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Original Article

The TANDEM Euratom project: Context, objectives and workplan

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ABSTRACT

The TANDEM project is a European 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 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 study two hybrid systems covering the main trends of the European energy policy and market evolution at 2035's horizon: a district heating network and power supply in a large urban area, and an energy hub serving energy conversion systems, including hydrogen production; the energy hub is inspired from a harbor-like infrastructure. TANDEM will provide assessments on SMR safety, hybrid system operationality and techno-economics. Societal considerations will also be encased by analyzing European citizen engagement in SMR technology safety.

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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, Technical Safety Organizations, regulators, Non-Governmental Organizations and policy makers. The TANDEM consortium will involve 17 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 energy 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 energy systems.

1. Introduction

In 2022, global carbon dioxide emissions from fossil fuel combustion reached a new record high, increasing by almost 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 tend towards the 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 net-zero, 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 decarbonization of transportation, industry, and thermal energy used for domestic purposes.

European Union (EU) 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 %).

EU aims to be climate-neutral by 2050 – an economy with net-zero greenhouse gas emissions. In order to reach it, ambitious targets were 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 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 USA, Kazakhstan and Japan) [5] and district heating (e.g. in Switzerland, Russia and China).

The race for the development of advanced Small Modular Reactors (SMRs) has started and today, no less than 83 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 Rolls-Royce SMR (United Kingdom) and NUWARD™ (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 VOYGR™ (USA), ACP100 (China) or SMART (Korea, Saudi Arabia). In non-power applications, thermal energy produced by SMRs can be used for heating or conversion through industrial processes (hydrogen production, feedstock, etc.).

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.

These opportunities represented by SMR technologies have the potential to strongly contribute to the energy decarbonization in Europe and worldwide 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, energy 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 to provide perspectives, whenever possible, for the integration of Advanced Modular Reactors (AMRs) into hybrid energy systems at 2050's horizon, in the Generation-IV framework.

The purpose of this contribution is to describe the TANDEM project. The paper first provides a very brief overview of the project and presents the main scientific objective and the overall methodology implemented in the project. As the project started ten months ago, the status and first results of the project are also shared in the paper, as well as the work in progress and the work program for future actions.

2. Brief overview of the project

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

The consortium and the ambition of the project are described below.

2.1. Project consortium

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, CEA,
- *Germany*: GRS,
- *Italy:* CIRTEN (POLIMI, UNIPI), Ansaldo Nucleare, ENEA,

[1] https://heatroadmap.eu/.

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

- *Spain*: Empresarios Agrupados,
- *Ukraine:* Energorisk.

2.2. Ambition of the project

SMRs are nuclear reactors with a power output up to 300 MWe [8] (corresponding to about 1000 MWth) that incorporate by design higher modularization and standardization, 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™ project is in the basic design phase in France since 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 power 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.

3. Main scientific objective and overall methodology implemented in the project

The US Integrated Energy System program, supported by the Department of Energy's Office of Nuclear Energy (DOE-NE), has established in 2020 a roadmap [9] for the development of hybrid energy systems integrating nuclear reactors. This program is the pioneer in the analysis of integrated energy systems. However, this technical topic has just started to be investigated in Europe.

3.1. Main scientific objective of the project

The main scientific objective of the TANDEM project is to provide guidance in a deployment perspective for future integration of SMRs into well balanced hybrid energy systems. To reach this objective, the TANDEM project first needs to analyze the technical and economic feasibility of the SMR integration into hybrid energy systems, which relies on three main topics:

– The safety of SMRs integrated into a hybrid energy system: the safety assessment of SMRs integrated into hybrid energy 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 low-carbon- energy mix. It is necessary to demonstrate that SMRs, by cogenerating heat and electricity, can manage the flexibility of energy production in hybrid energy systems taking into account economic and environmental constraints when optimizing the sizing of hybrid energy 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 energy systems is not only technical and economic but also societal. That is why citizen engagement will be also analyzed in TANDEM: a hybrid energy system incorporating SMRs will be achievable only if the European citizens trust the SMR technology and its safety, for power and non-power application, and in particular targeted for domestic use (hydrogen use for transportation, district heating for the buildings, etc).

To perform the technical and economic feasibility studies, the TANDEM project will have to develop a tool to model the hybrid energy systems integrating SMRs, and will extend the capabilities of existing nuclear safety and techno-economics tools (CATHARE and ATHLET for safety, BACKBONE and PERSEE for techno-economics, see Section 4). No computational tool dedicated to the hybrid energy system simulation is available among the consortium partners. The studies of SMRs integrated into hybrid energy systems require computational tools able to model holistically the hybrid energy system behavior for both technical and economic assessments. Firstly, TANDEM will develop a set of numerical models, called the "TANDEM" library, for the simulation of the hybrid energy system components, with the Modelica[3] language [10]. This latter is a non-proprietary, object-oriented, equation-based language to conveniently model complex physical systems.

The coupling of the models included in the TANDEM library, according to the hybrid energy system architectures, will allow for the elaboration of a numerical hybrid system simulator. The investigation of the safety modeling strategy (see Section 4) for SMR safety assessment will require to take into account the physical coupling between SMRs and the rest of the hybrid energy system in the simulation. That is why a numerical coupling will be developed between reference nuclear safety codes and models of the TANDEM library during the project. Besides, in order to assess the hybrid energy system operationality by existing techno-economics tools, more detailed numerical models are required to simulate the hybrid energy system control: TANDEM will elaborate a coupling between models of the TANDEM library and the techno-economics tools already developed by consortium partners. Fig. 1 shows the synthesis of the simulation strategy in TANDEM.

3.2. Overall methodology implemented in the project

The overall methodology implemented in the project is described in Fig. 2. It can be split into four phases:

– Phase 1: this phase aims to define and characterize two hybrid energy systems by analyzing the European context, such national and EU energy scenarios to achieve climate-neutrality, energy market

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

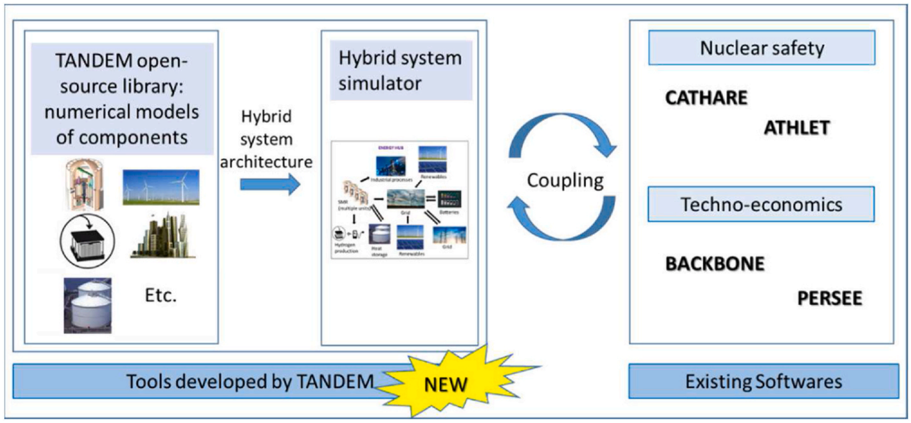

Fig. 1. Modeling and simulation strategy proposed by the TANDEM project.

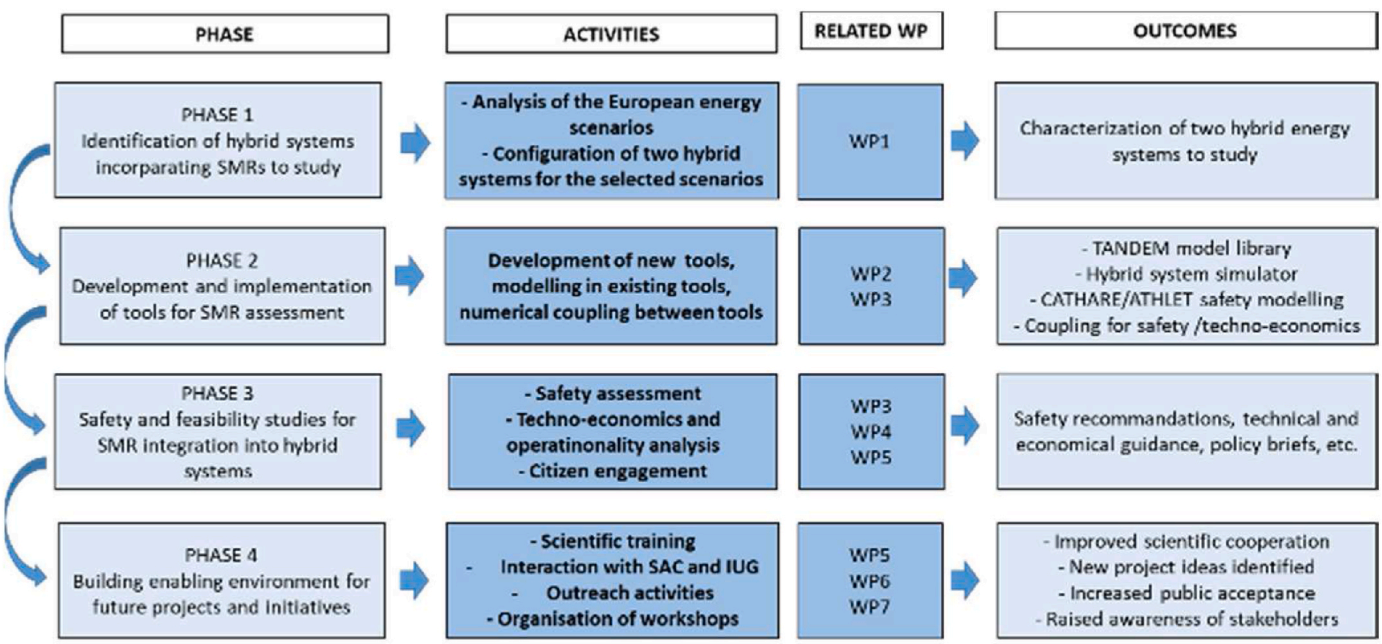

Fig. 2. Overall methodology implemented in the TANDEM project.

projections and energy technology readiness. These hybrid energy systems will be studied as use-cases within the framework of the project;

– Phase 2: this phase aims to develop modeling and tools to assess the technical and economic feasibility of hybrid energy systems in Phase 3: TANDEM model component library and hybrid energy system simulator in Modelica language, SMR modeling wih safety codes, hybrid energy system modeling with techno-economics optimization codes and numerical coupling between the existing tools (safety and techno-economics codes) and the TANDEM model library;
– Phase 3: this phase aims to carry out feasibility studies for the integration of SMRs into hybrid energy systems, from a safety, operational and techno-economic point of view, using the modeling and tools developed in phase 2. From a societal point of view, citizen engagement in the safety of SMR technology is also assessed in this phase, with the organization of specific workshops.
– Phase 4: this phase aims to create favorable environment for future project and initiatives, building on TANDEM activities related to the dissemination and communication of project results, Education & Training (E&T) and the engagement of citizens and stakeholders (regulators, utilities, SMR designers, industrial energy end-users, etc).

The resulting Work Package (WP) breakdown is presented in Fig. 3. The TANDEM project is organized into five technical WPs, numbered from 1 to 5, with an additional WP dedicated to Education & Training, to accomplish the four different project phases. WP7 is dedicated exclusively to project management.

The project has interactions with two external groups:

- a Scientific Advisory Committee (SAC), thanks to which the project gets feedback on the results and recommendations for orientations of the technical activities, in synergy with developments in international organizations inside and outside Europe,
- an Industrial User Group (IUG) to engage in a constructive dialogue about the technological feasibility of the hybrid systems incorporating SMRs, regulatory, societal and economic issues related to implementation of such systems and the different energy markets and their particularities. The IUG is still under construction, and an organization interested in being involved in the group can contact the project coordinator with the email of the corresponding author.

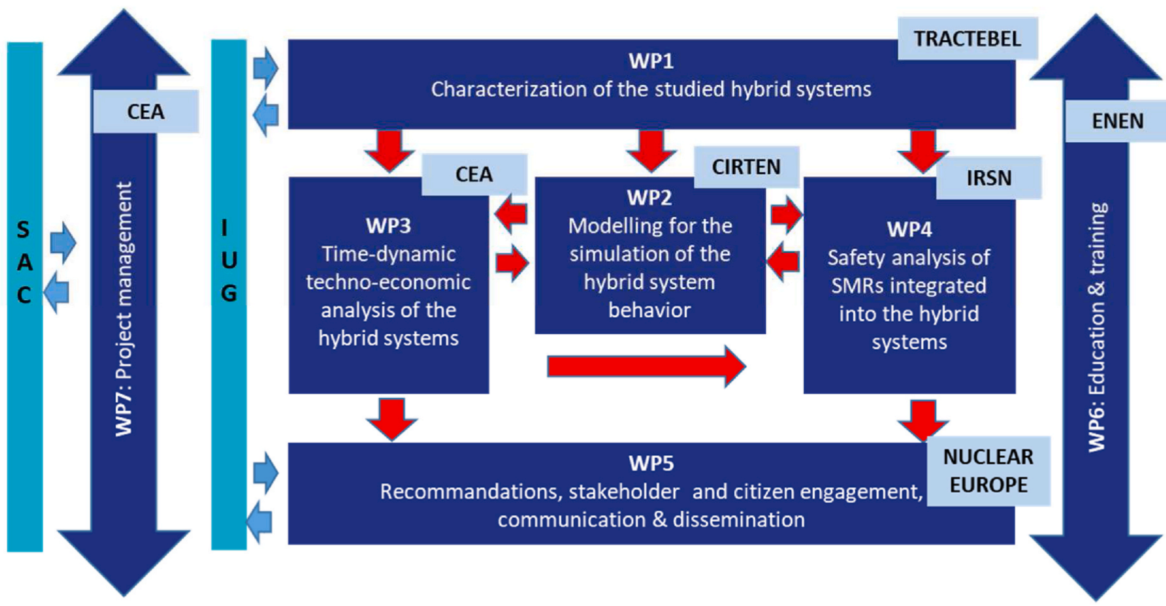

Fig. 3. Work package breakdown in TANDEM (the organization leading each WP is indicated in a light-blue box).

4. Status and workplan of the project

By the tenth month of the project, Phase 1 has been completed and the main activities of the other phases launched. The status of the project and future actions are presented below for each phase.

4.1. *Phase 1: Identification of hybrid energy system to study*

The first phase of the project is devoted to characterizing two hybrid energy systems to be studied throughout the project. 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 briefly reviewed the energy scenarios including nuclear, in the light of existing studies, with the following considerations:

- priorities set by the European Commission,
- priorities set by European country policies thanks to the knowledge of the consortium partners,
- energy market development and growth,
- spatial scale,
- new energy usage.

Through these energy scenarios, the transformation of the current energy systems as well as the development of new low-carbon alternatives were considered in the perspective. The TANDEM project decided to focus its studies on hybrid energy systems in two timeframes, 2035 and 2050, considering two scenarios for SMR deployment, one high and one low, for each timeframe [11]. The low SMR deployment scenario considers that no SMR will be deployed in the EU by 2035, while the high scenario suggests the deployment of first SMRs by the same date. In 2050, both scenarios envisage the deployment of SMRs, with capacity three times higher for the high scenario.

Two hybrid energy systems [12] aligned with the EU policies and energy market projections were defined in Phase 1. The first hybrid energy system is related to a district heating network and power supply for a large urban area (Fig. 4). The second one corresponds to an energy hub serving energy conversion systems, including hydrogen production (Fig. 5); the energy hub is inspired from a harbor-like infrastructure. Both hybrid energy systems integrate renewable energy sources (photovoltaics and wind power) and controllable energy sources (Combined-Cycle Gas Turbines or "CCGTs", but it could also be coal-fired plants, SMRs, and heat pumps in the hybrid energy system for district heating and power supply). They are connected to a heat network and the local power grid, which in turn are connected to thermal and electrical storage, and energy end-user applications, in particular High-Temperature Steam Electrolyzers (HTSE) for hydrogen production (in the case of the energy hub only).

Then, different hybrid energy system configurations are derived depending on the timeframe and the SMR deployment scenario

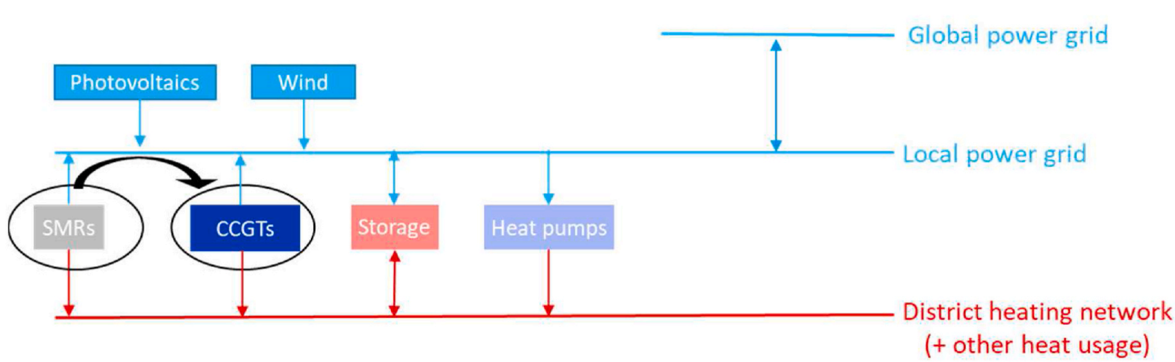

Fig. 4. Schematic configuration of the hybrid energy system for district heating and power supply.

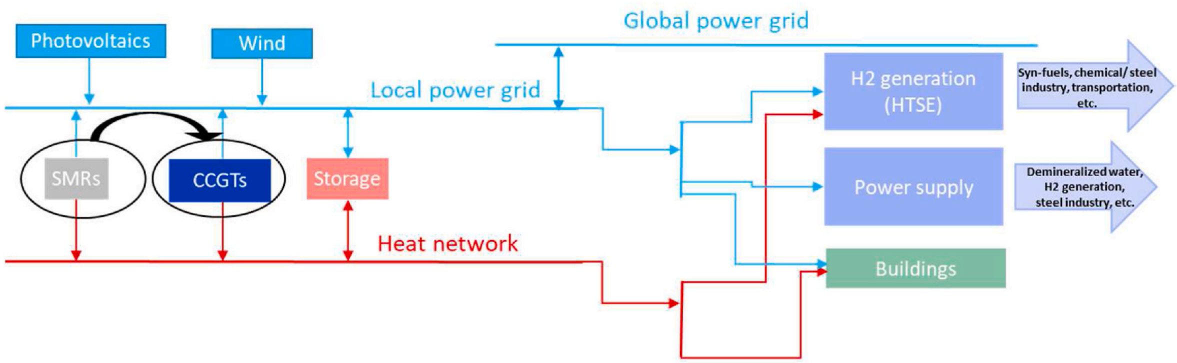

Fig. 5. Schematic configuration of the hybrid energy system corresponding to the energy hub.

considered. No SMR is incorporated in the configuration of the hybrid energy systems for 2035, with the low SMR deployment scenario; it is considered as a baseline. In the other configurations, SMRs are deployed progressively, replacing CCGT. In the high SMR deployment scenario, SMRs completely replaced CCGTs at timeframe 2050 to achieve energy transition. These different configurations will be studied in Phase 3 of the project to highlight the benefits of SMR penetration in the future low-carbon energy mix.

During this phase, discussions were held to identify the most suitable technologies in the hybrid energy system configurations. Lessons learned from the Euratom ELSMOR project[4] contribute to characterize the SMR concept to be considered: the SMR concept chosen as use-case in TANDEM relies on the E-SMR academic concept [13] developed by VTT, POLIMI and GRS in ELSMOR. It is an integrated Generation III + pressurized water reactor, which is inpired from the design philosophy of the NUWARD™ concept for the reactor system.

4.2. Phase 2: Development and implementation of computational tools for assessing hybrid energy systems

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

4.2.1. 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 modeling offered by the Modelica modeling language will enable to develop the models of the hybrid systems characterized in the previous phase and to make available to the scientific and industrial community a modeling library that can be used for future analyses. Additional hybrid energy system components with respect to the ones defined in Phase 1 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 behavior 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 energy systems and E&T activities.

Note that the FMI/FMU standard considered in the library will enable the models in the library to be interfaced with safety and techno-economics simulation tools for the purposes of the project, and with other FMI/FMU-compatible tools outside the scope of TANDEM.

4.2.2. Tools for safety assessment (WP2)

The tools used to assess the safety of SMRs integrated into hybrid systems are presented below:

- *CATHARE* (Code for Analysis of THermalhydraulics during an Accident of Reactor and safety Evaluation) [14] is a two-phase thermal-hydraulics code in development since 1979 at CEA, with the support of EDF, FRAMATOME and IRSN. The software is currently in its second major revision. It is used, in particular, in pressurized 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) [15] 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 modeling 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 models on the other hand.

4.2.3. Tools for techno-economics and operationality analysis (WP3)

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

- *BACKBONE* [16] is a highly adaptable energy systems modeling 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 kinds of units, cogeneration, storage systems, reserves, and forecast errors in time series. Techno-economic modeling 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 of Backbone can be downloaded at https://gitlab.vtt.fi/backbone/backbone;
- *PERSEE* is a modeling software dedicated to techno-economics assessment of several designs of energy systems at local, industrial

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

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 [17] and the PEGASE platform [18]. 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-dependent 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 Modelica-based models on the other hand.

By the tenth month of the project, the modeling strategies for the development of the Modelica-based TANDEM library and for the development of SMR modeling with safety tools have been defined.

4.3. Phase 3: Feasibility studies for SMR integration into hybrid energy systems

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

4.3.1. Safety assessment (WP4)

The integration of SMRs into a hybrid energy system will involve specific interactions between 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-controllable generators have priority over controllable means will necessarily introduce specific interactions with the energy network and constraints to ensure the electricity grid reliability. Energy network and electricity grid balancing through SMR load following capabilities, energy storage systems or cogeneration flexibility, will be assessed; it may have an impact on SMR safety, in particular depending on the magnitude and frequency of the energy ramp speeds.

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 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 analyzed with both CATHARE and ATHLET modeling in order to check the consistency of the developed modeling;
- 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 may be stressed during potential accident situation studies.

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

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

By the tenth month of the project, a review of the state-of-the-art of European studies on the SMR safety analysis from the operational flexibility and cogeneration viewpoint [19] has been completed. The number of studies carried out in Europe and worldwide on the safety aspects of integrating SMRs operating in cogeneration into hybrid energy systems proved limited. It has therefore been necessary to draw information from the wider field of studies on nuclear cogeneration applications for different reactor types, where experience has been accumulated in specific projects. Nuclear power plants are currently used as heat sources for desalination, district heating and process heat [20], also in Europe, suggesting the possibility and necessity of addressing related issues through a systematic study. Considerable work has been carried out under the European Nuclear Cogeneration Industrial Initiative (NC2I)[5] platform for (very) High Temperature Reactors ((V)HTRs), with interesting analogies to the work to be carried out in TANDEM; having already addressed relevant issues, the related projects provide very useful information for initiating similar work on light water SMRs.

Work is underway to define the safety approach that will be implemented during this phase, extending the traditional safety approach for conventional light-water reactors producing only electricity to the reactor coupling with energy end-user applications and cogeneration.

4.3.2. Techno-economics and operationality analysis (WP3)

The SMR integration into hybrid energy systems have to be studied in the light of a specific regional context to carry out a relevant techno-economics analysis; indeed, the economic viability of such systems 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, the associated policy and energy markets, will be selected at this stage. The hybrid energy system related to a district heating network and power supply for a large urban area will be studied in the specific context of a Nordic country (Finland) and a Central Europe country (Czech Republic); the second hybrid energy system related to an energy hub serving energy conversion systems, inspired from a harbor-like infrastructure, will be studiedin 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.

Firstly, a global techno-economic and environmental dynamic assessment of the case studies will be carried out to investigate the profitability and environmental impact (restricted to carbon footprint) of the studied hybrid energy 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. The optimization process is based on the minimization of an objective function by finding an optimal sizing of system components and an optimal control of the

[5] https://snetp.eu/nc2i/.

system to meet 1 year demands at a given time step (typically 1 h). This optimization process may be enriched by additional constrained, like for instance maximum integrated CO_2 emissions over the life of the system.

BACKBONE and PERSEE are two modelling frameworks for conducting techno-economic and environmental analysis owing to a Mixed Integer Linear Programming (MILP) formalism. They allow to optimize the sizing of components (the number of SMRs, the installed capacity of wind turbines, the size of the HTSE, the size of the storage capacity) and their operation to minimize or maximize an objective function. In techno-economic analysis, generally, the objective function is the net present value (NPV) that should be maximized but it could also be the total levelized costs of the system.

The way to consider the system to analyze can be different depending on the study case. For example, for the Northern European case, a district heating network and power supply in an urban area will be considered. In this case, thermal loads are pretty well known, so the thermal energy required for district heating as well as selling prices will be fixed assuming values on the horizon (2035–2050), being able to perform sensitivity analyses at a subsequent stage to check the impact of the assumptions on the final results. A potential HES architecture for the Southern European case will be an energy hub. In this case the alternative product (H_2, fresh water, clean molecules, etc.) production and its storage will be defined as a variable to be optimized.

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 energy 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 h). Compliance with technical constraints and control action feasibility of the hybrid energy system components will be checked with the TANDEM hybrid system simulator and the ECOSIMPRO tool[6] developed by Empresarios Agrupados Internacional, for comparison.

4.3.3. Citizen engagement (WP5)

The assessment of 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. 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 SMR technologies.

Citizens will be mapped and invited to participate in 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 during the TANDEM project. The workshops will be either face-to-face meetings or virtual.

4.4. Phase 4: Building favorable environment for future projects and initiatives

Outreach activities, involving publications in international scientific conferences and journals, stakeholder and citizen engagement workshops, communication & dissemination, will share the innovative features and results raised by TANDEM.

TANDEM will train 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 into 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 into 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),[7] the Scientific Advisory Committee and the 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.).

5. Conclusion and outlook

TANDEM is a Euratom project, started on September 1, 2022, 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.

By the tenth month of the project, Phase 1 has been completed and the main activities of the other phases launched. Phase 1 was devoted to characterizing two hybrid energy systems to be studied throughout the project. Two hybrid energy systems aligned with the EU policies and energy market projections were defined in this phase. The first hydrid energy system is related to a district heating network and power supply for a large urban area; the second one corresponds to an energy hub serving energy conversion systems, including hydrogen production. The TANDEM project decided to focus its studies on hybrid energy systems in two timeframes, 2035 and 2050, considering two scenarios for SMR deployment, one high and one low, for each timeframe. The low SMR deployment scenario considers that no SMR will be deployed in the EU by 2035, while the high scenario suggests the deployment of electricity-only SMR by the same date. In 2050, both scenarios envisage the deployment of SMRs for cogeneration of electricity and heat, with capacity three times higher for the high scenario. Relying on the TANDEM

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

[7] https://snetp.eu/.

studies, this will highlight the benefits of SMR penetration in the future low-carbon energy mix.

TANDEM is a project ambitious and fundamental for the future of Europe's energy transition. 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/). Most of the documents produced by the project are public and can be downloaded from the TANDEM website. Besides, the TANDEM Modelica-based library, and the associated documentation, will be open-source and delivered on the TANDEM website. Thus, the developed methodologies and tools will be used beyond the project and will be accessible to a wider audience, with the possibility of being applied to non-water cooled SMRs. Indeed, the library can be enriched by the addition of new component models developed outside the scope of the project.

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.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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