The TANDEM Euratom project

« Small Modular ReacTor for a European sAfe aNd Decarbonized Energy Mix »

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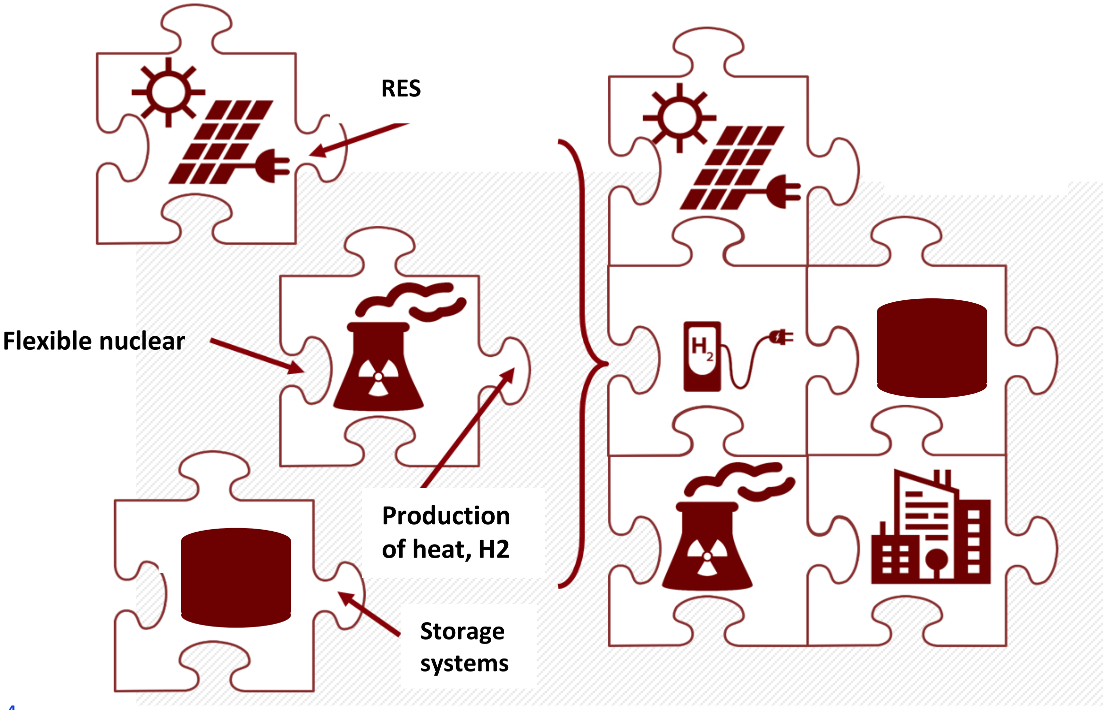
Outline

- Context and main features of the project
- Project work program
- Some results of the project

Context and main features of the project

General question addressed by the TANDEM project



How can we combine all low-carbon energy sources, thermal and electrical storage systems and the production of energy carriers to meet energy demand in the future sustainable, reliable and affordable energy mix ?

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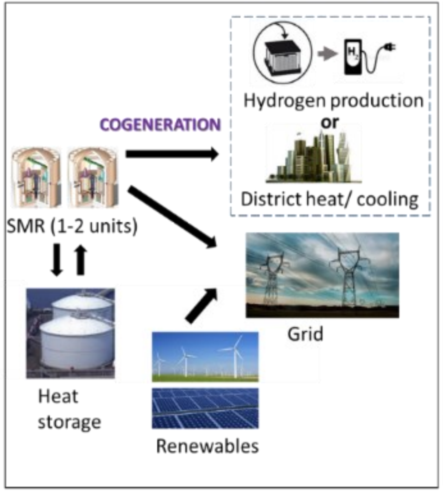
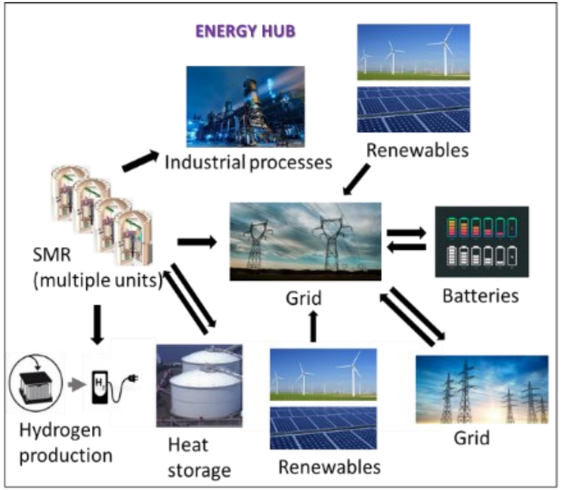
Need to study Hybrid Energy Systems



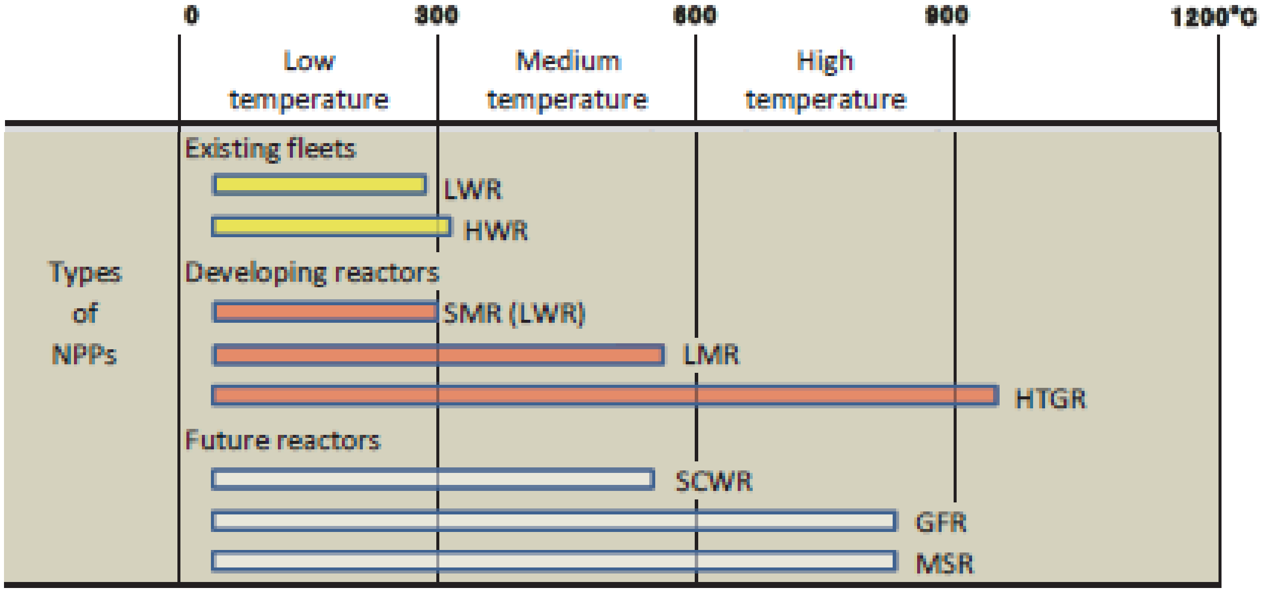


Multipurpose SMRs for electrical and non-electrical applications are well suited to operate flexibly in ***tandem*** with other energy sources and energy storage systems to provide **electricity, heat and hydrogen**. Thus SMRs can **be "hybridized"** with other energy sources, storage systems and energy conversion applications; they are **integrated into hybrid energy systems.**

Integrated vision of the energy mix

=> New topics to be adressed due to the system approach: nuclear safety, flexibility of energy production, techno-economics, environmental impact, citizen engagement, etc.

Working temperature ranges for different nuclear technologies



Note: GFR — gas cooled fast reactor; HTGR — high temperature gas reactor; HWR — heavy water reactor; LMR — liquid metal reactor; LWR — light water reactor; MSR — molten salt reactor; NPP — nuclear power plant; SCWR — supercritical water reactor; SMR — small modular reactor.

Source: AIEA, Opportunities for cogeneration with nuclear energy, No NP-T-4.1, 2017

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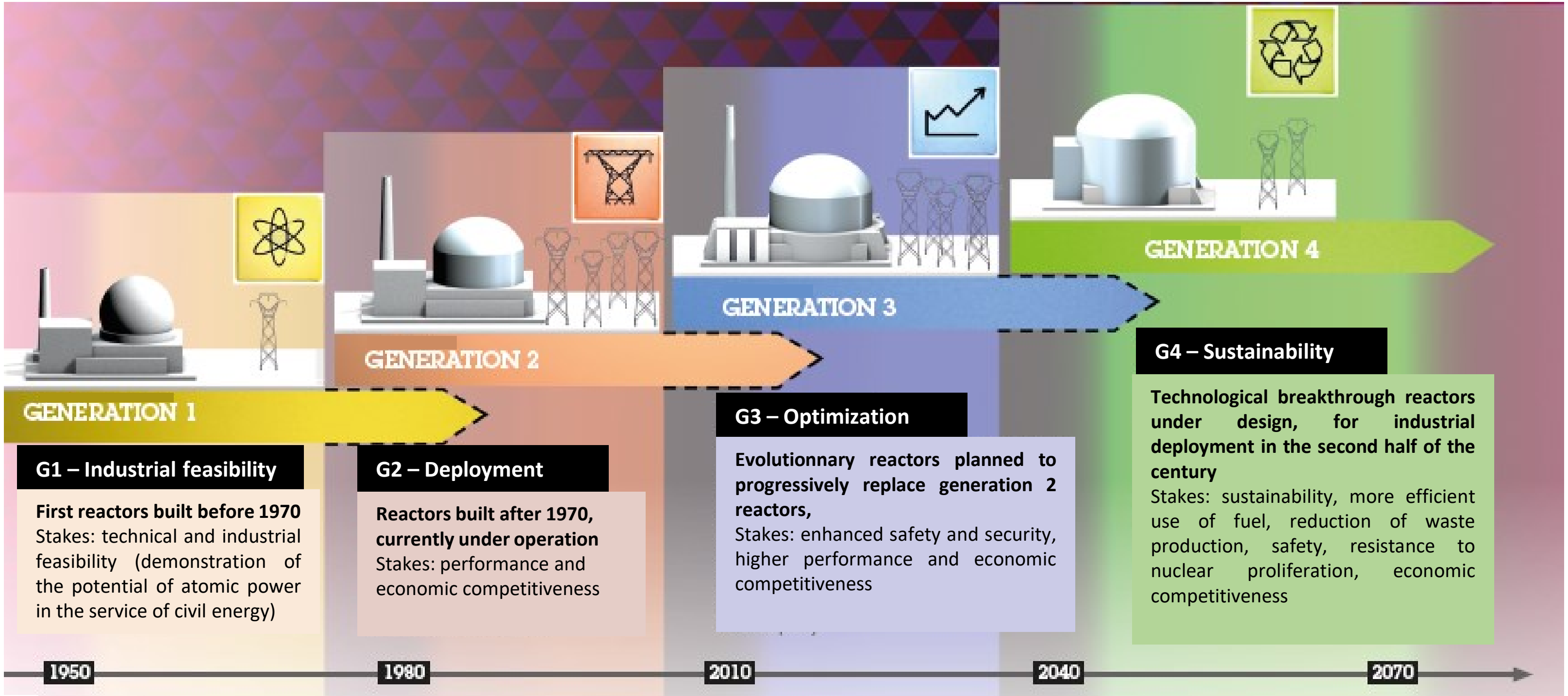
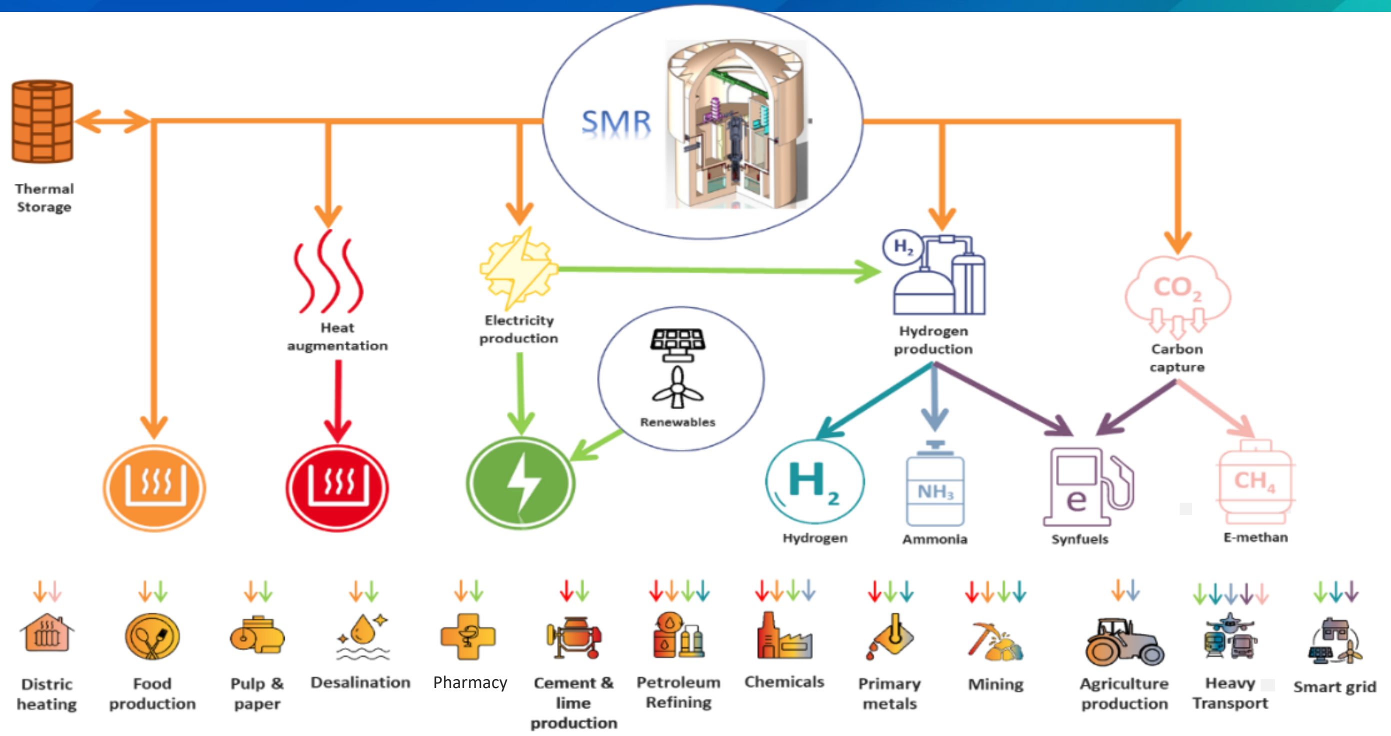
Different generations of nuclear reactors



Source: Filières et générations de réacteurs nucléaires (cea.fr)

Illustration of potential industrial applications for direct electrical and thermal coupling with SMRs



Source: Ph. Amphoux et al, « IDNES, a CEA project dedicated to SMR concepts for decarbonization beyond pure power generation, Proc. Int Conf. IAEA on SMR and their applications, Vienna, Austria, October 2024.

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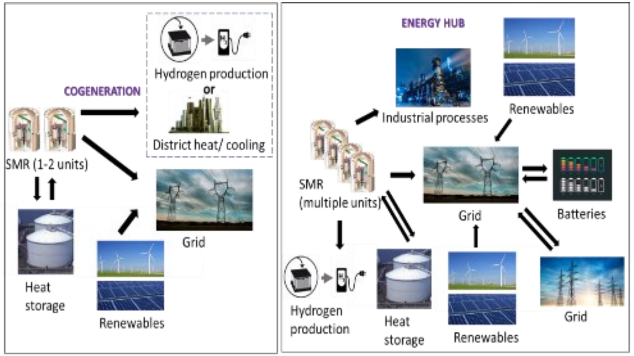
Objectives and ambitions of the TANDEM project

TANDEM: Small Modular ReacTor for a European sAfe aNd Decarbonized Energy Mix

High-level objectives:

- Assess the **safety compliance** of **SMRs** to be **integrated** in the future European energy mix
- Provide **guidance in a deployment perspective** for the future integration of SMRs and AMRs into well-balanced hybrid energy systems
- **Create an enabling environment** for the development of hybrid energy systems based on SMRs and AMRs



Ambitions of TANDEM:

- **Promote versatile SMRs integrated into hybrid energy systems** as reliable, resilient, and affordable clean energy options in Europe
- **Become a pioneer initiative** in gathering efforts and expertise around the development of SMR integration into hybrid energy systems in Europe

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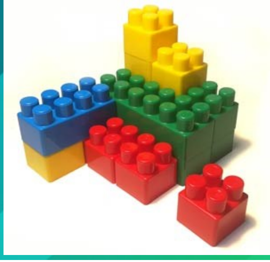
SMR use-case in TANDEM

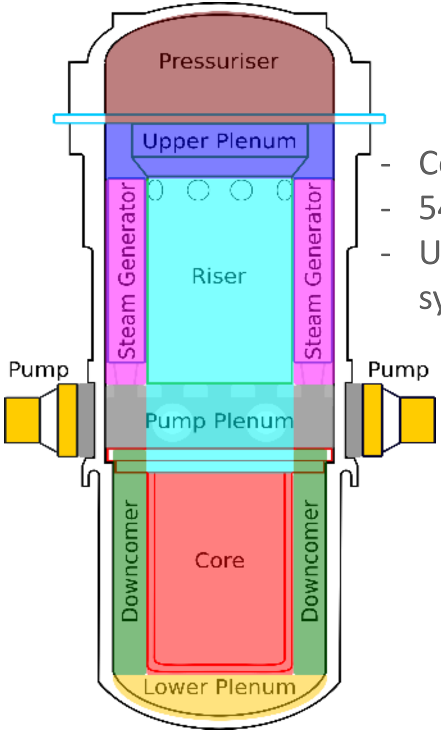


SMR use-case in TANDEM: the light-water E-SMR academic concept developed by POLIMI, GRS and VTT in the framework of the ELSMOR Euratom project.

ELSMOR
Towards European Licensing of Small Modular Reactors

http://www.elsmor.eu/

E-SMR dataset open and available:
https://etsin.fairdata.fi/dataset/00b62da2-7b96-4e70-82ef-1e8afaa0ecb1/data



- Compact design
- 540 MWth/170MWe
- Use of passive safety systems

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General description of the TANDEM project

- Submission of the project in October 2021 to a EURATOM call for EC funding (topic: NRT01-02 « Safety of advanced and innovative nuclear designs and fuels »)
- Project start: September 1, 2022
- Project duration: 36 months
- Budget: 3.8M€ (including EC grant: 3.4M€)
- Organization leading the project: CEA (French Alternative Energies and Atomic Energy Commission)

- For further information :
  Browse our website: https://tandemproject.eu/
  Follow us: https://www.linkedin.com/company/tandem-project-eu/

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What is the EURATOM program ?

- **EU's key funding program for nuclear research and innovation,** with a budget of 1.38 billion euros between 2021 and 2025. It stems from the Euratom Treaty establishing the European Atomic Energy Community, and was signed in 1957 in Rome, along with the Treaty establishing the European Economic Community.
- **Objectives of the EURATOM Research and Training program:**
  - ✓ To improve and support nuclear safety, security, safeguards, radiation protection, safe spent fuel and radioactive waste management and decommissioning, including the safe and secure use of nuclear power and of non-power applications of ionising radiation
  - ✓ To foster the development of fusion energy as a potential future energy source for electricity production
  - ✓ Fto acilitate collaboration and strengthen the impact of research and innovation in developing, supporting and implementing EU policies while tackling global challenges. It supports creating and better dispersing of knowledge and technologies.

TANDEM consortium

Belgium: European Commission, nucleareurope, TRACTEBEL ENGIE, enen

Czech Republic: ÚJV

Finland: VTT, fortum

France: cea, EDF, IRSN

Germany: GRS

Italy POLITECNICO MILANO 1863, UNIVERSITÀ DI PISA, ENEA, ansaldo nucleare

Spain: EMPRESARIOS AGRUPADOS

Ukraine: ENERGORISK

18 partners from 8 European countries, composed of:

universities, research institutes, TSO, industrials and engineering organizations

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Project work program

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Overall methodology and expected outcomes

PHASE	ACTIVITIES	RELATED WP	OUTCOMES
PHASE 1 Identification of hybrid systems incorparating SMRs to study	**- Analysis of the European energy scenarios - Configuration of two hybrid systems for the selected scenarios**	WP1	Characterization of two hybrid energy systems to study
PHASE 2 Development and implementation of tools for SMR assessment	**Development of new tools, modelling in existing tools, numerical coupling between tools**	WP2 WP3	- TANDEM model library - Hybrid system simulator - CATHARE/ATHLET safety modelling - Coupling for safety /techno-economics
PHASE 3 Safety and feasibility studies for SMR integration into hybrid systems	**- Safety assessment - Techno-economics and operatinonality analysis - Citizen engagement**	WP3 WP4 WP5	Safety recommandations, technical and economical guidance, policy briefs, etc.
PHASE 4 Building enabling environment for future projects and initiatives	**- Scientific training - Interaction with SAC and IUG - Outreach activities - Organisation of workshops**	WP5 WP6 WP7	- Improved scientific cooperation - New project ideas identified - Increased public acceptance - Raised awareness of stakeholders

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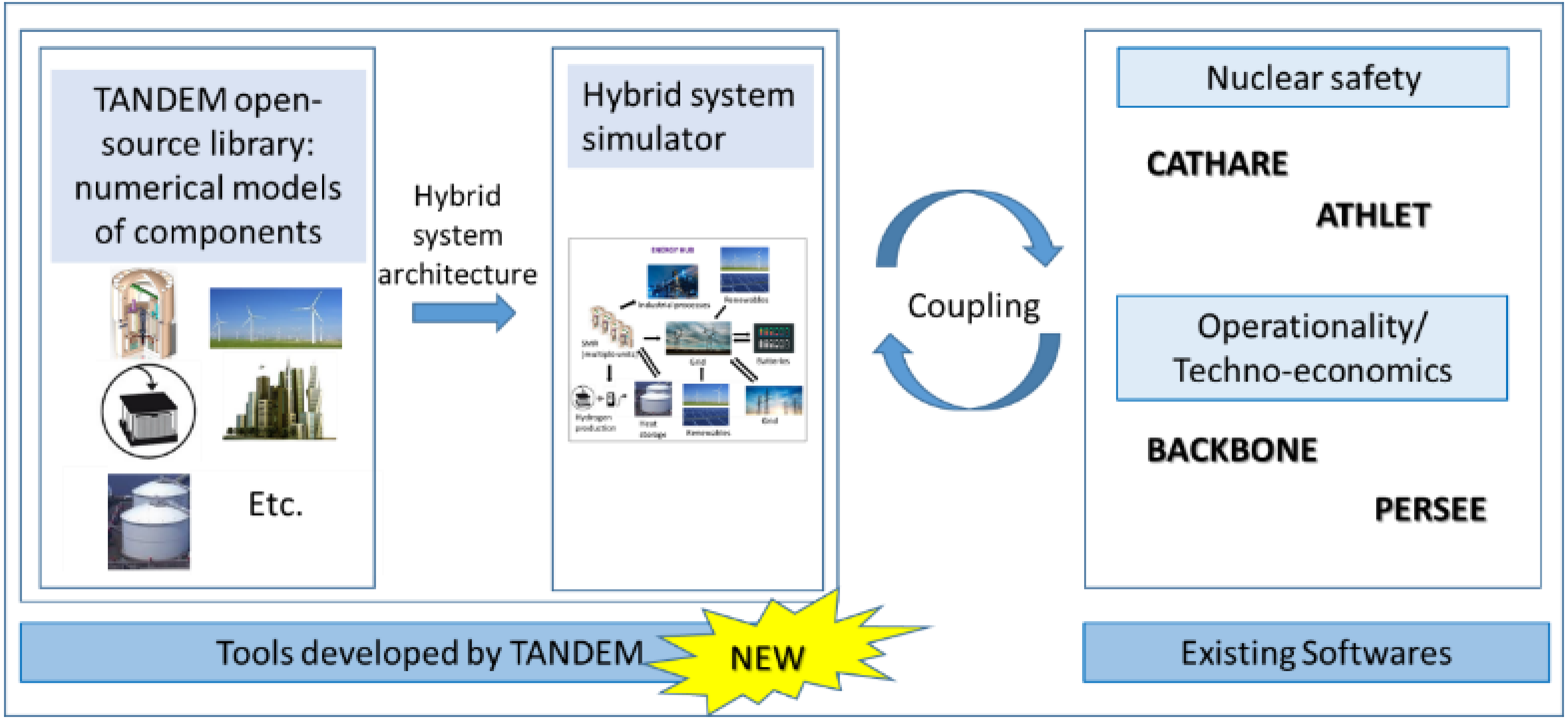
Modeling and simulation strategy implemented in TANDEM



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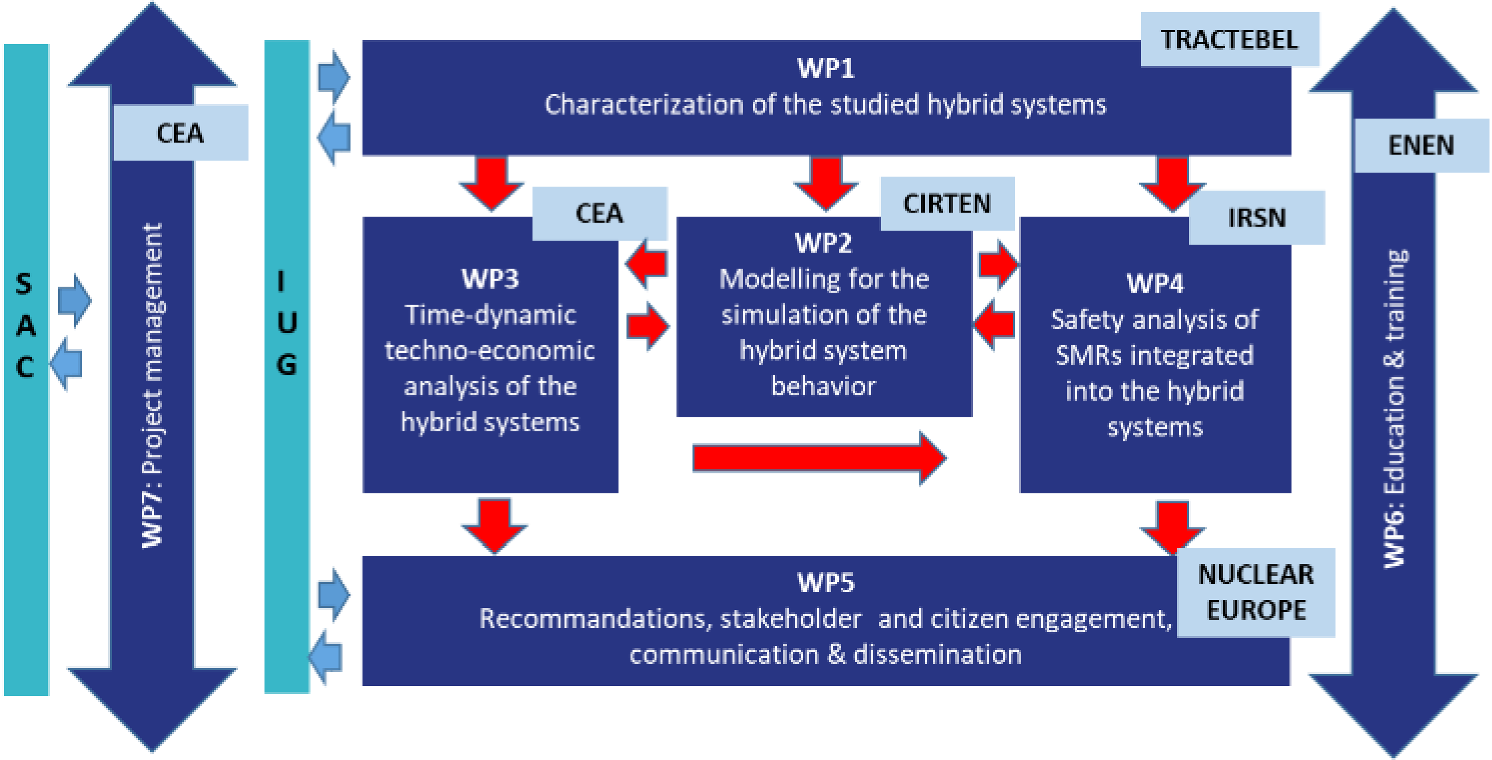
Work Package breakdown



Connection of TANDEM with various stakeholders and international initiatives

- **A Scientific Advisory Committe (SAC)**: representatives from IAEA, EC-JRC, INL, MIT

  Objective: 1/to provide feedback and recommendations on the results, scientific choices and directions of the project; 2/ support interactions with other European and international initiatives which the SAC members are involved in and which are related to the activities of the project

- **An Industrial User Group (IUG)**: a dozen of members

  Objective: to engage with TANDEM in a constructive dialogue around: 1/ the technological feasibility of the hybrid energy systems incorporating SMRs, 2/ the different energy markets and their particularities, 3/ regulatory, societal and economic issues related to the implementation of such systems.

- **Other Euratom projects on SMR safety and nuclear cogeneration**, such as ELSMOR, SASPAM, GEMINI 4.0, NPHyCo, ESFR-SIMPLE, SANE.

- **Other international initiatives**, such as the IEA/Task Force 44 on HYdrogen from Nuclear Energy (HYNE)

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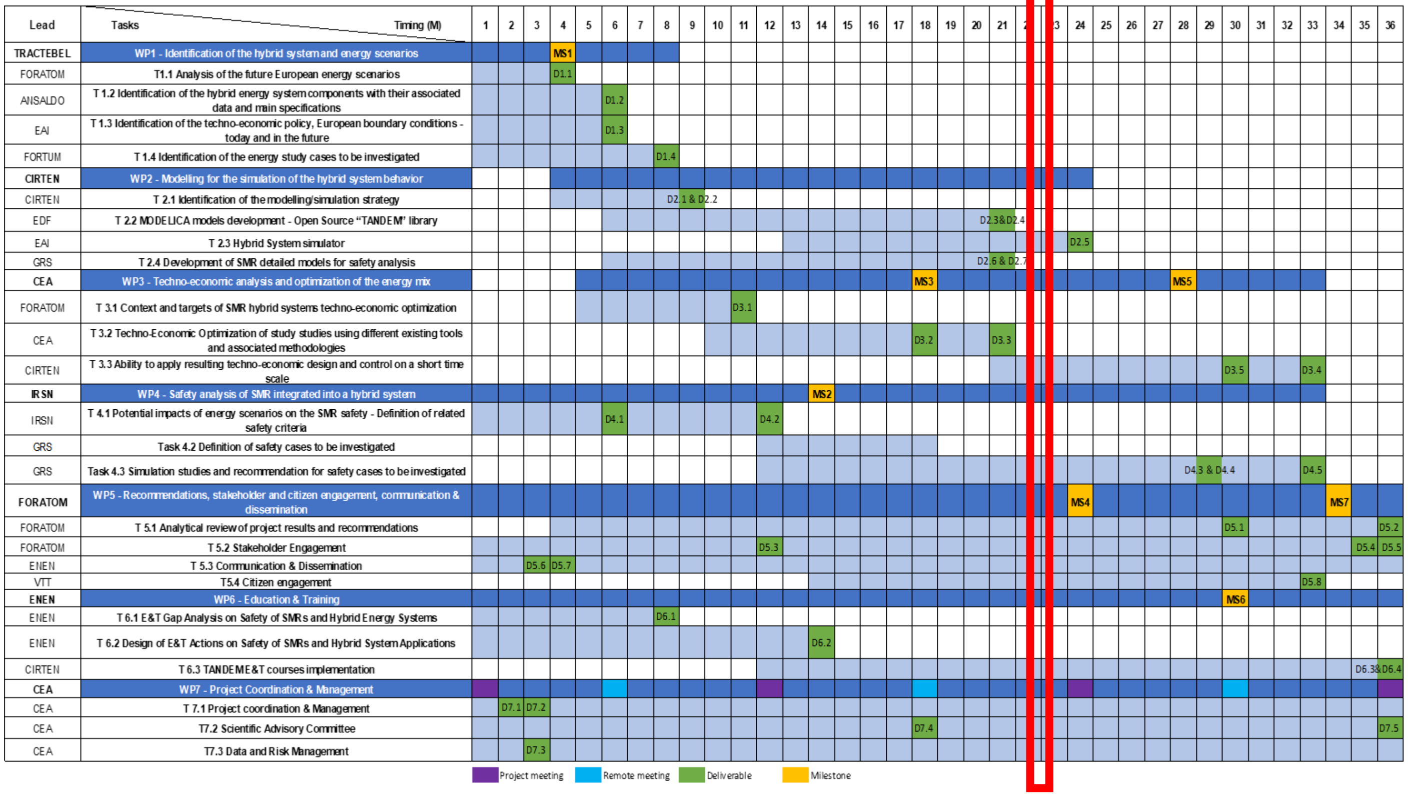
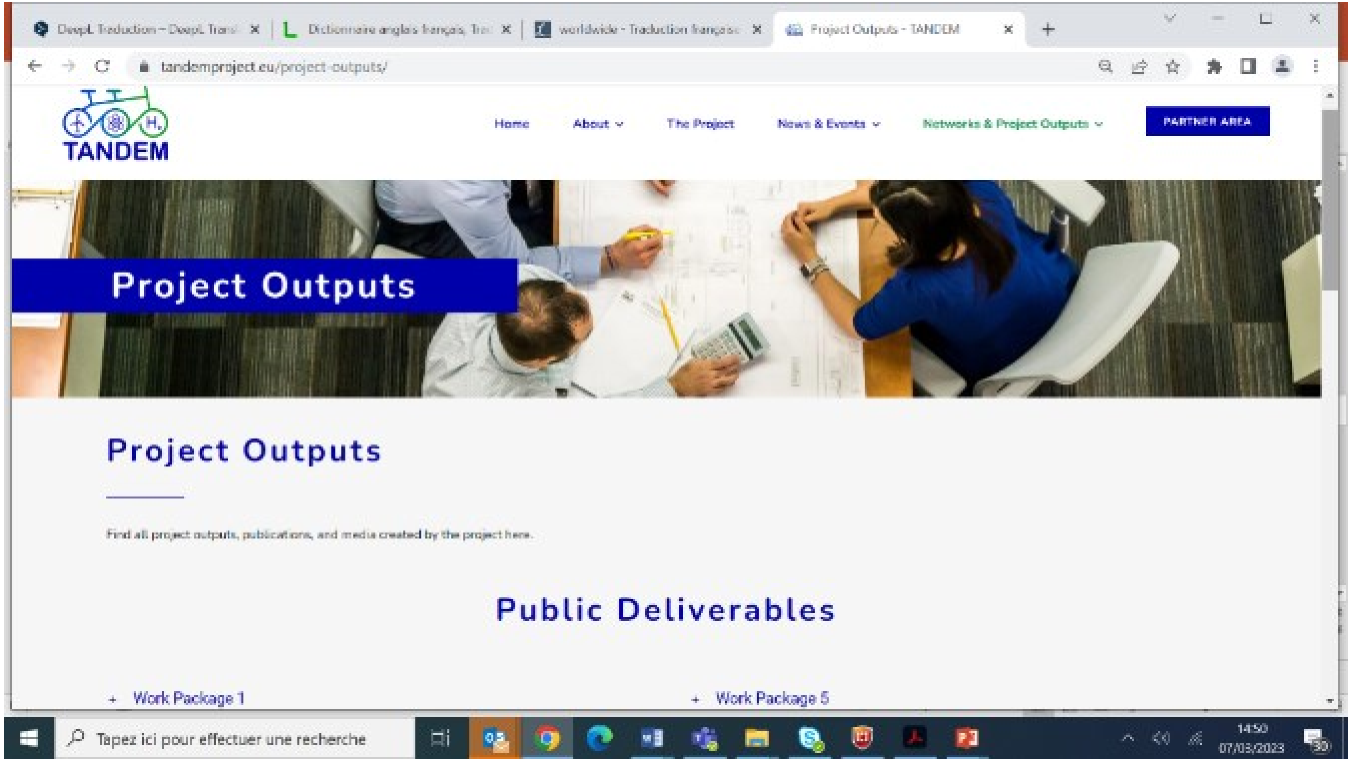
TANDEM Gantt Chart



To access TANDEM deliverables



All our deliverables (or almost) for the European Commission are public.

They are available on our website: https://tandemproject.eu/

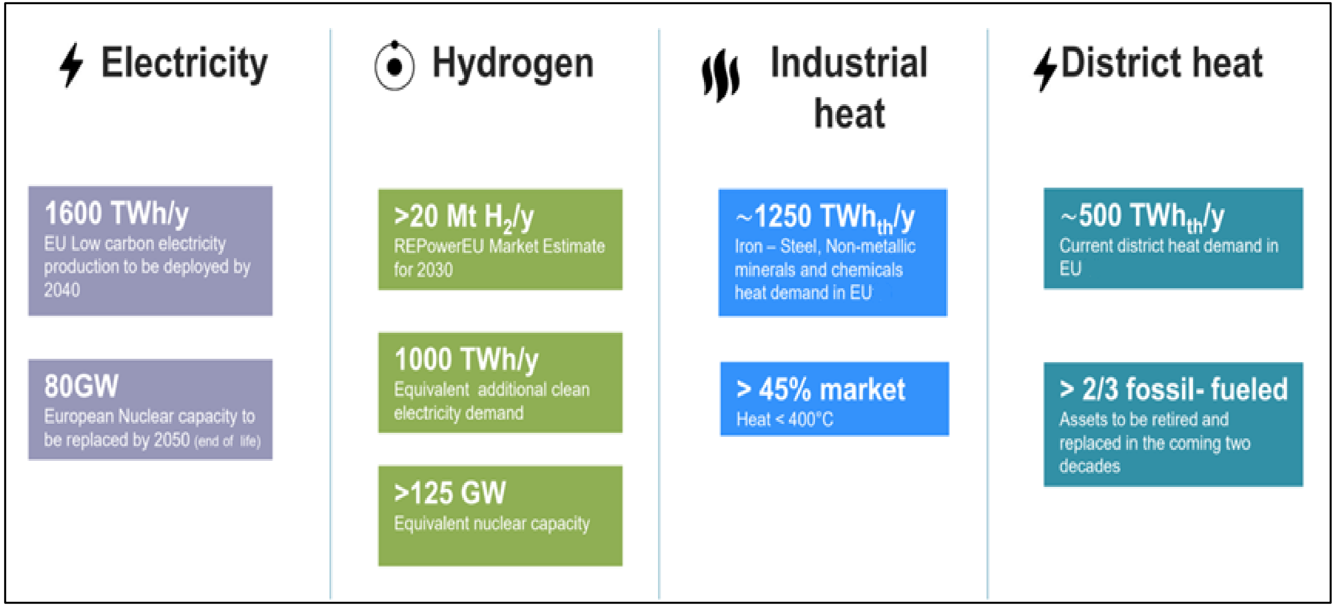
Some results of the TANDEM project:

1/ Energy context in EU and HES configuration

2/ Brief illustration of techno-economics studies
3/ Specific safety considerations for SMRs integrated into HES

Analysis of the energy context: EU energy needs and priorities

Energy market needs in EU



Source: TANDEM/Deliverable 1.3

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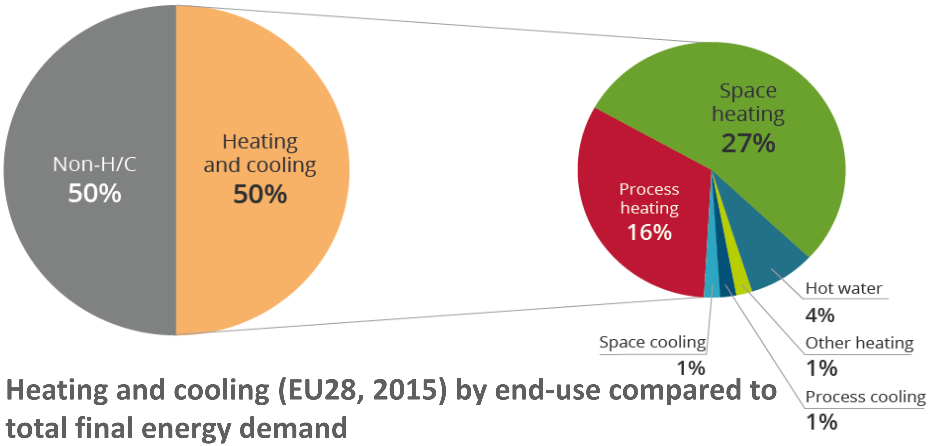
Analysis of the energy context: EU energy needs and priorities

❑ Objectives set by the European Commission for climate (Fit for 55 package, 2021):
- In 2030: reduction of greenhouse gas emission by 55%
- In 2050: carbon-neutrality

❑ Heating and cooling: current needs



Heating and cooling (EU28, 2015) by end-use compared to total final energy demand
Source : Heat Roadpmap Europe

❑ Hydrogen: projection needs

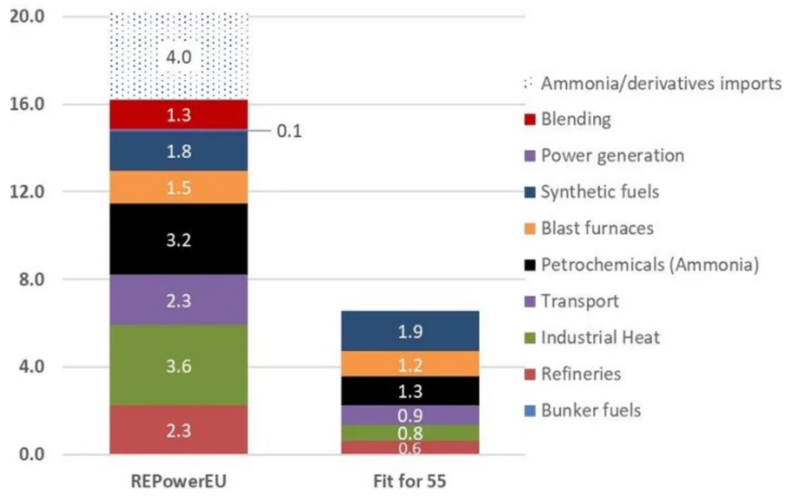


Illustration through the use of green hydrogen in 2030
Source : REPowerEU Plan

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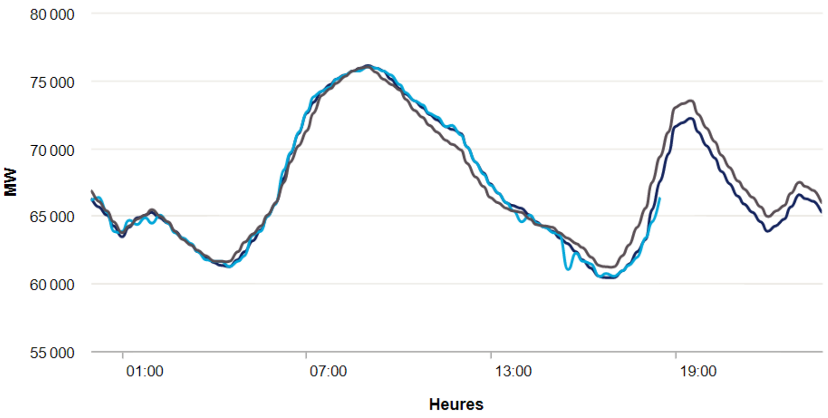
Need of flexibility for power supply on the grid: illustration with the French power consumption

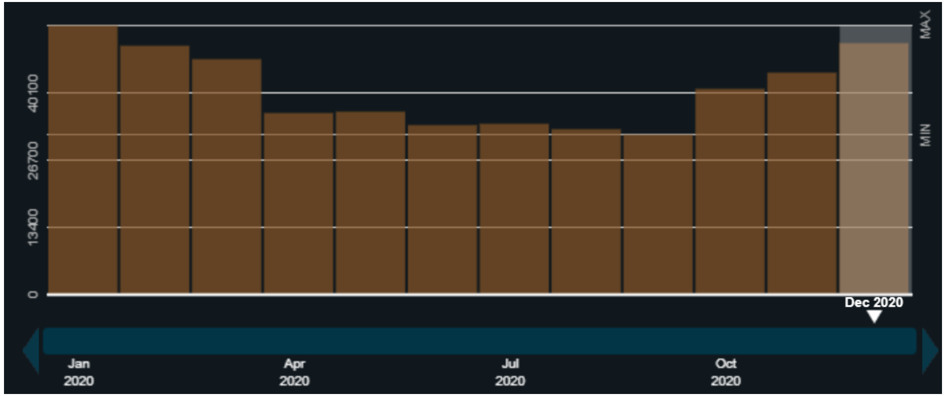
Daily variations



Power consumption in France, on March 2, 2023
Source : RTE (French power transmission system operator)

(fluctuation: 25%)

Seasonal variations



Power consumption in France in 2020 (en GWh)
Max : 53404 GWh in January/ Min : 33773 GWh in August
Source : RTE

(fluctuation: 37%)

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Hybrid energy system configurations analyzed in the project

Two distinct configurations of hybrid energy systems:

- **District Heating configuration**: the hybrid energy system for district heating and power supply is envisaged at a local scale, e.g., for a large urban area. Overall, the primary goal is to decarbonise the production of heat and electricity with emphasis on heating;
- **Energy Hub configuration**: it is a hybrid energy system concept where multiple energy carriers issued from various energy sources can be converted, stored, and supplied for end-user segments.

Two timeframes and a total of three energy contexts considered for the hybrid energy systems analysed by TANDEM:

- **2035 with no SMR deployment** (energy sources: renewables and fossil-fuel fired plants)
- **2035 with the start of SMR deployment** (energy sources: renewables, SMRs and fossil-fuel fired plants)
- **2050 with no fossil-fuel fired plants** (energy sources: renewables and SMRs)

Source: TANDEM/Deliverable 1.4

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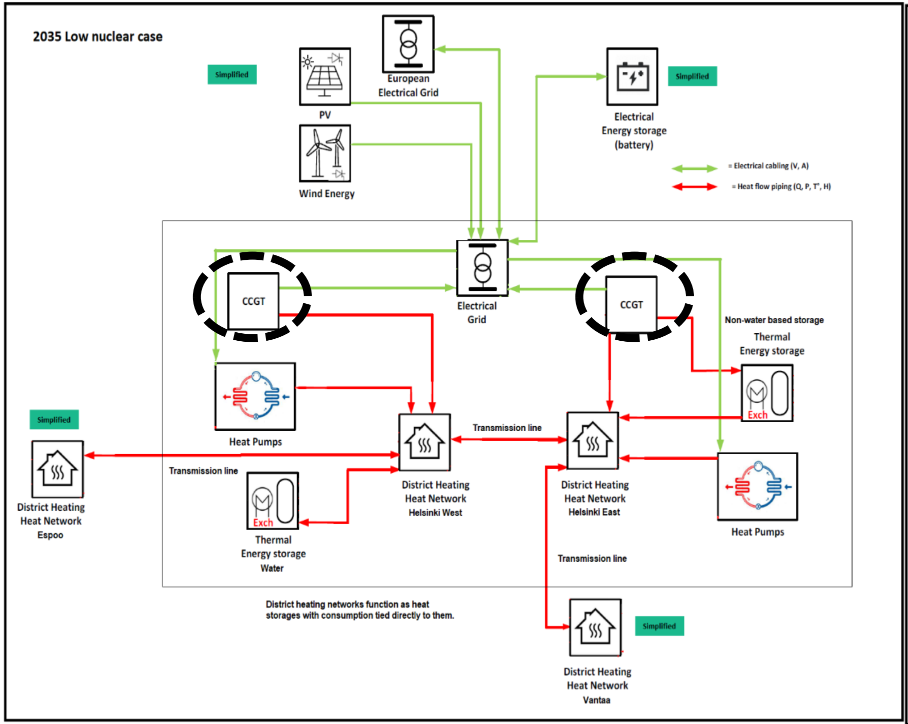
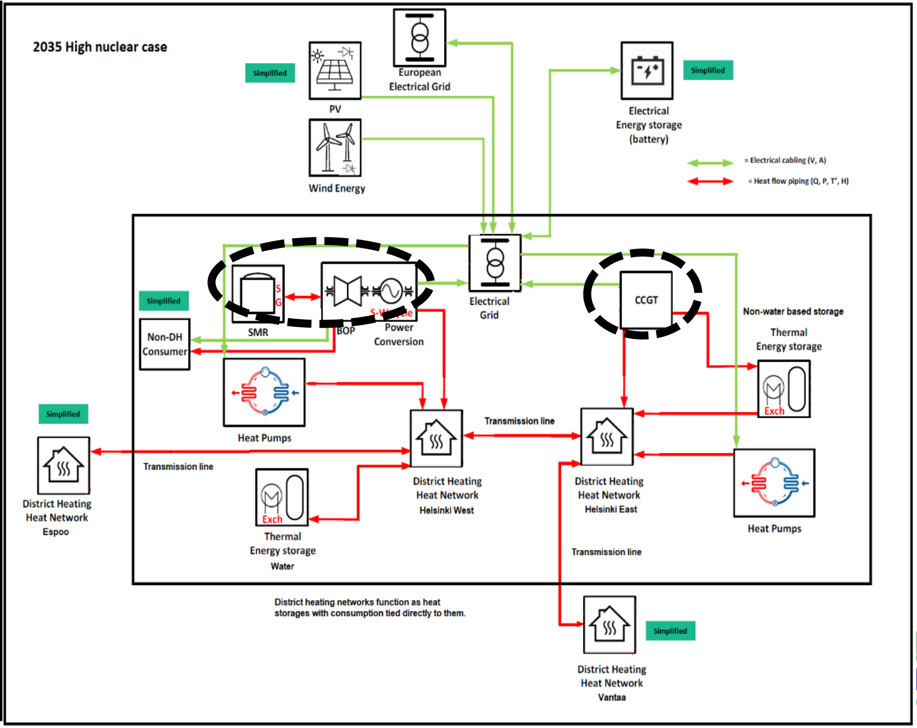
District heating configuration in 2035 (Finland case)





Source: TANDEM/Deliverable 1.4

Case studies for the District Heating configuration

The study of the district heating configuration depends on the local context in Europe.

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 with growth for specific technology deployment conditioned by national resource limits. Two variation case studies in TANDEM have been studied. They are based on specific regional needs and policies in:

- Nordics => study of an energy system in Finland,
- Central Europe => study of an energy system in Czech Republic.

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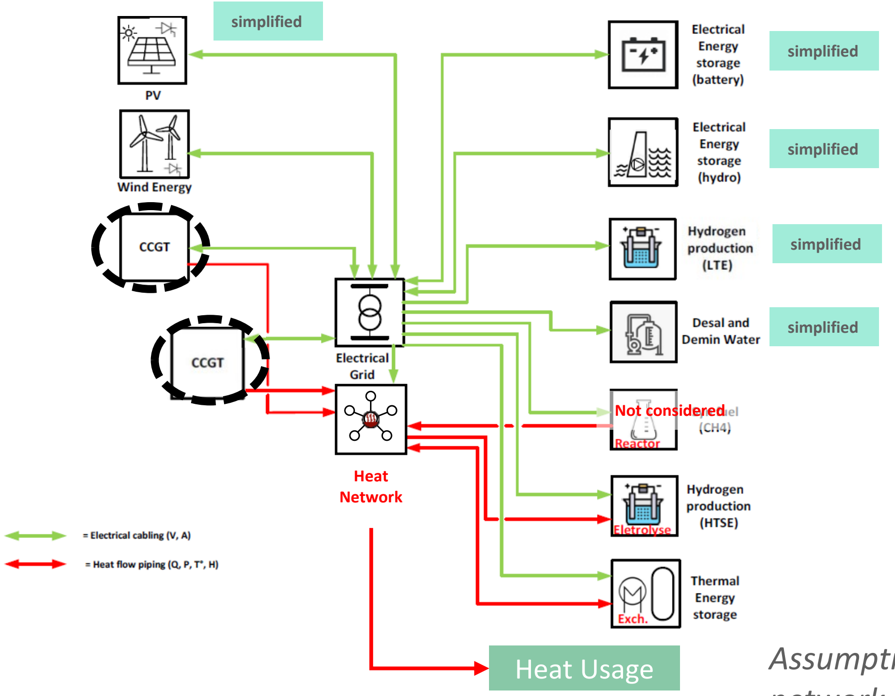
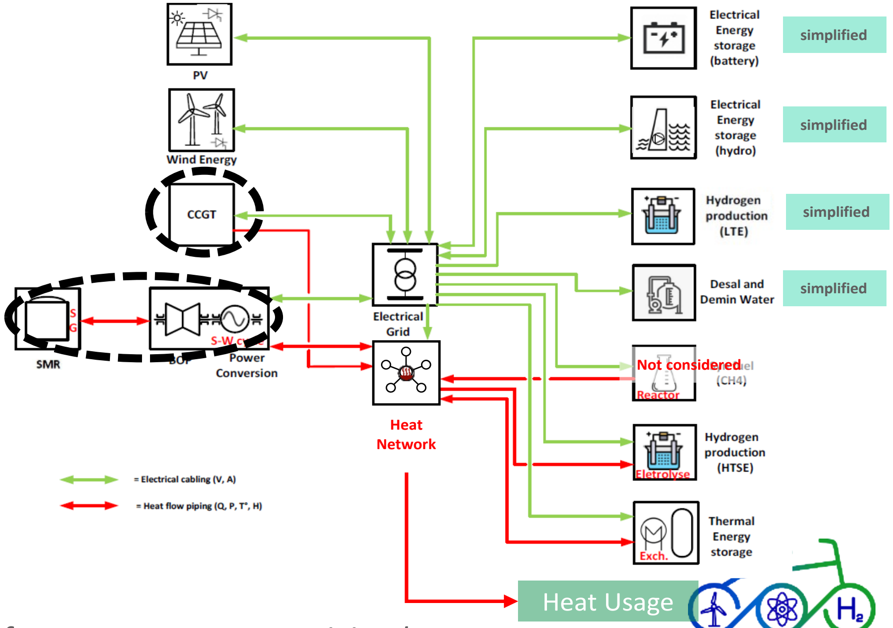
Energy Hub configuration in 2035

Low SMR deployment



High SMR deployment



Assumption for component connectivity: heat network and power grid

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Source: TANDEM/Deliverable 1.4

Case studies for the Energy Hub configuration

The study case must be aligned with the decarbonization goals of net-zero transition and hence, typical end-user segments beyond pure power grid supply are to be considered :

- Hydrogen production as a must with respect to current market evolution,
- Additional industrial end-uses can be added like demineralized water production,
- Additional conventional end-uses can be added like heat supply to local buildings or local industry processes.

The case study for the Energy Hub is a **virtual harbour** located in Southern Europe.

For demonstration purposes and in order to keep a good balance between modelling complexity and representativeness of the energy hub architecture, only electrical power and heat are considered as distributed energy carrier fluxes.

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Some results of the TANDEM project:

1/ Energy context in EU and HES configuration

2/ Brief illustration of techno-economics studies

3/ Specific safety considerations for SMRs integrated into HES

Illustration of techno-economics studies for the energy hub

- Due to the difficulties of accessing the detailed characteristics of the energy fluxes involving several industrials in existing European harbours, it was decided to arbitrarily set an initial architecture involving a 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.
- In the study, optimization process implemented in the PERSEE* tool: it is based on the minimization of a single objective function (the total costs) by finding an optimal sizing of system components.
- Study conducted with a 20 year lifetime project with a hourly one-year simulation
- E-SMR reactors operate at full load in cogeneration mode with a fix ratio of about 10% for heat extraction from the reactor.
- Fourteen optimal states have been run by increasingly limiting CO_2 intensity (considering both CO_2 grey and direct emissions).

* RUBY, A., CREVON, S., PARMENTIER, P, GAOUA, Y., LAVIALLE, G., "PERSEE, a single tool for various optimizations of multi-carrier energy system sizing and operation", Proc. Int. Conf. ECOS 2024, Rhodes, Greece

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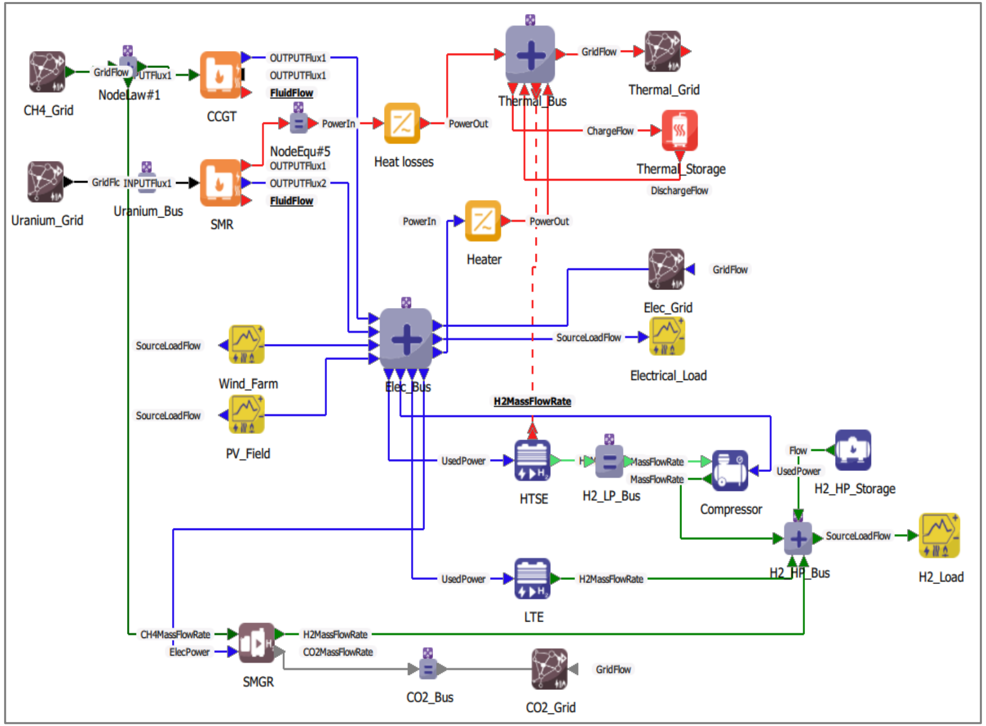
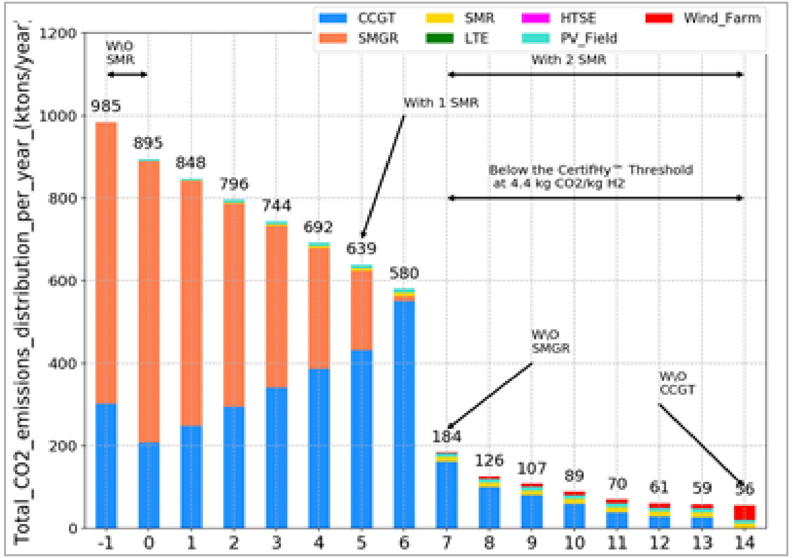
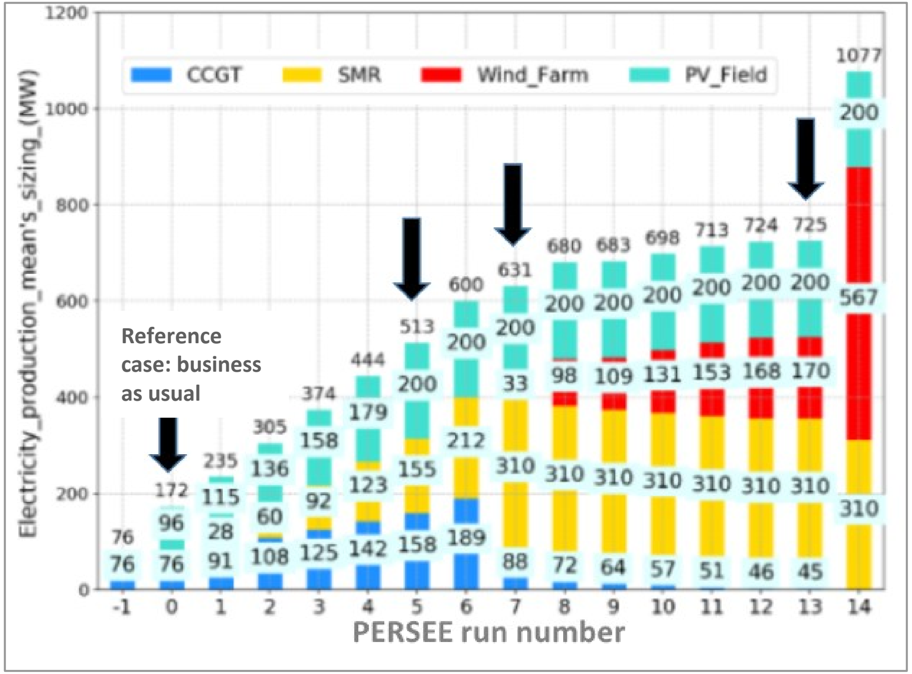
Illustration of techno-economics studies for the energy hub





Source: TANDEM/Deliverable 3.2

Illustration of techno-economics studies for the energy hub



Analysis of run 7:

- ✓ **Integration of 2 SMR in the HES**
- ✓ **Energy system 80% decarbonized compared with the "business as usual" reference scenario**
- ✓ LCOE and the $LCOH_2$ respectively close to 61 €/MWhe and 3.2 €/kg H_2 => **extra cost of the decarbonisation for the hydrogen production is about 26.1 €/MWh_e and 2.2 €/kg H_2** compared with the “business as usual” hydrogen production mean (SMGR, in run0).

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Source: TANDEM/Deliverable 3.2

Some results of the TANDEM project:

1/ Energy context in EU and HES configuration

2/ Brief illustration of techno-economics studies

3/ Specific safety considerations for SMRs integrated into HES

General framework for the safety of SMR integrated into hybrid energy systems

- ❑ Use of nuclear power plants for cogeneration effective for many years in several countries [*IAEA, No NP-T-4.1, 2017*], mainly for desalination and district heating applications

⇒ Configurations often considered as the juxtaposition of two industrial processes with a customer-supplier relationship and a small number of interfaces

⇒ Risk analyses seen as independent, considering the other process as a potential external hazard

- ❑ **Considerable work carried out on safety for reactors operated in cogeneration in the framework 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) => related Euratom projects (EUROPAIRS, NC2I-R and GEMINI+)

⇒ **Useful general safety considerations for nuclear co-/poly-generation**

- ❑ **SMR integration into hybrid energy systems induce multiple and more dynamic interfaces** between the nuclear reactor and non nuclear components of the hybrid energy system

⇒ **Need for the development of additional specific guidelines for safety analysis.**

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General framework for the safety of SMR integrated into hybrid energy systems

- Complement of the safety approach implemented for reactors in "conventional use" to take into account the specific hazards due to the coupling between SMRs and the various non-nuclear system components (such as the hydrogen production plant)

⇒ Investigation of the possible disturbances that will be caused by the integration of SMRs into HES

⇒ **Consideration of "hybridization transients"**

Perimeter of the studies carried out in TANDEM

General nuclear safety principles
(Western European Nuclear Regulators Association - WENRA)

- Defense-in-depth currently structured in five levels, aiming at preventing the occurrence and limiting the consequences of technical, human and organizational failures that could lead to incidents or accidents
- Various levels of defense-in-depth applied to the different states of the plant, from normal operation to core meltdown accidents.
- Each level of defense-in-depth, with the exception of level 5, including provisions designed to prevent the development of more serious situations

Levels of defence in depth		Objective	Essential means	Radiological consequences	Associated plant condition categories
Level 1		Prevention of abnormal operation and failures	Conservative design and high quality in construction and operation, control of main plant parameters inside defined limits	No off-site radiological impact (bounded by regulatory operating limits for discharge)	Normal operation
Level 2		Control of abnormal operation and failures	Control and limiting systems and other surveillance features		Anticipated operational occurrences
Level 3 [1]	3.a	Control of accident to limit radiological releases and prevent escalation to core melt conditions [2]	Reactor protection system, safety systems, accident procedures	No off-site radiological impact or only minor radiological impact [4]	Postulated single initiating events
	3.b		Additional safety features[3], accident procedures		Postulated multiple failure events

Source: WENRA, Safety of new NPP, Study by Reactor Harmonization Working Group RHWG, March 2013.

General nuclear safety principles (WENRA)

Beyond Level 3-a, levels not considered in TANDEM, because specific studies are already done for the nuclear plant itself, and should be sufficient for the hybridized configuration.

Levels of defence in depth	Objective	Essential means	Radiological consequences	Associated plant condition categories
Level 4	Control of accidents with core melt to limit off-site releases	Complementary safety features[3] to mitigate core melt, Management of accidents with core melt (severe accidents)	Off-site radiological impact may imply limited protective measures in area and time	Postulated core melt accidents (short and long term)
Level 5	Mitigation of radiological consequences of significant releases of radioactive material	Off-site emergency response Intervention levels	Off site radiological impact necessitating protective measures[5]	-

Source: WENRA, Safety of new NPP, Study by Reactor Harmonization Working Group RHWG, March 2013.

General nuclear safety principles (WENRA)

Focus in TANDEM on normal considitions (level 1/ DBC-1), AOO (level 2/ DBC-2) and DBA transients (level 3-a/ DBC-3-4

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Source: WENRA, Safety of new NPP, Study by Reactor Harmonization Working Group RHWG, March 2013.

Ongoing study in TANDEM

Transients characterized by a significant coupling between the Nuclear Steam Supply System and the Balance of Plant and downstream non-nuclear applications.

- ❑ ***A normal operation transient***: a load rejection transient that successfully leads to house load operation.
- ❑ ***Anticipated Operational Occurrence transients***: 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.

They will be simulated both with:

- *reference safety codes ATHLET and CATHARE in stand-alone*, using boundary conditions beyond the steam generator interface with the secondary circuit
- *a coupling between ATHLET and CATHARE and components of the Modelica-based hybrid energy system simulator*.

⇒ **Analysis of study methodology impact**

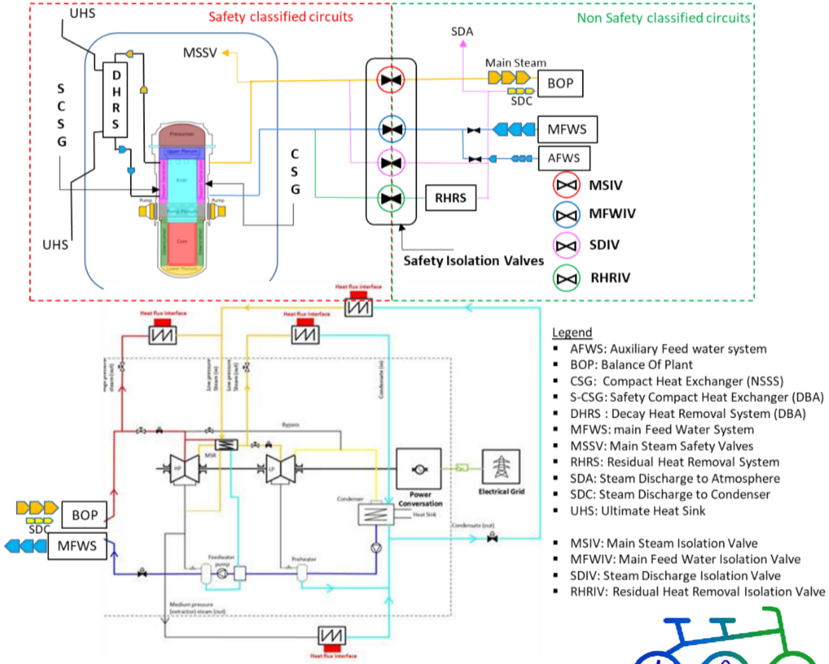
Remark concerning the study of the accident sequence for DBA (Level 3-a/ DBC3-4)

After occurrence of the initiating event, in the first accident moments, implementation of the emergency and reactor protection procedures

⇒ in particular, isolation of the Nuclear Power Plant (closure of the safety valves) from the rest of the HES

The first accident moments may be different due to the coupling with the HES, compared to a reactor operating in a « conventional » mode (without coupling).

⇒ *This is what TANDEM is studing for DBA*



Source: TANDEM/Deliverable 4.2.

General conclusion

Conclusion (1/2)

- The energy context at the international level, EU level, country level, keeps evolving. We can only make assumptions regarding energy policies, energy market evolution and nuclear/SMR deployment, at a given point in time, but these assumptions may no longer be relevant a few months later.

- However, the TANDEM project aims to achieve results that are not linked to changes in the energy context by:
  - ✓ Developing tools and methodologies to study hybrid energy systems
  - ✓ Implementing **demonstrative** study cases to highlight the benefits of SMR integration into hybrid energy systems

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Conclusion (2/2)

- **Ongoing activities in the TANDEM project:**

- *Development of a Modelica-based simulation tool* to increase the knowledge about the dynamics behaviour and safety of hybrid energy systems,
- *Techno-economics analysis*: minimization of a single objective function (the total costs) by finding an optimal sizing of system components & sensitivity studies,
- *Simulation and analysis of safety transients*,
- *Assessment of citizen engagement* and workshop organization,
- *Interactions with stakholders*,
- *Organization of E&T events.*

Announcement of E&T events

- TANDEM Summer : Lecco, Italy – June, 24-28, 2024

- TANDEM technical workshops
  - ✓ Workshop n°1 on ”*Non-electric applications of SMRs, hybrid energy systems and their components*” – at Cadarache (France) – September 18-19, 2024
  - ✓ Workshop n°2 on ”*Modelling and optimization tools to assess hybrid energy systems integrating nuclear reactors*” - at Pisa (Italy) – February 20-21, 2025

- Programmation of the technical webinars organized in the framework of TANDEM: https://tandemproject.eu/events/

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