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REGULAR ARTICLE **OPEN ACCESS**

Outcomes of three Euratom projects on cogeneration of electricity, heat and hydrogen

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Abstract. This paper deals with the assessment of low-carbon energy generation solutions (heat, electricity, hydrogen) provided by nuclear reactors in the general framework of nuclear co-generation addressed by three ongoing Euratom projects, GEMINI 4.0, NPHyCo and TANDEM. It gives a short overview over the three projects, points out the respective objectives and methodologies and describes the current results. Focus is given to the common outcomes of all three projects. The main common outcomes are that low-carbon hydrogen production via nuclear energy is generally feasible and can be done safely. This is easier to be achieved with new-build plants (Small Modular Reactors and High Temperature Reactors) than with existing nuclear power plants in operation. With current price of carbon dioxide certificates and the existing hydrogen infrastructure, low-carbon hydrogen production is not economically competitive compared to hydrogen from fossil sources. Thus, governmental support (national and EU-wide) is needed to foster low-carbon hydrogen production as a means to real decarbonization goals.

1 Introduction

The Energy decarbonisation, as well as the energy security of supply and sovereignty, are strategic goals in the European Union (EU). REPowerEU[1] plan was set up in May 2022 by the European Commission in the context of the energy crisis after the Russian invasion in Ukraine. Building on the Fit for 55 packages of proposals to meet climate-neutrality in 2050 in EU and complementing the actions on energy security, the REPowerEU plan put forward a set of actions to save energy, to produce carbon-free energy and diversify its supplies. In March 2023, the European Commission introduced the Net Zero Industry Act, which is part of the Green Deal Industrial Plan's pillar for a predictable and simplified regulatory environment, which aims at promoting investments in the production capacity of products that are key in meeting the EU's climate neutrality goals. The overall goal is to put EU on a path to domestically manufacture at least 40% of its clean energy technology needs by 2030.

The energy transition strategy relies heavily on substantial electrification of many sectors, replacing fossil fuels, supported by the accelerated deployment of renewable electricity generation capacity. Nuclear and renewable energies are considered as the backbone of a carbon-free European power system. However, decarbonizing only the electricity sector is not enough, representing only about one-third of the way to net-zero emissions [1]; achieving net-zero emissions will require a radical transformation in the supply, conversion, and usage of energy. That is why it is crucial to address the use of nuclear energy beyond just electricity production. In this case, nuclear reactors can be dedicated to a non-electric application or operate in co/poly-generation. Depending on the considered nuclear technologies (Generation 2, Generation 3 and Generation 4), the temperature level of the produced heat can range between 100 °C and 1200 °C.

This paper focuses on the assessment of low-carbon energy generation solutions (heat, electricity, hydrogen) provided by nuclear reactors in the general framework of nuclear cogeneration, through the description of the outcomes of three ongoing Euratom projects:

– NPHyCo[2] (**N**uclear **P**owered **Hy**drogen **Co**generation): the project aims to assess the implementation feasibility of coupling between Generation 2 reactors (especially VVER) with a hydrogen production plant.

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

[2] `https://www.nphyco.org/`

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- GEMINI 4.0: the project aims to consolidate the design of a High Temperature Reactor (HTR) to demonstrate that the GEMINI+ system can, in addition to low-carbon process heat, provide a global solution for the competitive and safe decarbonisation of industrial activities, and confirm that this new form of cogeneration of various energy products does not negatively affect the safety of the combined plant.
- TANDEM[3] (Small Modular Reac**T**or for a European s**A**fe a**N**d **D**ecarbonised **E**nergy **M**ix): the project studies the integration of Small Modular Reactors (SMRs) of Generation 3 into Hybrid Energy Systems (HES), by providing tools and methodologies to assess such systems and implementing them on demonstrative cases to show the role that SMRs have to play for the energy transition.

The projects consider the production of low-carbon hydrogen with nuclear implementing different processes:

- Low Temperature Electrolysis (LTE) for NPHyCo: the **A**lkaline **EL**ectrolysis (AEL) is the most mature process of electrolysis. Most large-scale hydrogen production by electrolysis is today based on alkaline electrolysers. The share of **P**roton **E**xchange **M**embrane electrolysis (PEM) is growing because of the specific advantages of this technology. Both processes use electricity and water only. To some extent, the possibility of high temperature steam electrolysis was investigated as well.
- High Temperature Steam Electrolysis (HTSE) for TANDEM: in this case, the SOEC (**S**olid **O**xide **E**lectrolysis **C**ell) technology is considered. It uses heat (produced by the nuclear reactor and recovered from the electrolysis process) and electricity to electrolyze water molecules; its efficiency is higher than LTE. However, its maturity remains one step behind LTE because the hydrogen production with SOEC still requires to be scaled up in the industrial scale (the GW scale). Development work is ongoing to meet this objective in the coming years.
- LTE, HTSE, thermo-chemical electrolysis or thermochemical water splitting such as the Sulphur-Iodine (S-I) process and Copper-Chlorine process (Cu-Cl) for GEMINI 4.0: the process to be coupled with the HTR is still open. It can use only electricity, only heat or both electricity and heat.

NPHyCo, GEMINI 4.0 and TANDEM are funded by the Euratom Research & Training program (2021–2025) dedicated to nuclear research and innovation in the framework of the Horizon Europe program. They started in 2022 and will be completed in 2025. After a brief description of each project, the current outcomes of the projects are presented in the paper. Then, common considerations for the three projects are discussed in the last section of the paper; this analysis comes from the close collaboration established between the projects.

2 Summary of the three Euratom projects

2.1 NPHyCo

NPHyCo [2] is a European research project focusing on the potential for developing large scale, low-carbon, and hydrogen production facilities linked to existing nuclear power plants. It started by assessing the feasibility of producing hydrogen near an existing nuclear power plant as well as the added value of such project. Furthermore, it is looking at potential locations where a pilot project could be implemented.

The project has seven different work packages in total: WP1 Conceptualization, WP2 Technical Roadmap, WP3 Economic Roadmap, WP4 Licensing Roadmap, WP5 Implementation Roadmap, WP6 Communication, dissemination & public awareness and WP7 Project Management.

The Conceptualization Roadmap is identifying the needs and benefits of hydrogen produced from nuclear and ensuring that research undertaken addresses the challenges faced by nuclear power plants appropriately. It also prepares for the implementation of the Pilot Project.

The Technical Roadmap focuses on the technical conditions related to the coupling of a hydrogen production facility to an existing Nuclear Power Plant (NPP). This includes identifying the needs of a hydrogen plant, the services, and resources of an existing NPP which could be shared with a hydrogen facility and the interactions between the two facilities.

The Economic Roadmap aims to develop a business plan for hydrogen produced from nuclear power. This includes assessing the economic feasibility of such projects, estimating potential costs and revenues, identifying the market needs for low-carbon hydrogen and how nuclear can help to meet the demand and the economic comparison between nuclear and other hydrogen production sources. It has three different tasks which are the "Determination of costs for the H_2 plant and the NPP modifications", the "Determination of operational strategies and potential incomes due to H_2 and miscellaneous sales, electricity dispatch and avoided costs" and the "Assessment of economic key figures and nuclear H_2 feasibility comparison with other H_2 production methods".

The Licensing Roadmap is focusing on licensing requirements. This includes the identification of key licensing issues to be considered when planning a hydrogen facility coupled to an NPP and defining ways in which the licensing process can be optimized. The first task here is to create an overview of existing guides and regulations for NPP-hydrogen cogeneration and in a second step to analyse the safety interactions of NPP and hydrogen cogeneration.

The Implementation roadmap finally elaborates a decision matrix to be used as a tool for comparing cogeneration solutions for different locations and integration scenarios and thus possible help to identify best suited sites in Europe. Moreover, the Communication Work package focuses on communication around the project. This includes sharing the outcomes of the project with stakeholders and getting feedback. It also analyses how such

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[3] https://tandemproject.eu/

projects affect public acceptance and identify potential education and training needs [2].

2.2 GEMINI 4.0

The GEMINI+ project (previous project held from 2017 to 2019) has already shown that High Temperature Reactor systems can provide a competitive and safe solution for the CO_2 free cogeneration of the process heat and electricity needed by industry.

Many industrial processes require not only heat (e.g. in the form of steam) but also large amounts of hydrogen or other energy products. Consequently, the GEMINI 4.0 project intends to show that the GEMINI+ system can, beyond CO_2 free process heat, provide a global solution for competitive and safe decarbonisation of industrial activities. It shall confirm that this new form of poly-generation of various energy products has no negative effect on the safety of the combined plant.

To clear the way towards safety demonstration and subsequent deployment of this solution, the GEMINI 4.0 project will:

- Consolidate the GEMINI+ system safety demonstration and have its licensing readiness assessed by regulators and Technical Safety Organizations (TSOs) including when used in poly-generation mode,
- Develop the capability of the GEMINI+ system to operate in a cost-effective way in poly-generation mode,
- Plan for the development of a European consistent fuel cycle for this type of reactor with respect to fissile resources and to a safe and acceptable back end,
- Launch an ambitious communication plan towards political and industry stakeholders, as well as towards the public, aiming at removing obstacles to nuclear solutions for decarbonisation of industry.

The GEMINI 4.0 project is organized around six Work Packages (WP) covering reactor and fuel designs, with associated safety issues and licensing readiness evaluation [13,14]. The poly-generation mode is analysed in term of safety and techno-economic point of view. Communication to the public and politician is addressed to promote nuclear option for poly-generation.

Although no significant showstopper has been identified in GEMINI+ safety analysis, the review performed by TSOs has pointed at some open questions listed in the GEMINI+ Safety Options Report (SOR). Therefore, the objective of WP1 is to bring some technical contributions necessary to substantiate the safety analysis of the generic GEMINI+ design to strengthen the licensing readiness of this design for industrial applications at the European level.

The WP2 will identify technical options, evaluate their economics and policy impact, and identify the safety options addressing the safety requirements defined in W4 of such a nuclear poly-generation plant. This scope goes beyond the earlier analyses performed in the GEMINI+ project, which was purely dedicated to steam generation, and focus mainly on Hydrogen production to complete the GEMINI+ evaluation.

In GEMINI 4.0, the objectives of WP3 are to assess the feasibility of building a consistent fuel cycle for HTRs with respect to fissile resources and safe and acceptable back-end to initiate the development of High Temperature Gas Reactor (HTGR) fuel in Europe. Elements for a strategy of the sovereign whole fuel cycle have to be gathered to be sure that it can be developed consistently from the front end (including uranium enrichment) to the back-end without any hurdle at some point. Licensing hurdles will be identified all along the fuel cycle.

As several fuel development programs made progress, WP3 will also review possible fuel design alternatives.

The objectives of WP4 are to assess the licensing readiness at European level of the GEMINI 4.0 HTR design concept and to set-up a guidance that could be used for the pre-licensing of an HTR. A few pending safety issues have been identified based on exchanges with designers and assessment of the safety options report (SOR). In a first step, the objective of the WP4 will be to inform WP1 to resolve these issues. In a second step, WP4 partners shall assess the specific safety options of the GEMINI 4.0 concept that would result from the integration of the reactor in a poly-generation scheme.

The general objective of WP5 is to increase the awareness of European citizens about:

- The fact that decarbonization of European economy cannot only be addressed through decarbonization of power generation, most particularly because the industry and transport sectors emit more CO_2 than power generation.
- The existence of a short-term solution (deployable within the next 10 years) to supply industrial process heat and hydrogen required to decarbonize these two sectors with High Temperature Gas-cooled nuclear reactors.

WP5 will identify targets for maximizing the impact of communication and implement communication actions towards these targets.

The main objectives of WP6 are to carry out an effective technical, scientific, legal, financial, and administrative coordination. The main outcomes of his WP are:

- An appropriate governance structure and internal communication methods.
- Project monitoring & risk management.
- Project Quality Plan, Data Management Plan.
- Enforcing gender equality.
- Assessing the project impact through a monitoring & evaluation framework.

2.3 TANDEM

The TANDEM project [3] addresses the safe and cost-effective integration of light-water SMRs into Hybrid Energy Systems (HES). HES are composed of multiple energy generation, storage, conversion, transportation, and distribution technologies to achieve net-zero goals.

Indeed, the traditional power systems based on single-generation sources to support a single energy demand do not match economical and technical efficiency requirements for clean energy transition anymore. The European pre-partnership, prefiguring the set-up of the European SMR Alliance, carried out an analysis [4] of the potential European energy market and provided orders of magnitude low-carbon energy needs in the European Union (EU):

- For electricity: an extra low-carbon electricity production capacity by 1700 TWh/y must be deployed by 2050.
- For hydrogen: the REPowerEU plan estimates a use of hydrogen by 20 Mt/y in EU by 2030. The production of this hydrogen amount by electrolysis implies an extra low-carbon electricity production capacity by around 1000 TWh/y.
- For heat required by industrial processes: the major demand in low-carbon heat comes from industries for iron and steel, for metallic minerals and chemicals. It represents 1250 TWh_{th}/y. About half of the need is for low temperature heat below 400 °C.
- For district heat: the current need in EU represents 500 TWh_{th}/y and around 2/3 is still produced by fossil-fuels.

Even if improved energy performance of buildings and optimized energy use in industrial processes can reduce energy demand, the global demand of low-carbon electricity, heat and hydrogen will remain huge in EU by 2050. That is why all the available low carbon-energy sources and carriers must be implemented to achieve the energy transition; we cannot afford to choose which energy sources should or should not be implemented.

SMR and Generation 4 Advanced Modular Reactor (AMR) technologies have the potential to strongly contribute to the energy decarbonization if successfully implemented. It is now required to envisage the use of these technologies not only for electricity supply but also for non-electric applications to supply heat, hydrogen, but also fresh water, etc. The race for the development of SMRs and AMRs is ongoing and today, no less than 83 concepts are under development covering a wide range of technology approaches and maturity levels; first construction projects have already been launched. Considering a near-term deployment in Europe at 2030's horizon, the project is mainly focussed on light-water technologies of the Generation 3. However, for a longer-term deployment in EU, the project also intends to provide insights for AMR technologies of the Generation 4, when the project results are not technology dependent.

Due to the evolution of the economic but also geopolitical balances worldwide, the energy paradigm and strategy at the international level, EU level and country level, keeps evolving. It is important for the TANDEM project not to get result-dependent from these changes. In the context of the different initiatives promoting the integration of sustainable energy sources to the energy mix, the overall aim of the TANDEM project is to highlight the potential role of SMRs and AMRs in the development of the future European low-carbon energy mix and build an open and long-term community that will ensure expertise in the domain and support the wide acceptance of SMRs and AMRs at different levels. To achieve this, TANDEM has launched actions to analyse the feasibility of SMR integration into hybrid systems regarding safety, operationality, techno-economics and citizen engagement, and to provide recommendations for the future development of HES.

The major contribution of the project is to facilitate the future deployment of SMRs and hybrid energy systems in providing technical and scientific data on the HES safety and feasibility. The delivery of methods and simulation tools for the assessment of SMR safety and HES feasibility supports the development and licensing of European multipurpose SMR concepts in hybrid systems at 2030's horizon.

TANDEM provides a groundwork for a science-based assessment process of SMRs integrated into HES. It will contribute to make European countries access to intrinsically safe and cost-effective installations for electricity supply or non-electric applications. SMR flexibility of location offers new application possibilities such as district heating, water desalination, heat production to supply industrial processes, hydrogen production and energy production in remote locations or in the support of decentralized energy production. The efficiency of the energy conversion between nuclear thermal energy and power is about one third. The consideration of non-power applications makes envisage a better efficiency of thermal nuclear energy produced by SMRs, potentially leading to a better return on Investment.

TANDEM supports the development of new expertise and cross-cutting knowledge among R&D teams, and an increased understanding for the SMR technology and safety, as well as their non-electric applications, among key stakeholders, including end-users and wide public.

The TANDEM project is made up of five technical Work Packages (WP), from WP1 to WP5, dealing with the characterization of HES to be studied in the project, the development of tools and methodologies to assess HES from the viewpoint of safety, technical performances, techno-economics and citizen engagement, and their implementation on demonstrative study cases. WP6 focuses on Education & Training activities and WP7 on project management.

3 Currents outcomes of the projects

3.1 NPHyCo

Current outcomes of the economical part:

The main conclusions obtained in the techno-economic analysis performed in WP3 area. In case of Low Temperature Electrolysis (LTE), the hydrogen production costs are significantly dependent on the cost of the electricity, being the highest cost share in Levelized Cost of Hydrogen (LCOH) indicator. Other sources as demineralized water consumption costs are almost negligible, and the hydrogen production plant amortization, falls to a second position in terms of cost relevance. The large nuclear power plants are not usually located in the vicinities of hydrogen consumers (chemical industry, steel industry) and the transport costs could also penalize the hydrogen costs in case the hydrogen plant is located next to the NPP (Nuclear Power Plant) and not close to the consumer. Therefore, in case of LTE, it would be more beneficial to use only the low-carbon electricity produced by NPPs to feed the electrolyser, waive other integration option and to place the H_2-plant close to the consumers or the future H2 grid instead. With the current hydrogen infrastructure, it is easier and cheaper to transport electricity than hydrogen.

In case of High Temperature Electrolysis (HTSE) this is different. As HTSE is working on a much higher temperature level than LTE and processes steam instead of water in the electrolyzer, the NPP can provide heat (in form of steam) in addition to electricity. But this is asking for a reasonable vicinity of NPP and H2 production plant. With HTSE the hydrogen production costs are currently higher than those for LTE although HTSE has higher efficiency rates. The more complex plant design creates higher CAPEX and esp. the cost for the more frequent replacement of electrolyzer stacks creates higher OPEX cost. According to NPHyCo calculations the cost of electricity moves to second place on the list of contributors to the LCOH. Based on a specific case study performed during the project performance, it is expected that, by year 2029, HTSE will could reach the same level of prices as PEM technology and in year 2031, lower costs than both LTE technologies. In conclusion, HTSE technology is envisaged as a promising solution for NPPs in a medium-term period. The steam production can be leveraged for producing hydrogen by means of a technology with higher efficiency levels and with less dependency on electricity prices variation. However, it requires a technology progress that allows the manufacturers to reduce the costs as it is projected.

The economic work package is developing business plans to show under which circumstances and with which operational models nuclear hydrogen becomes competitive compared to “grey” hydrogen derived from fossil sources. It can be stated that today low-carbon hydrogen is not competitive. This is the case for other green low-carbon hydrogen production as well e.g., hydrogen produced with electricity from renewable sources (wind, photovoltaic) as well. It is necessary that policy makers develop the necessary regulation framework to foster low- carbon hydrogen production [5].

Current outcomes of the technical part:

NPHyCo looked at the three main technologies for hydrogen production i.e., LTE such as alkaline electrolysis and PEM electrolysis, and as well HTSE such as SOEC. With respect to the NPP technology, BWR, PWR and VVER reactor types were to be considered. To better understand the possibilities of existing NPPs to serve the needs of hydrogen production, operators of nuclear power plants were contacted and consulted. As the suitable or preferable production scale for coupled hydrogen production was undefined initially, a reasonable pilot plant size of 30 MWe was envisaged as a starting basis for quantitative approaches.

The needs of hydrogen production via electrolysis and the potential availability of the associated resources (electricity, water, cooling, nitrogen and other) in a nuclear powerplant site built the basis for considerations regarding the potential levels of integration, onsite the grounds of a NPP or offsite, but in close vicinity. Impacts of a coupled hydrogen production with the nuclear power plant were investigated, especially the potential safety impacts (fire and explosion) but as well the possibilities for flexible load operation. Finally, the requirements necessary or in favour for hydrogen cogeneration were summarized and explained.

The result of the technical roadmap was that the integration of a hydrogen production unit with an existing nuclear power plant is generally feasible. It needs to be shown that the impacts of a coupled hydrogen production plant are safe, but the safety impacts can be reasonably addressed and rationalized. This might be easier in new build projects where respective mitigation measures may be implemented in the design of the nuclear power plant, which is not possible for already existing structures. In existing power plants, this need to be overcome with the selection of suitable locations for the hydrogen production unit and especially for the (eventually) necessary hydrogen storage tanks. The storage is the spot with higher amount of hydrogen and thus respectively higher level of hazards. In any case are the conditions in favour or against a coupled plant highly site-specific, and detailed analysis needs to be carried case by case out for any specific site in question.

Very site specific as well is the respective local hydrogen market and the hydrogen users as potential off takers. This defines the needs for storage and transportation of the cogenerated hydrogen, which has significant impact to the technical solution.

Current outcomes of the safety part:

The technical installations of Hydrogen Production Plants (HPPs) do not have a specific hydrogen related regulatory regime to comply with. The requirements to fulfil are covered by various acts dealing with chemical and/or industrial installations with generic safety and risk requirements. The regulatory regime is determined by several national acts that are derived from the relevant EU directives. For the design and construction of a HPP’s the relevant EU-directives are Seveso directive, ATEX directive, Pressure Equipment Directive (PED) and Industrial Emissions Directives (IED).

The size of the facility and the amount and conditions under which hydrogen is stored are important factors for the safety distances that must be considered. Smaller facilities are often so called Categorial Facilities with standardized safety distances and a limited number of specific requirements. Generally, the larger the facilities, the more requirements must be fulfilled and the more calculations for determination of specific safety distances must be performed. Overall, it has to be shown that the facility is safe and complies with all safety and risk-related regulations, technically, organization-wise and with respect to the environmental impact. The licensing process for a

HPP is comparable to a chemical facility or storage facility for dangerous substances of equivalent size.

Moreover, NPPs are highly regulated and all changes to a plant itself, to the direct environment or any additional hazard introduced that may cause damage to the plant, need to be justified from a safety point of view and may require a license modification [18].

Constructing an HPP near a NPP will most likely have influence on the NPP safety case and on the license, depending upon the distance and the utilities and systems shared. Various cases are described below:

- An HPP in the vicinity of a NPP, but not on the NPP-site, may have impact on the NPP license. This will depend on the distance of the HPP to the NPP. The HPP should be outside the sanitary zone and/or risk contour of the NPP (where specific activities are prohibited) and the safety distance of the HPP should be smaller than the distance to the NPP. If those restrictions are fulfilled, the HPP needs its own license and no impact on the NPP license is to be expected.
- In the case of an HPP on a NPP site, without any coupling or integration, the hydrogen activities need to be incorporated into the NPP license, which requires a license update. The license update consists of a description of the additional buildings, installations, and an update of the licensed activities to include hydrogen production. In most countries, the NPP license specifically mentions the activities that the NPP operator is allowed to perform in this case the activities related to the generation of hydrogen need to be authorised in a license update. A license update is also required because the NPP safety case also must be updated, since the HPP is a potential additional hazard to the NPP. It must be shown that this hazard does not in any case jeopardize the safety of the NPP. This can be shown by demonstrating that the HPP will not have any significant impact on the NPP installations and operation, or that the necessary measures will be taken to prevent an increase of the NPP risks to the public and environment.
- When coupling a nuclear power plant to an HPP, safety reassessment is required to confirm that an appropriate level of safety is maintained in case of design modification. The safety assessment should be documented in a safety study, which should be updated to reflect the analyses and modifications made to the facility and site conditions. Depending upon the number of systems shared and the kind of modifications required, the safety case and license update can require significant effort, time, and costs.
- Direct sharing of the electricity produced by the NPP, while having the HPP off-site at a significant distance would impose minimal licensing changes. The HPP would simply be seen as a consumer of electricity.

So, the most important conclusion from the licensing part so far is that licensing requirements do not prevent HPPs on-site nor closely integrated HPP with an NPP. Also, a HPP on-site – and even more a closely integrated HPP – will have significant cost consequences from a design/technical point of view, as well as from an organizational, operational, and managerial point of view. To answer the question whether such a coupling is safe, the main potential external hazard identified relates to hydrogen storage, but this can be resolved by establishing a minimum distance.

It should be mentioned that in some European countries NPP are not licensed to produce anything else than electricity. This means that extending the licence of a NPP to allow cogeneration of hydrogen may need exemptions from or even changes of national regulations.

3.2 GEMINI 4.0

The GEMINI 4.0 project is organized in six work packages. WP1 to 4 are dedicated to technical part. WP5 is related to the communication towards the European citizens and the WP6 considers the project management.

The WP1 is called "Optimizing safety and competitiveness of the GEMINI+ Design". A review of the GEMINI+ Safety Option Report (SOR), provided in the former GEMINI+ project, was performed on the core design and the related calculations. 46 recommendations were discussed and considered in the core design optimization of the GEMINI+ system. The purpose is to reduce fuel temperatures in accident conditions but also reduce the height of the core to increase the performance of the reactivity control system. Reactor physics and accidental transients' calculation were performed to define a set of changes of the GEMINI+ system core design. Finally, the optimized core design leads to a shorter core length with 10 fuel blocks axially instead of 11 and a fuel temperature lower than the fuel temperature core criteria of 1600 °C. The new design was considered for the improved Safety Option report.

For the design of the lower plenum and hot cross duct, the HTTF (High Temperature Test Facility) benchmark was performed to validate the CFD calculation of the assumed amplitude and frequency of temperature fluctuations in this zone. Experimental data from the HTTF facility from Oregon State University (OSU), representing the MHTGR (Modular High Temperature Gas cooled reactor) reactor at a 1/4 scale, was compared with the calculation, not only for the distribution of temperatures, but also for other physical parameters. Thanks to this modelling and its experimental validation, the GEMINI+ core outlet and the hot gas duct designs were optimised for reducing the amplitude of temperature fluctuations if any. Then the impact of residual temperature fluctuations for the optimised design was assessed on thermal fatigue risks on structures downstream of the core.

A workshop on the core instrumentation was conducted to prepare an instrumentation test plan for the demonstration plant and research plant.

The analysis of B4C oxidation experiments present post-experimental examinations focusing on the quantification of the oxidation reaction rate and the derivation of a general correlation for the reaction kinetics.

Some actions were launched to prepare European codes and standards for a demonstration project of high temperature nuclear cogeneration. The readiness of the European codes and standards (RCC-MRx French nuclear codes from AFCEN (Association Française des Codes Et Normes) for metallic materials was assessed and gaps have been identified. Same assessment was done for the European and international design codes for graphite and ceramic composite core components and assemblies [15].

The WP2 is called "Towards full decarbonization of European industry with nuclear poly-generation".

The WP2 aims to determine the poly-generation systems compatible with industrial requirements, to analyse the techno-economic feasibility of poly-generation systems, and to establish the technology readiness of selected poly-generation systems and identification of R&D gaps.

The first version of flowsheet requirements for hydrogen production was provided including the collection of information from industrial partners.

HTGRs are well suited to integrate with high-temperature hydrogen production technologies, such as Sulphur-Iodine Cycle, but these are often still under development and not viable for near term deployment. The integration of HTGRs with other hydrogen production processes, such as Solid Oxide Electrolysis Cells (SOEC) and thermochemical cycles like the Copper Chlorine (Cu-Cl) Cycle, needs high temperatures and often more electricity. These solutions offer standalone nuclear and opportunities for hybrid energy configurations through integration with renewables to optimize the cost of hydrogen production and downstream utilization of hydrogen to decarbonize various industries reliant on fossil fuels. HTGRs can also be used for industrial process heat supply or a combination of heat and electricity (cogeneration) for one or more industrial applications.

Table 1 presents yield of hydrogen per hydrogen production process scaled down to a single GEMINI+ type reactor with 165MWth net thermal power output and with and without grid connection. Electricity production is assumed at 41% of the energy production.

Three of presented processes synergize well with GEMINI+ type HTGR: Copper-Chloride, Sulphur-Iodine and Solid Oxide Electrolyser cell. Out of the three processes, SOEC has the higher technology readiness level and is actively pursued by the industry. Both S-I and SOEC processes require part of the heat input at temperatures higher than the temperature of steam supplied by the GEMINI+ type system. HTSE and the thermochemical hydrogen production methods make use of the high temperatures reached by the nuclear reactors in contrast to conventional methods such as PEM and alkaline electrolysis that operate at lower temperatures. HTSE is the only method that makes direct use of steam produced from a nuclear reactor, which lowers the demand for electricity in order to produce hydrogen, and it is the most promising method. It is expected that HTSE coupled to a nuclear reactor can produce hydrogen with 20% more efficiency when compared to nuclear coupled to more conventional electrolytic methods, including PEM. Despite HTSE being a very promising technology, R&D gaps and needs remain and this method is estimated at a TRL 6.

Development of the S-I process started in 70s. Despite decades of development TRL is assessed at 4 as only basic technological components have been tested and integrated to date. The Cu-Cl process has received significant attention in Canada until recently. However, the XU-Cl cycle has not been pursued further on the basis that is significantly more complex than the other processes and it is not competitive with steam electrolysis. The TRL was assessed to be 3.

PEM is already commercial around 1 MWe for nuclear enabled hydrogen. The main challenge of his method is scalability. But higher power output projects are underway globally to produce hydrogen using PEM.

Key Performance Indicators (KPI) for poly-generation systems are defined to perform case studies for different regions and countries, to compare centralized vs. decentralized hydrogen production, and to perform a comparative assessment of results with the projects TANDEM and NPHyCo. Input for non-electric uses is collected including for steel making, H2 production and its derivatives (ammonia, synfuels, …). The feasibility has been checked, and nuclear solutions were compared with non-nuclear approaches.

For further development of the hydrogen market, enabling hydrogen technologies to become more competitive, efficient, and sustainable alternatives to traditional fossil fuels and other energy technologies, there are several challenges to be overcome such as:

- Economic barrier: the current hydrogen production prices are significantly higher than fossil fuels. Additionally, the costs of transportation and technologies (e.g. fuel cells, expensive transport facilities) further increase the price of hydrogen;
- Lack of differentiation: the absence of an established method to identify the origin of hydrogen means consumers have no opportunity to ascertain its source and, consequently, its environmental impact. Regulations and a certification mechanism have to be developed to identify the hydrogen origin as it exist for the electricity origin.
- Limited infrastructure: adapting existing infrastructure and establishing new facilities suitable for hydrogen transportation and storage require significant financial resources. Presently, there are only about 4500 kilometres of hydrogen pipelines worldwide. But respective initiatives like the European Hydrogen Backbone Initiative (EHB)[4,5] are in place and the respective governmental decisions were taken e.g. the plan to build 9.700km of hydrogen pipelines in Germany. Energy losses: the processes involved in producing, transporting, and storing hydrogen result in energy losses and leakages that directly impact the efficiency of hydrogen technologies.

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[4] `http://www.ehb.eu`

[5] `http://www.bundesregierung.de/breg-de/aktuelles/energiewirtschaftsgesetz-2240764`

Table 1. Hydrogen production per process scaled to a GEMINI+ type reactor

Hydrogen Production System	Outlet temperature [°C]	Grid connection	Electric energy (MJ/kg H_2)	Thermal energy (MJ/kg H_2)	Yield [kg/s]	TRL
Sulphur Iodine	750	No	31.9 – HI concentration72.1 – boosting	237.0	0.34	4
		Yes			0.70	
	850	No	31.9	309.1	0.43	
		Yes			0.54	
Solid Oxide Electrolyser Cell		No	91.2	27.5	0.66	7
		Yes			6.00	
Copper Chlorine		No	63.7	150.7	0.50	<3
		Yes			1.09	
Alkaline electrolysis			216.0	n/a	0.31	9
Polymer Electrolyte Membrane electrolysis			162.0	n/a	0.42	9

- Policy: specific regulations related to the broad use of hydrogen are required to support and facilitate the development of this technology.

In the structure of hydrogen generation in 2021 based on different methods and raw materials, predominant share (96%) is generated using fossil fuels (i. e. 47% natural gas, 27% coal, 22% oil). The most popular methods of hydrogen generation from fossil fuels are:

- Steam Methane Reforming,
- Autothermal Reforming,
- Partial oxidation,
- Gasification.

In the EU, it is clearly visible that the most profitable technology considering current regulation and technologies development levels is Steam Methane Reforming. Hence, the levelized cost of hydrogen generation around 2 €/kg is current benchmark for developing technologies.

Possible impact of poly-generation on safety features of the combined plant, the identification of risk mitigation methods, the specification of plausible accident scenarios and benchmarking with advanced computer tools, as well as proposals for specific design options for WP4 and for the completion of the GEMINI+ Safety Options Report, was analysed. This produced a Risk analysis of flammable release in the nuclear plant vicinity using CFD codes and safety options for a combined nuclear/conventional plant.

The identification of requirements (started in GEMINI+) regarding coupled facilities has been completed. Feedback on coupling with industrial facilities serve as a basis for structuring the feedback information. Also completed was the definition of the level of detail in the flowsheets (layout and buildings) needed for the CFD modelling in this task, which required discussion with WP1.

The WP3 is about “Fuel technology options and fuel cycle strategy for GEMINI+ system”.

The implementation of HTR fuel supply in Europe was investigated since no European company is presently able to deliver fuel for GEMINI+ reactor. It was split in three parts:

- The definition of a roadmap for deployment of HTR fuel fabrication capabilities in Europe (including HA LEU (High-Assay Low-Enriched Uranium) supply, TRISO (Tri-structural Isotropic particle fuel) and HTR fuel fabrication.
- A specific focus was made on Fuel Inspection (key to demonstrate HTR fuel quality): it supports the characterization of fuel samples, the qualification of production means, as well as the industrial production quality. The plan of Quality Control Methods for the Graphite Matrix and the Compacts has been drawn as for TRISO particle controls (for R&D and industrial applications).
- For fuel qualification, the project drafted a path to provide proof to European safety authorities that the fabrication equipment performs as well or better than the old equipment that produced the samples of the irradiation database for licensing.

A review of the back-end options of the HTR fuel cycle was performed to recommend the most economic and realistic strategy in Europe (direct disposal of the irradiated fuel elements, separation of compacts and i-graphite, etc.). The decontamination techniques for graphite waste (so that i-graphite can be managed as a lower waste category) was reviewed. The viability of these technics has been assessed thanks to preliminary final storage cost estimates. The reuse of irradiated graphite (closed graphite cycle) is of special importance for minimizing the HTR-specific waste streams and needs further evaluation. A recommendation was done for a reference back-end scenarios of HTR fuel in OTTO (Once Through Then Out) fuel cycle, based on preliminary safety and technical-economic analysis of possible options. Closed fuel cycle was also investigated [16].

Possible fuel alternative (UCO, UN), alternative coatings, alternative heavy metals (Thorium and Pu), matrix material (FCM-Fully Ceramic Microencapsulated) were identified and compared to the reference solution defined for the GEMINI+ system.

The WP4 is about “Assessment of the licensing readiness of the GEMINI+ system for multipurpose industrial cogeneration”.

The review of the safety options of the GEMINI reactor concept and subsequently to identify technical areas where additional development is needed were performed, including simulation models of neutronics and thermal-hydraulics. This review addressed the reactor concept as specified at the end of the GEMINI+ project. The purpose was to inform WP1, before further optimization/adaptation of the reactor design.

Most of the topics addressed in the WP4 review was acknowledged by WP1 and reflected in the revised version of the safety option report (SOR). Issues related to core cooling flow path in certain operation modes are being discussed in a dedicated had-hoc exchange group.

Proposals for instrumentation options were made to inform WP1 with the position of a TSO regarding the expected safety relevant measurements to be implemented in an HTR. These expectations were discussed with WP1 partners during a workshop and a document was released.

The final objective is a drafting of guidance for pre-licensing of high temperature cogeneration reactor in Europe [17].

The WP5 is about "Nuclear High Temperature Cogeneration for European Citizens".

A lessons learnt exercise was performed from cogeneration experience in Europe. The exercise has allowed identifying some of the favourable factors to the development of cogeneration or on the contrary factors that can inhibit its development.

Favourable factors are as follows:

- A local infrastructure of district heating network facilitates the substitution of boilers, just providing hot water or steam by cogeneration plants.
- With the recent political push to the development of renewables, there will certainly be an adaptation in the grid infrastructure to the connection to cogeneration plant since this plant have the capacity to bring the necessary complementary support required by the intermittent renewables.
- The simplest operating mode of a cogeneration system is to work only for its direct customers.
- For solving the issues raised by the need to match both internal and external requirements, a solution is to introduce a buffer energy storage.
- The governmental policy can be implemented in financial terms, subsidies, taxes, or marketable CO_2 permits and in terms of energy planification. What is the most important in terms of public support is to keep stability of the policy in the long term.
- It is important to have operators dedicated to cogeneration.

On the contrary, some historical, cultural or geographical, as well as infrastructural features can be obstacles: country with large hydraulic or wind resources, or very centralized electric grid. Connecting a cogeneration system with some external system, an electric grid or an intermittent renewable system is not simple: for instance, a large national electric grid has intangible stringent requirements for interconnection, which might not be easily compatible with the requirements of the internal customers to be satisfied by the cogeneration system, and which in addition, will request costly interfaces.

For communication and dissemination on the objectives and benefits of nuclear cogeneration, plans have been developed for three countries, Finland, Poland and UK, in which nuclear energy, already developed or considered for short-term implementation, is already considered favourably by the majority of people. These plans will help partners to go from the empirical communication that they usually practice to a more systematic approach.

3.3 TANDEM

WP1 is dedicated to the analysis of the characterization of the studied HES during the project [3]. The analysis of the energy policy at the European and national level and the energy market projection in the next decades enabled to highlight the main needs for energy decarbonization in EU. These needs consist in the production of low carbon-energy carriers, i.e. heat, electricity and hydrogen, to supply energy-intensive industrial processes, space heating and cooling networks, transportation, and the production of feedstock's such as fresh water. This led to configure two typical HES, in which SMRs must be considered as a combined electricity and heat provider: a district heating structure associated with an electricity supply, and an energy hub with industrial applications or energy conversion systems as end-uses segments at a local scale. The generic architectures of the two HES were inspired from real cases:

- For the district heating structure associated with an electricity supply: the architecture in the metropolitan area of Helsinki, which includes the large cities of Espoo and Vantaa in Finland.
- For the energy hub: a harbour-like architecture, such as the Dunkirk port region[6].

The analysis of different technologies available or under development was carried out in TANDEM to characterize each component integrated into the HES. All the HES components are connected to the electrical grid and heat network.

WP2 aims to develop modelling and tools to simulate the physical behaviour of HES. On the one hand, TANDEM has developed an open-source modelica-based library [6] containing the numerical models of the components for the HES configured in WP1 (SMR, High Temperature Steam Electrolyzer for hydrogen production, district heating network, storage systems, etc). The first version (V1.0) of the library has been made publicly available in a git repository (`https://gitlab.pam-retd.fr/tandem/tandem/`) under the 3-clause BSD-license slightly modified. The documentation containing the modelica model description has also been released by the project. Based on this library, the development of hybrid energy system simulators has been carried out; it enables the analysis of the system dynamics across different scenarios and the exploration of different control strategies and operational philosophies.

On the other hand, a modelling of the SMR use-case implemented in TANDEM has been developed with two references safety codes, ATHLET [7] and CATHARE [8]. The SMR use-case relies on the E-SMR academic concept, developed by the ELSMOR[7] project: the data has been open in a git repository (`https://etsin.fairdata.fi/dataset/00b62da2-7b96-4e70-82ef-1e8afaa0ecb1`). It

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[6] `https://www.agur-dunkerque.org/blog/toile-energetique-schema-des-relations-energetiques-de-la-region-flandre-dunkerque-billet-4802.html` [in French]

[7] `https://www.elsmor.eu/`

is a 540MWth reactor with an integrated design. All the components of the primary circuit are modelled as 0-D or 1-D elements, as typically assumed in the nodalization of Nuclear Power Plants with such system thermal-hydraulics codes. Eight compact plate-type once-through steam generators are in the reactor pressure vessel. Six are dedicated to normal operation and two for accident conditions. They are modelled as 1-D elements coupled to the primary circuit by means of heat walls, representing the steam generator plates. Boundary conditions are provided at the steam generator inlet and outlets to impose the feed water mass flow rate and enthalpy, and the downstream pressure, respectively. These boundary conditions are key elements to set up the coupling between the safety code models of the secondary circuit and the modelica model of the balance of plant; the development of such a coupling is an ongoing action in the project. The E-SMR safety systems consists in: 1/ a passive heat removal system designed to cool down the primary circuit in case of accident. It composed of two safety steam generators, two condensers and a water pool used as a heat sink; 2/ four identical accumulators connected to the upper plenum in the reactor pressure vessel. Their models have been implemented in both E-SMR ATHLET and CATHARE modelling to simulate design basis accidents in WP4.

WP3 is dedicated to time-dynamic techno-economic analysis of HES. HES can constitute low-carbon energy solutions defined on a case-by-case basis depending on local/regional features (economics, energy policy, natural resources, meteorology) and needs of energy decarbonisation (domain of the industry, domestic applications, transportation) of the area where the HES are implemented. Three case studies have been derived from the HES configured in WP1, two case studies corresponding to the district heating structure associated with electricity supply in Finland and in Czech Republic, and a third case study corresponding to an energy hub supposed to be located in Fos-sur-Mer, a port in the South of France. The two first case studies are simplified but rely on realistic architectures and data defining the energy demand and production, whereas the architecture and the data for the energy demand for the energy hub have been arbitrarily fixed, no data being publicly accessible for such a study in a European harbour. Note that these studies do not have the ambition to establish real future plans to define future energy mixes, they are used only as demonstrative case studies. Different energy scenarios have been considered in 2030's and in 2050. The principle of these studies is to find optimal (Net Present Value – or NPV – optimizations with technical and economic data) architectures and the associated sizing of the components, where CO_2 emissions are limited and constrained, considering different energy scenarios (such as business as usual, start of the deployment of the SMRs, full replacement of fossil fuel plants by SMRs, etc). Optimizations were carried out with the Backbone [9] and PERSEE [10] tools in stand-alone; they were based on the simulation of one-year period. Sensitivity analyses considering different assumptions – regarding the existing infrastructure, investment costs, electricity prices, the choice of the HES components, etc. – were performed for the two case studies (the case in Finland and the energy hub in Fos-sur-Mer); it enabled to put in perspectives the results in sight of some uncertain assumptions that were considered. Besides, a coupling between Backbone or PERSEE within the PEGASE platform [11], and the HES simulator developed in WP2 is currently used to study the HES operationality and to check the sizing obtained with on an assessment for one-year period, by operating refined models under a 24-hour period.

WP4 is dedicated to analysing the safety of the SMRs integrated into hybrid energy systems. In this case, SMRs are considered as provide of heat and electricity to downstream applications; they are often supposed to operate in cogeneration mode. Energy demand fluctuates in a hybrid energy system, depending on the variation in consumer demand over the course of a day or between seasons, and the intermittency of renewable energies. The share of renewables is constantly increasing to contribute to decarbonize the energy mix, which makes it even more necessary to vary energy production and balance the power grid when a HES is deployed. The flexibility of heat and power production can be managed by the SMR, operating on a load-following basis. In addition, the rate of heat and electricity production can also change, within a range permitted by the design. The use of storage energy systems in HES can be another way to accommodate the variation of the energy demand and intermittency of renewables if SMRs operates in baseload, with a constant thermal power.

Before working on the definition of a methodology to assess SMR safety when integrated into HES, the project analysed the state-of-the-art of nuclear reactor safety analysis in Europe from the operational flexibility and cogeneration viewpoint. It appeared that the amount of work done in Europe and abroad in relation to the safety aspects of the integration of SMRs into HES in cogeneration was limited in open literature. This requested to draw information from the broader field of the studies on nuclear cogeneration applications for different types of reactors, where experience has been accumulated by specific projects on desalination, district heating and process heat.

Assessing the safety of a SMR integrated in a hybrid energy system requires a comprehensive methodology considering specific safety considerations beyond the conventional safety approach implemented for large water reactors and SMRs: the analysis of specific external hazard studies due to the proximity of the various HES components and the analysis of "hybridization" transients. The deterministic safety analysis of such transients 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 analysing the impact of hybridization on nuclear reactor safety. The study of hybridization transients is ongoing, by implementing the CATHARE and ATHLET E-SMR modelling and the coupling with modelica models developed in WP2.

Beyond activities on communication, dissemination and stakeholders' engagement, **WP5** contains activities to assess citizen engagement related to the new SMR technologies and their use to provide commodities beyond electricity. To do so, workshops are organized to meet a panel of citizen in some partners' countries; SMR technologies are presented, as well as their potential applications for energy decarbonization, and citizens' feedback are collected during the workshops. The first workshop has been organized early September 2024 in Kuopio, in Finland, and gathered around 70 people. The workshop has been co-designed with city municipalities, local energy company, and VTT. A synthesis of the results coming from all the workshops will be provided by the end of the project.

The progress status of the project at mid-term [12] was presented at the International Conference on Small Modular Reactors and their Applications, organized by IAEA in Vienna, Austria, in October 2024. All the technical reports released by the project are publicly available in the project website (`https://tandemproject.eu/`).

4 Common outcomes of the projects

NPHyCo, GEMINI 4.0 and TANDEM identified four topics of common interest:

- Safety for nuclear cogeneration,
- Communication and public acceptance,
- Techno-economics & short- and long-term impact of nuclear on energy decarbonization,
- Flowsheet for hydrogen production.

Four Working Groups (WG) have been set up to highlight synergies between the projects, share key results and identify points of convergence and divergence The work of the working group is still under progress. This paper provides a first analysis.

The technical feasibility of hydrogen production coupled to nuclear power plants was the starting point of NPHyCo and GEMINI 4.0. Both showed that there is a technical feasibility and described potential technical solutions to realize such cogeneration.

More in question as the general technical feasibility was the question whether such cogeneration could be implemented without major safety issues. The targeted production processes bear specific risks that need to be considered to ensure a safe operation and with regards to the impacts they may have to the coupled nuclear power plant. Examples are the flammability and explosibility of hydrogen or the hazardous nature of chemicals used in some physico-chemical processes of hydrogen generation that are investigated in NPHyCo and GEMINI 4.0. TANDEM focuses on the study of hybridization transients that come from the interactions of the NPP with the HES rest (in particular downstream applications) for nuclear cogeneration mode. The respective safety analyses are not yet fully accomplished in the three projects, but the current results already allow to indicate that safety risks emerging from cogeneration can be reasonably mastered. With the development of new reactor technologies like targeted by GEMINI 4.0 or TANDEM, safety requirements can be addressed with the innovation reactor designs. NPHyCo is focussing on operating nuclear plants with already given characteristics of building structures or technical systems and thus given resistance and resilience against impacts. These impacts are highly dependent of the location of the coupled hydrogen production plant in comparison to sensitive structures of the NPP. Furthermore, they depend on the size of such a plant (esp. hydrogen content), the production process and mitigation measures related to safety. It is obvious that this asks for detailed site-by-site and case-by-case investigations. NPHyCo performed such an analysis for some specific sites where enough information was available. From that it can be stated that cogeneration of hydrogen coupled to a nuclear power plant can be feasible under certain circumstances even for already existing NPP.

The most important question to be addressed beyond the technical feasibility and safety considerations is whether such cogeneration is economically viable. To answer this, the estimated LCOH must be compared considering hydrogen produced from nuclear, renewable, and fossil sources (with and without carbon capture techniques in place). All three projects are performing evaluations. Current results show that nuclear hydrogen will become competitive with grey hydrogen when CO_2 emissions are sufficiently taxed to support the energy transition. This will be fostered by the expected improvements in electrolyzer technology and corresponding reductions in equipment costs.

Another important aspect is hydrogen transportation. Existing nuclear power plants are usually in remote places, and in almost every case, far from potential end-users of the nuclear hydrogen. Thus, hydrogen transport has a significant impact on the LCOH. With the European Hydrogen Backbone, an international grid of hydrogen pipelines across Europe, not yet existing today, it is cheaper to transport the electricity to end-users and produce low-carbon hydrogen there close to the end-users' sites. Newly built smaller reactors, such as light-water SMRs and HTRs investigated by TANDEM and GEMINI4.0, may minimize the problems associated with hydrogen transport, by being sited close to end-users, especially in industrial areas.

One last aspect all three projects looked at was public awareness and acceptance. NPHyCo addressed the question of nuclear hydrogen production as a means to foster decarbonization that can also increase public acceptance of nuclear energy production. Respective surveys showed that public knowledge about use and production of hydrogen is rather low and awareness about chances and risks of cogeneration of hydrogen with nuclear power is even lower. GEMINI 4.0 has similar results. Given the novelty of SMR technology, TANDEM is organizing workshops to raise citizen awareness of this technology and non-electric applications of nuclear technology.

5 Conclusion

This paper deals with the assessment of low-carbon energy generation solutions (heat, electricity, hydrogen) provided by nuclear reactors in the general framework of nuclear cogeneration addressed by three ongoing Euratom projects, GEMINI 4.0, NPHyCo and TANDEM. It gives a short overview over the three projects, points out the respective objectives and methodologies and describes the current results. Besides, it provides a first analysis of the common outcomes from the three projects. In particular, it showed that there is no showstopper to the production of low-carbon hydrogen from nuclear power. There are several ways of production that are technically feasible and can be shown to be reasonably safe. It could be shown as well that all potential solutions are not competitive today compared to currently established high-carbon hydrogen production from fossil sources e.g., hydrogen production from natural gas via steam methane reforming.

Although the cost of production of low-carbon hydrogen is expected to decrease with technical improvements in the coming years, decarbonization goals can only be achieved when the avoidance of CO_2 emission is funded, and/or the emission of CO_2 is penalized. Only then would conventional hydrogen production plants be equipped with carbon capture and storage (CCUS) technology and the competition with electrolysis from low carbon electricity becomes fairer.

Transportation is another key feature. If production of hydrogen far from the off taker is wanted e.g., to make use of idle capacity of existing nuclear power plants an effective and wide-spread network of hydrogen pipelines is needed. Such network will not come to life if there is no profitable market for low-carbon and green hydrogen.

Support from the EU and national governments is needed to turn idealistic decarbonization goals into economically rewarding technical solutions. The CO_2 certificate prices need to increase accordingly and decisions to foster production change to low-carbon technologies are required such as change of regulations or granting of licensing exemptions.

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Conflicts of interest

The authors declare that they have no competing interests to report.

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All authors contributed to the preparation, structure and writing of the general overview given for the three Euratom projects in this paper. The writing was coordinated by M. Glückler and C. Serin. All authors proofread the final version of the paper.

Disclaimer

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

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