THE TANDEM EURATOM PROJECT TO STUDY THE INTEGRATION OF SMRS INTO LOW-CARBON HYBRID ENERGY SYSTEMS: PROGRESS STATUS AT MID-TERM

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Abstract

The TANDEM project (Small Modular Reac**T**or for a European s**A**fe a**N**d **D**ecarbonised **E**nergy **M**ix) is a Horizon-Europe project funded under the Euratom program. The main goals of TANDEM are as follows: firstly, to develop an integrated vision of energy systems through the implementation of hybrid energy systems incorporating Small Modular Reactors (SMRs) to produce heat, electricity and hydrogen at a local scale. Secondly, to develop tools and methodologies to study hybrid energy systems. And thirdly, to show the role and benefits of multipurpose SMRs integrated into hybrid energy systems for the energy transition. Considering SMR near-term deployment in Europe, the project mainly focuses on light-water technologies. The project started on September 2022 for a 3-year period. The objective of the paper is to present the mid-term progress of the project. Two generic hybrid energy systems have been configured for study within the framework of the project: a district heating configuration and an energy hub. A TANDEM open-source Modelica-based library has been developed. It is a collection of models representing different components required to build a hybrid energy system simulator. The safety approach classically implemented on SMRs for a conventional use (electricity production only) has been extended to SMRs integrated into hybrid energy systems. Several operational transients have been identified by TANDEM as relevant for analyzing the impact of hybridization on nuclear reactor behaviour, inducing potentially new safety considerations. Three case studies (in Finland, in Czech Republic and in France) have been derived from the two generic hybrid energy system configurations, as demonstrative cases supporting the energy transition; different architectures have been assessed for each study case from the standpoint of techno-economics and environmental impact.

1. INTRODUCTION

Small Modular Reactors (SMRs) can be hybridized with other energy sources, storage systems and various energy 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 (Small Modular Reac**T**or for a European s**A**fe a**N**d **D**ecarbonised **E**nergy **M**ix) project [1] aims to study the safe and cost-effective integration of SMRs into low-carbon hybrid energy systems. It is a European initiative funded under the EURATOM program. It was launched in 2022 for a 3-year period. The main expected outcomes of the project are as follows:

- The development of tools and methodologies to assess hybrid energy systems from the standpoints of nuclear safety, techno-economics, environmental impact and operability,
- Illustrative results from the assessment of hybrid energy systems on which the tools and methodologies developed have been applied,
- The development of a technical and scientific community connected to other Euratom projects on nuclear cogeneration, other international initiatives and industrial stakeholders.

The project involves 18 partners (universities, research institutes, technical safety organizations, industrials and engineering organizations) from eight European countries (Fig. 1).

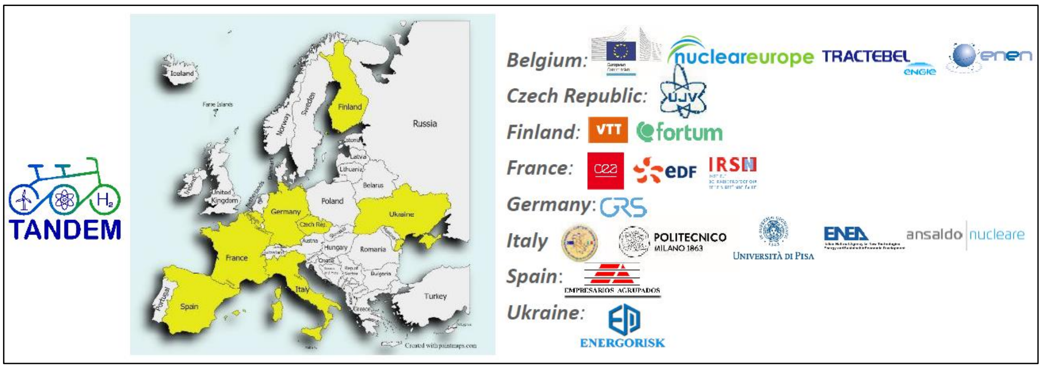

FIG. 1. Partners involved in the TANDEM consortium.

Considering a near-term deployment in Europe at 2030's horizon, the project is mainly focused on light-water technologies. That is why "SMR" refers to light-water SMR in this paper. 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 objective of this paper is to share the progress status of the project at mid-term. After characterizing the hybrid energy systems studied in the project, the paper briefly presents the safety approach to be implemented for SMRs integrated into hybrid energy systems, as well as the study cases illustrating the assessment of techno-economics and environmental impact.

2. CHARACTERIZATION OF THE HYBRID ENERGY SYSTEMS STUDIED IN THE PROJECT

This section deals with the generic configuration of two hybrid energy systems reflecting European energy needs and priorities, as well as the development of a hybrid energy simulator, within the TANDEM activities.

2.1. Generic configuration of two hybrid energy systems considering European energy needs and priorities

Many scenarios present strategic plans for energy transition at different levels (national, regional and EU). Building on the Fit for 55 package of proposals to meet climate-neutrality in 2050 in the European Union (EU) and complementing the actions on energy security, the REPowerEU[1] plan put forward a set of actions to save energy, to produce low-carbon energy and diversify its supplies. While the EU's clean energy transition strategy heavily relies on substantial electrification of many sectors, supported by the accelerated deployment of renewable electricity generation capacity, all strategies take into account energy demand reductions supported by higher energy-efficiency targets.

Heating and cooling constitute today about 50 %[2] of the final energy demand in EU and represent by far the most significant energy sector to be decarbonized. Most of the thermal energy is used in buildings (space heating segment including private, commercial and public) and industry (process segment). One third of the heat required for heating industrial processes corresponds to low-temperature heat, i.e. below 200°C.

The hydrogen demand in EU in 2020 was estimated at around 8.7Mt. The biggest share of hydrogen demand came from refineries, which were responsible for 50% of total hydrogen use (~4.4 Mt), followed by the ammonia industry with 29% (~2.5 Mt). Emerging "decarbonisation" applications, like transport, accounted for less than 0.1% of the market. The REPowerEU plan sets a target of 20Mt of renewable hydrogen use by 2030, a 3-fold increase when compared with the Fit for 55 program. Refining and ammonia are still predicted to take a big share of the hydrogen demand but other uses are also considered, such as transport, blast furnaces and synthetic fuel production.

The TANDEM project configured two hybrid energy systems consistently with European energy needs and priorities, heat, electricity and hydrogen supply [2]. These two configurations (Fig. 2) are the baseline of the different study cases and architectures to be studied in the project:

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[1] https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52022SC0230&from=EN

[2] https://heatroadmap.eu/

— a *District Heating configuration,* for district heating and power supply at a significant local scale, e.g., for a large urban area;
— *A Energy Hub configuration,* where multiple energy carriers issued from various energy sources can be converted, stored, and supplied for end-user segments.

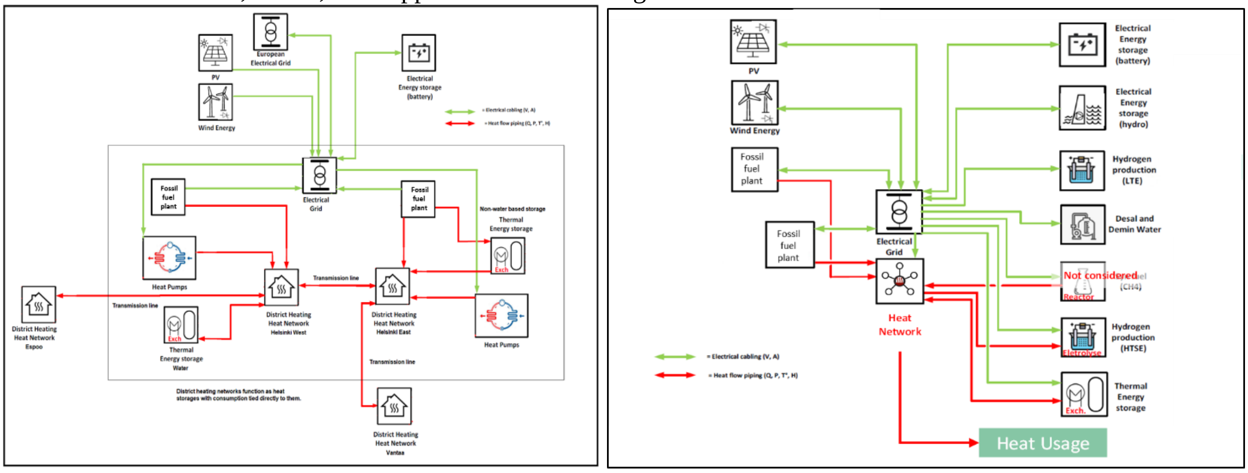

FIG. 2. Generic configuration of hybrid energy systems studied in TANDEM: left, district heating configuration; right, energy hub.

Fig. 2 shows the generic configuration of two hybrid energy systems with the reference architecture, which is to be decarbonized, as it is today. In the studies carried out in TANDEM, the architectures evolve progressively in order to meet the net-zero target: fossil energy sources are replaced by low carbon energy sources, SMR and renewables.

Based on the study of the state-of-the-art and ongoing developments [3], the technologies associated with the components of the hybrid energy systems have been defined in particular for:
— SMR: academic E-SMR concept[3] characterized in the framework of the ELSMOR[4] project.
— High Temperature Steam Electrolyzer for H_2 production: Solid Oxide Electrolyzer Cell.
— Low Temperature Electrolyzer for H_2 production: Polymer Electrolyte Membrane.
— Thermal Energy-Storage: two-tank system with thermal oil.
— Electrical energy storage: Li-ion, lead-acid, Vanadium Redox Battery or Sodium-Sulphur Batteries.

2.2. Development of a hybrid energy system simulator

In the framework of the TANDEM project, a set of modelling tools is being developed with the purpose of increase the knowledge about the dynamics behaviour and safety of hybrid energy systems. A TANDEM open-source, Modelica-based, library is under development [4] to analyze, compare and optimize the hybrid energy systems from a technical point of view, especially under operational transients. The 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:
1. SMR: a) Nuclear Steam Supply System; b) Balance of Plant and Power Conversion System.
2. Combined Cycle Gas Turbine (simplified).
3. Heat pump (simplified).
4. Electrical Grid.
5. District Heating Network.
6. Storage : a) Thermal; b) Electrical (simplified).
7. Desalination (simplified).
8. H_2 production: a) Low temperature electrolizer (simplified); b) High temperature steam electrolyzer.

The components labelled as “simplified” above can be treated as a black box, providing the amount of produced commodity with a certain power flow in input, for example. The other models in the library are physics-

[3] E-SMR dataset available at https://etsin.fairdata.fi/dataset/00b62da2-7b96-4e70-82ef-1e8afaa0ecb1

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

based. The library, by coupling of different components, will enable to build a hybrid energy system simulator, for the simulation of the dynamic behaviour of the system.

As for the safety analysis, a ATHLET [5] and CATHARE [6] modelling of the nuclear island has been developed to be coupled with models of Balance of Plants and Power Conversion Systems present in the TANDEM Modelica library in order to assess possible additional safety concern coming from the hybridization from a modelling point of view. 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. APPROACH TO ASSESS THE SAFETY OF SMRS INTEGRATED INTO HYBRID ENERGY SYSTEMS

The use of nuclear power plants for cogeneration has been effective for many years in several countries [7], mainly for desalination and district heating applications. These configurations have often been considered as the juxtaposition of two industrial processes with a customer-supplier relationship and a small number of interfaces. The risk analyses are independent, 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 (very) high temperature reactors ((V)HTR); the related Euratom projects (EUROPAIRS, NC2I-R and GEMINI+) [8] [9] provided useful general safety considerations for nuclear co-/poly-generation.

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. 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 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 to consider “hybridization transients” with regard to the usual assessment of hazards [10]. 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 Design Basic Conditions (DBC) which could be affected by the coupling between the SMR and the rest of the energy system, or potential new DBC.

(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 [11] 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 study are already done for the nuclear plant itself, and should be sufficient for the hybrid configuration.

The deterministic safety analysis therefore consists in studying the event initiators specific to the hybridization combining the SMR reactor and its balance of plant, with the additional non-nuclear components of the system. Several transients have been identified by TANDEM as relevant for analyzing the impact of hybridization on nuclear reactor behaviour, inducing potentially new safety considerations:

- A normal operation transient: a load rejection transient that successfully leads to house load operation.
- Anticipated Operational Occurrence transients, such as a rapid increase or decrease of the thermal demand by end-users, a loss of thermal storage, a loss of hydrogen production.
- A Design Basis Accident: a load rejection transient that fails, leading to a loss of off-site power scenario.

These transients are characterized by a significant coupling between the Nuclear Steam Supply System and the Balance of Plant and downstream non-nuclear applications. They will be simulated with a coupling between reference safety codes ATHLET and CATHARE, and components of the Modelica-based hybrid energy system simulator.

4. STUDIES ILLUSTRATING THE ASSESSMENT OF TECHNO-ECONOMICS AND ENVIRONMENTAL IMPACT

Three study cases were derived from the two hybrid energy system configurations defined in Section 3, as demonstrative practical cases to carry out studies on techno-economics and environmental impact. Note that the study cases are of a working nature for the purposes of the TANDEM project and do not have the ambition to define real future plans supporting decarbonization with the construction of SMRs. The E-SMR reactor (total 540 MWth/170MWe power) is the SMR use-case implemented by TANDEM in its studies of hybrid energy systems.

The study cases have to be defined in the light of a specific regional context, depending on local resources, geography, energy markets and policy, and industry, to perform a relevant sizing and assessment. To illustrate this point, the choice of heating solutions depends on the area where district heating is used. District heating is an interesting solution in Northern and Central Europe. 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 [12] concerns a district heating system in the metropolitan area of Helsinki, the capital of Finland, which includes the large cities of Espoo (population of 293,000) and Vantaa (population of 237,000). District heating production in each city is handled by separate companies: Helen Ltd. in Helsinki, Fortum Ltd. in Espoo, and Vantaa Energia Ltd. in Vantaa. The district heating networks of Espoo and Vantaa are connected to the Helsinki district heating network with limited transfer capacity. Currently, the district heating supply in Helsinki and Espoo relies on natural gas and coal-fired units, although the use of heat pumps and biomass is increasing. Waste incineration in Vantaa produces a significant amount of energy demand in the area, about half of the district heat demand and 30 % of the electricity demand.

The aim of the Central European case [12] is to propose i) a way 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" in the Moravian-Silesian region in Czech Republic. This region is highly industrialized with a large rate of CO_2 emission. The most significant carbon-emitters are mainly large stationary sources e.g. iron and steel industry (Třinec, Vítkovice and Ostrava), power plants (Dětmarovice and Třebovice) and heating plants (Karviná and ČSA). In the whole Moravian-Silesian region, more than 214,000 flats are supplied with heat from district heating. There are 1238.9 km of heating networks. The most optimal solution for Central European case study is to interconnect several heat networks (Bohumín/Orlová and DHN Havířov/Karviná) and supply these connected systems with heat from SMRs deployed in Dětmarovice site.

The study case for the energy hub configuration is inspired from an harbour-like infrastructure in France. In Europe, there are several examples of industrialized harbours, responsible of a high rate of CO_2 emissions and involved now in a process of decarbonization. The port of Rotterdam is the first European port considering the Twenty-Foot Equivalent (TFE) criteria[5] with 14.5 TFE in 2020 and it is responsible for about 20% of the national CO_2 emissions of the Netherlands. Since 2016, the port of Rotterdam has started to build a decarbonization strategy that resulted in the 2019 Rotterdam Climate Agreement. The French industrial port zones of Dunkirk and Fos-sur-Mer are also involved in a decarbonization process. They are the winners of the "low-carbon industrial zones" call for projects launched as part of the France 2030 plan[6]. The port of Dunkirk contributes to 21% of the French CO_2 emissions due to the industrial sector. Various complex energy fluxes exist in these ports. There are

[5] It is a general unit of cargo capacity, often used for container ships and container ports

[6] With a budget of €54 billion, France 2030 is an investment plan aiming to sustainably transform the key sectors of the French economy (energy, automotive, aeronautics or space) through research, innovation and industrial investment. 50% of France 2030's credits are dedicated to emerging stakeholders with environmentally friendly innovations, and 50% to decarbonise the economy.

several energy producers (depending on the ports, it can be a nuclear power plant, fossil fuel plants, waste recovery plants, wind farms, photovoltaics), hydrogen producers and several energy consumers, potentially including a district heating network in the area, and a lot of industrial end-users in different sectors, such as steel industry, chemical industries, refineries. Due to the difficulties of accessing the detailed characteristics of these energy fluxes, involving several industrials in existing European ports, it was decided to arbitrarily set an initial architecture [12] involving a Combined Cycle Gas Turbine (CCGT), a photovoltaics field, an offshore wind farm, and energy storage systems, to produce constant hydrogen and electricity loads (72.3 ktons of hydrogen and 657 GWh of electricity per year, as a baseline, but which can easily be scaled up) for the definition of the study case.

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, and replacing progressively fossil fuel plants by low-carbon energy sources, SMRs and renewables, so as to decarbonize the system. The Backbone [13] and PERSEE [14] tools, respectively developed by VTT and CEA, have been implemented to analyse the three study cases. An illustration of the energy hub study with PERSEE is given in Fig. 3. The study is conducted with a 20 year lifetime project (considering a discount rate of 5%) with a hourly one-year simulation and taking into account a residual value for the E-SMR and CCGT components. The E-SMR reactors are operated at full load in cogeneration mode with a fix ratio of about 10% for heat extraction from the reactor, meaning that the reactor delivers 155 MWe electricity and 50 MWth heat. In the study, an optimization process is implemented in PERSEE: it is based on the minimization of a single objective function (the total costs) by finding an optimal sizing of system components. Fourteen optimal states have been run by increasingly limiting CO_2 intensity (considering both CO_2 grey and direct emissions). The results cannot be detailed in this paper; the whole analysis of three study cases is summarized in [12].

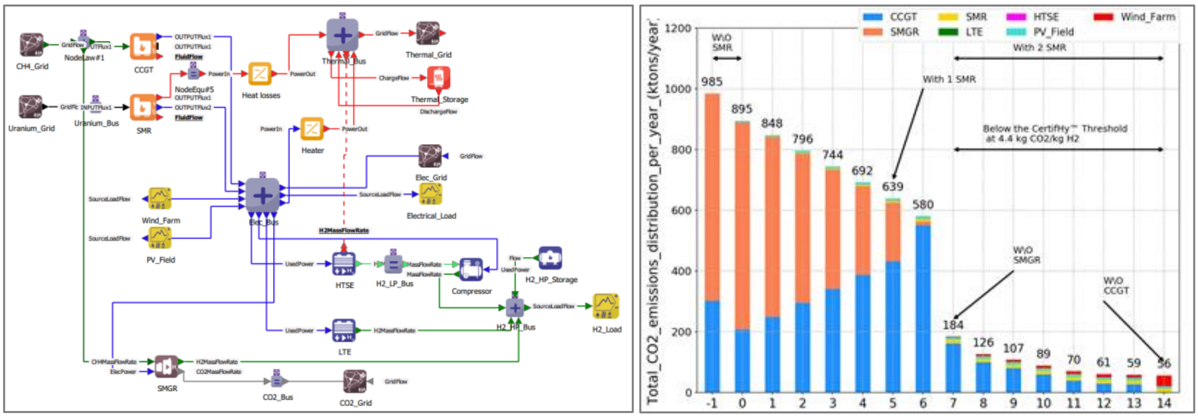

FIG. 3: Study of the energy hub with PERSEE: left, representation of the global architecture; right, total CO2 emissions per year for the energy hub (W/O SMGR means "Without Steam Methane Gas Reforming" for hydrogen production).

5. CONCLUSION

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, and to provide illustrative results from the assessment of hybrid energy systems. At project mid-term, two hybrid energy system have been configured, consistently with European energy needs and priorities: a district heating configuration and an energy hub. A TANDEM open-source Modelica library has been developed; it gathers the numerical models of hybrid energy system components, which will be coupled to build a hybrid energy system simulator in the last part of the project. The safety methodology which has to be implemented when SMRs are integrated into hybrid energy systems, operating in cogeneration mode to produce heat, electricity and hydrogen, has been clarified. Several transients under normal, off-normal and accident conditions, have been identified by the project as relevant for analyzing the impact of hybridization on nuclear reactor behaviour, inducing potentially new safety considerations; they result from the interaction between the SMR and energy applications. The safety analysis relies on the transient simulation; modeling development of these transients with system thermal-hydraulics codes (ATHLET and CATHARE) coupled with the hybrid energy system model of the system rest is ongoing. Besides, three study cases were derived from the two configurations of hybrid energy system; the components of these study cases were sized using a cost and environmental impact optimization process. Sensitivity studies to input parameters are ongoing to complete the analyses of the three study cases.

At the end of last year, the project also launched activities for assessing citizen engagement, which is very important in the preparation of SMR deployment, beyond technical and economic considerations. A first workshop will be organized in 2024 in Finland, to increase citizens' understanding of SMR technology and to study how European citizens perceive the benefits, potential and risks of SMRs for electrical and non-electrical applications.

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/).

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