarbonization relies on the deep transformation of the energy production and consumption, facilitated by EU and national policies for energy, transport, economics and climate, and induced by new energy market development; it leads to envisage several realistic energy scenarios to be deployed in the next decades. The project will review briefly the scenarios including nuclear energy, in light of existing studies, with the following considerations:

- spatial scale,
- type of deployed nuclear technologies,
- priorities set by the European Commission,
- priorities set by European country policies thanks to the knowledge of the consortium partners (own countries and others),
- energy market development and growth.

Within an energy scenario, the transformation of the current energy systems as well as the development of new low-carbon alternatives have to be considered in the perspective. Near-term scenarios by 2035's and long-term ones by 2050's will be differentiated.

TANDEM will focus on hybrid system configurations aligned with the EU policies and energy market evolution, implementable at near-term by 2035's; it is a project choice to reduce early the wide scope of possible hybrid system architectures in order to provide relevant results considering the short project duration. Two hybrid system configurations will be derived from the energy scenarios:

- A hybrid system configuration related to a *district heating network and power supply for an urban area*, at a local scale ;
- A hybrid system configuration related to *an energy hub serving energy conversion systems, including hydrogen production, in a regional perspective* (e.g. at a country scale).

A preliminary list of the possible hybrid system components is already identified: SMR unit(s), renewable energy plants, fossil fired plants, electrical and thermal energy storage, hydrogen, synfuel, desalination plants, district heating, grid (local-regional, country-interconnections). The final list will depend on the detailed configurations of the hybrid systems studied in the project. The components will be defined and characterized by intrinsic inputs (engineering properties and technical/operational constraints, economical properties), connectivity rules and quantities, and Figures of Merit.

Lessons learned from the Euratom ELSMOR project[4] in progress will contribute to further characterize the SMR concepts to be considered: the SMR concept chosen as use-case in TANDEM will rely on the E-SMR concept [9] developed by ELSMOR. It basically shares the same design philosophy for the reactor system as the NUWARD^{TM} concept with potential for extended applications.

The current European techno-economics context will also be analysed at this stage to characterize the SMRs and the associated hybrid systems, considering that European boundary conditions will certainly evolve. It will combine technological knowledge of SMR cost structure and elements from market knowledge of the European Power grid. The scope of the task will cover more generally:

- power system economics, regulatory policies,
- market design, generator dispatch, grid balancing,
- network capacity: transmission & distribution system studies,
- SMR investment and costs evaluation.

It will integrate the analysis of the EU countries' energy markets: distribution of energy generation, energy needs, analysis of perspective programs for national markets development and when possible the implementation of the EC directives.

The two hybrid system configurations and their key components will combine one parametrizable SMR in a grid/network of selected sets of conversion systems to build the energy study cases able to match any geographical/economic framework and related timeframes. The latter will be defined from the identification of typical combinations for representative EU areas with geographical needs and constraints for decarbonizing the energy mix scenarios. Variations due to the heterogeneity of those needs and constraints will be specified as optional modules or possible range for input parameters with respect to one reference/representative case. In particular, the balance of plant will be relative to the technological coupling between nuclear and non-nuclear components in the study case, and in particular to the choice to include or not hybrid system capacities in the plant design. Coupling energy storage for live steam production or feedwater heating has specific configurations/ dynamics/ requirements. The same applies for process heat applications depending on the required enthalpy/reliability/distance of end user. Therefore, one or more balance of plant architecture(s) of the hybrid systems are to be identified, depending on the energy case study to consider.

PHASE 2: Development and implementation of computational tools for SMR assessment

The SMR safety assessment and the hybrid system operationality and techno-economics analysis (see PHASE 3) require the development and the implementation of modelling, simulation and optimization tools.

TANDEM Modelica-based library and hybrid system simulator (WP2)

A configurable Modelica-based tool-box of connectable hybrid system components will be developed in TANDEM (WP2). The objective is to deliver a reference and modular library of multiphysics engineering-oriented of hybrid system components. The flexibility of object-oriented modelling granted by the Modelica modelling language will allow to develop the models of the hybrid systems configured in the previous phase and to make available to the scientific and industrial community a modelling library that can be used for future analysis. Additional components with respect to the ones defined in WP1 could be also developed during the TANDEM project or in the near future. The library component models will have to be numerically coupled according to user-defined design architectures to simulate the physical behaviour of a whole hybrid energy system.

The TANDEM model library will be open-source and able to be downloaded on the project website. They will be used for two main purposes: engineering analyses of hybrid systems and Education&Training (E&T) activities.

Note that the FMI/FMU standard considered in the library will enable to interface the simulator or library models with safety and techno-economics simulation tools for the project study needs, and with other FMI/FMU-compatible tools out of the TANDEM scope.

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[4] http://www.elsmor.eu/

Tools for safety assessment (WP2)

The tools used for the safety assessment of SMRs integrated into hybrid systems are presented below:

- *CATHARE* (Code for Analysis of THermalhydraulics during an Accident of Reactor and safety Evaluation) [10] is a two-phase thermal-hydraulic simulator in development since 1979 at CEA, as part of an agreement between the CEA, EDF, AREVA and the IRSN. The software is currently in its second major revision. It is used, in particular, in pressurised water reactor safety analyses, for the verification of post-accidental operating procedures, and in research and development activities. CATHARE is capable of simulating the physical phenomena that occur at the nuclear reactor system scale, during normal, off-normal and accident situations;
- *ATHLET* (Analysis of the Thermal-Hydraulics of leaks and Transients) [11] was developed by GRS for the analysis of the whole transient spectrum in western types of LWRs, WWERs, RBMKs and advanced gas, liquid or molten salt cooled fast reactors. ATHLET consists of several modules, such as thermal-hydraulics, heat transport and heat conduction, neutron kinetics, simulation of balance and control systems.

A SMR modelling based on the E-SMR design defined in the framework of the ELSMOR project will be developed for both codes, for the safety studies. CATHARE and ATHLET will be used in stand-alone on one hand and will also be coupled with the Modelica-based library to model the rest of the hybrid system components on the other hand.

Tools for techno-economics and operationality analysis (WP3)

The tools used for techno-economics and operationality analysis are presented below:

- *BACKBONE* [12] is a highly adaptable energy systems modelling framework developed by VTT to study the design and operation of energy systems. It can be used to implement models of both high-level large-scale systems and fully detailed smaller-scale systems. The modelled energy system can include many different kind of units, cogeneration, storage systems, reserves, and forecast errors in time series. Techno-economic modelling optimizes investments and the use of units and storage systems according to cost minimization, while simultaneously ensuring hourly balance between energy supply and demand, and respecting given boundary conditions, such as ramp rates, reserve requirements, etc. The open-source version can be downloaded at https://gitlab.vtt.fi/backbone/backbone;
- *PERSEE* is a modelling software dedicated to techno-economics assessment of several designs of energy systems at local, industrial and regional scales, while optimizing their operating costs. It has been developed at CEA since 2018 on the basis of past experiences from the Odyssey tool [13] and the PEGASE platform [14]. PERSEE provides a graphical user interface that allows users to model the system by assembling Mixed-Integer Linear Programming (MILP) model contributions from a C++ library, to build a time-dependant optimization problem solved by one of the solvers available to PERSEE through a multi-MILP-solver interface (OSI opensource, Cplex, Gurobi, …).

BACKBONE and PERSEE will be used in TANDEM project in stand-alone in one hand, and will be also coupled with the Modelica-based hybrid system simulator on the other hand.

PHASE 3: Safety and feasibility studies for SMR integration into hybrid systems

The feasibility studies are related to the safety assessment of SMRs, the techno-economics and operationality analysis of hybrid systems, for the energy study cases defined in PHASE 1. These studies rely on the implementation of the tools developed in PHASE 2. PHASE 3 also deals with citizen engagement regarding the SMR technology use and safety for power and non-power applications.

Safety assessment (WP4)

The integration of SMRs into a hybrid energy system will involve specific interactions between the SMRs and the rest of the hybrid system, and new potential risks; the objective of the safety methodology developed and implemented in the TANDEM project is to identify these risks and to assess them. In particular, the integration of SMRs in future low carbon and smart grids where some non-pilotable generators have priority over pilotable means will necessarily introduce specific interactions with the energy network and constraints to ensure the electricity grid reliability. Energy network balancing through SMR load following capabilities, energy storage systems or cogeneration flexibility, will be assessed; it may have an impact on the SMR safety, in particular depending on the magnitude and frequency of the energy ramp speeds. The coupling of the SMR secondary circuit with a heat storage may be a benefit for the SMR safety during stressfully situations, which needs further investigations.

Key impacted structures, systems, components and related parameters of SMRs will be identified mainly in a generic framework during the project, considering normal and abnormal SMR operation. The project will specify envelope operational transients and accident situations; it will investigate their impact on reactor safety by using the numerical models developed in the previous phase (PHASE 2). The operational transients will be primarily derived from European grid codes requirements (already in force for current pressurized water reactors). TANDEM will consider the coupling of the SMR with energy storage and cogeneration systems.

The safety case studies will be performed with:

- ATHLET and CATHARE stand-alone calculations as a baseline, using boundary conditions to take into account the interfaces between the SMRs and the rest of the hybrid system. Some safety case studies will be analysed with both CATHARE and ATHLET modelling in order to check the consistency of the developed modelling;
- CATHARE/Modelica and ATHLET/Modelica coupled calculations; the coupling between the reference nuclear system thermal-hydraulics codes and the Modelica-based library enables to take into account dynamically the physical interactions between the SMR and the rest of the hybrid system. The impact of the coupling will be quantified.

The impact of E-SMR passive safety features will be stressed during accident situation studies.

At the end of the safety studies, the project will provide recommendations on:

- the modelling approach to implement the safety studies of SMR integrated into a hybrid system,
- the hybrid system design and operating to enhance SMR safety.

Techno-economics and operationality analysis (WP3)

The SMR integration into hybrid systems have to be studied in light of a specific regional context to perform a relevant techno-economics analysis; indeed, the economic viability of such configurations is highly dependent on:

- the deployment location, including regional resources, feedstock and geography,
- regional energy markets, for electricity, heat, hydrogen, etc.,
- regional product markets and industries,
- the timescale.

That is why realistic “techno-economics” case studies, depending on the location in Europe, and the associated policy and energy markets, will be selected at this stage. The hybrid system configuration related to a district heating network and power supply for an urban area will be studied in the specific context of a Nordic country and a Central Europe country; the second hybrid configuration related to an energy hub serving energy conversion systems in a regional perspective will be studied for a country in Southern Europe. The case studies will be characterized by all the data required for the techno-economics analysis afferent to the considered locations (energy production/ consumption data, technological/ economical/ environmental data) in 2035’s. Energy policies scenarios / stakeholders and end-users’ targets will be defined, as well as the identification of the energy mix Key Performance Indicators and targets (including for example net present value – Levelized Cost Of Energy i.e. LCOE, carbon content).

Firstly, a global techno-economic and environmental dynamic assessment of the case studies will be carried out to investigate the profitability and environmental impact of the studied hybrid systems. A full global optimization approach will be implemented, using PERSEE and BACKBONE in stand-alone, to get the best values for a set of performance indicators for each case study and choose the most relevant ones. This approach enables to compute the optimal sizing of the system components under optimal control assuming perfect knowledge of load and energy productions over one-year duration. It describes the energy system in the framework of the Mixed Integer Linear Programming formalism to minimize an objective cost function (e.g. Net Present Value cost) under environmental and technical constraints (efficiencies, storage capacities and charge-discharge maximum flows, start-up shutdown costs, carbon direct or indirect emissions avoidance, etc.). Some sensitivity analyses of the optimization results will be performed at this stage considering the most uncertain parameters (electrical prices, carbon contents, key component economic features).

This global analysis uses an optimal control with one-year anticipation capability. Production capacity – as well as seasonal storage if it is considered - and flexibility are tightly linked with this ability. It can lead to over-optimized component sizes since the hybrid systems may not be operated considering a relevant time scale in the optimization process; indeed, in this case, the system has lower performance indicators, and may require more energy production flexibility. To assess this point, dynamic analyses using the Modelica-based library coupled to PERSEE and BACKBONE will be performed on a short time scale (from seconds to 24 - 48 hours). Compliance with technical constraints and control action feasibility of the hybrid system components will be checked with the TANDEM hybrid system simulator and the ECOSIMPRO tool[5] developed by EAI, for comparison.

Citizen engagement (WP5)

The assessment of the citizen engagement in TANDEM will increase the citizen understanding about SMR safety and energy mix concepts and will investigate how European citizens perceive the benefits and potentials as well as risks of SMR technology for power and non-power applications.

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[5] https://www.ecosimpro.com/

Citizens with different ages, genders and backgrounds will be invited into workshops where SMR technology will be introduced. In the workshops citizens will be encouraged to express their hopes and worries regarding the SMR technology. Interactive parts of the workshops will include also co-creative designing and new idea creation session, where citizens will be able to imagine the future of the SMR technologies.

Citizens will be mapped and invited e.g., from housing or city associations, also e.g. city employees are invited into the workshops. The regional coverage of the invitation will be limited to the partner countries in the TANDEM project, but the templates and ways to organize the workshops will be able to be replicated elsewhere after the TANDEM project end. The project will organize a total of five workshops in France, Italy, Spain, Belgium, Ukraine, Finland, Germany or Czech Republic. The decisions of the workshop locations will be made at the beginning of the TANDEM project. The workshops will be either face-to-face meetings or virtual.

On the basis of the matter produced during this phase on SMR safety, SMR integration into hybrid systems and citizen engagement, TANDEM will provide recommendations with respect to technical, economic and societal issues, and policy briefs in WP5.

PHASE 4: Building enabling environment for future projects and initiatives

Outreach activities, concerning publications in international scientific conferences and journals, workshop organizations for stakeholder and citizen engagements (WP5), communication & dissemination (WP6), will enable to share the innovative features and results raised by TANDEM.

TANDEM will train in WP6 young scientists and engineers to the new specific issues of SMR safety and integration into hybrid systems, enlarging their scientific knowledge. The current and expected future needs of E&T related to the SMR safety, including the implication of SMR integration in hybrid energy systems, will be analyzed. In response to these needs and an analysis of the currently available training offers on this topic, TANDEM will design, plan and deliver specific E&T actions and courses, and will develop a strategy to implement future E&T requirements. These courses will be designed and delivered in the form of one International School, international workshops, webinars and a series of lecture videos. These E&T actions will be constructed by addressing both knowledge, skills and competences identified as necessary in the domain of SMR safety and SMR integration in hybrid energy systems and project results. Aspects such as the range of technologies and components for SMRs and non-nuclear systems, SMR cogeneration, non-power applications and safety, will be considered.

The close interactions with the European Sustainable Nuclear Energy Technology Platform (SNETP), a Scientific Advisory Committee (already set up) and an Industrial User Group will enable to identify priorities to address during and after the project. These interactions will also foster the development of cooperation with international R&D teams and with European Industrials (utilities, designers of hybrid system components, end-users, etc.).

IV. CONCLUSION

TANDEM is a Euratom project, started on September 1, 2023, for a 36-month duration. It aims to develop methodologies and tools to facilitate the safe and efficient integration of SMRs into smart low-carbon hybrid energy systems. TANDEM will address the safety issues and provide assessments of the feasibility of SMR integration into hybrid energy systems, regarding techno-economics, operationality and citizen engagement. The academic E-SMR concept developed by the ELSMOR project will be implemented as use-case in the technical studies performed by TANDEM.

The project will focus on light-water SMR technologies which can potentially be deployed in Europe by the 2035s. At the same time, within the Generation IV framework, the project also aims to provide perspectives for the integration of Advanced Modular Reactors (AMRs) into hybrid energy systems by 2050.

TANDEM is a project ambitious and fundamental for the future of Europe’s energy transition.

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DISCLAIMER

Views and opinions expressed are however those of the authors 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

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