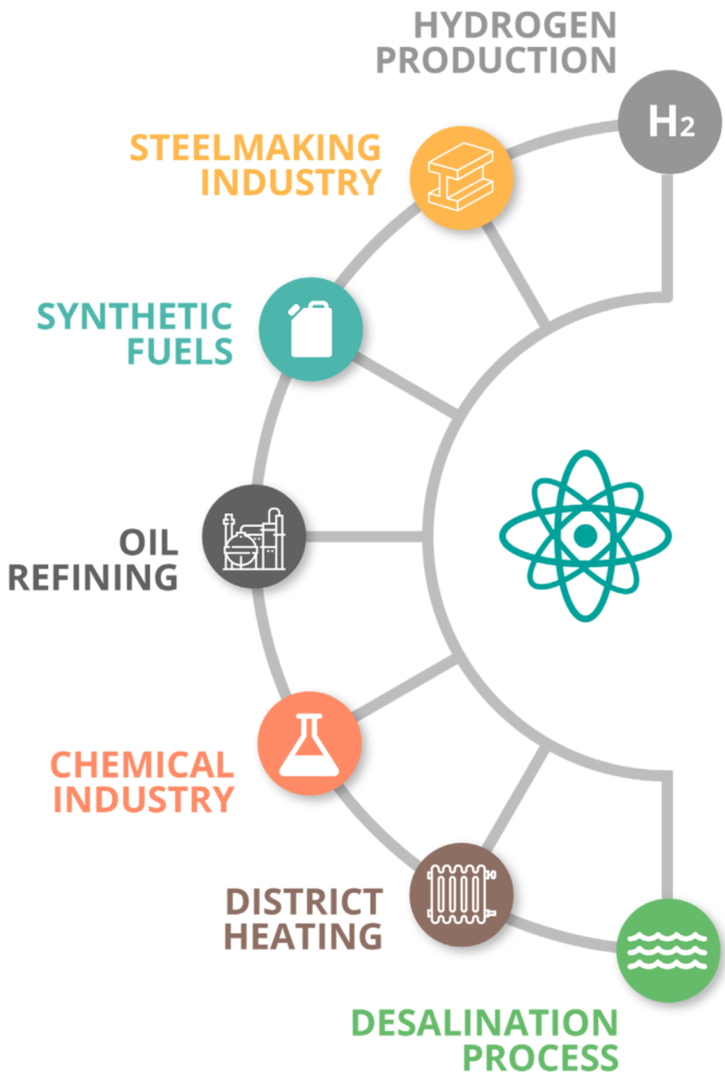
SNETP
Sustainable Nuclear Energy Technology Platform

NC2I
Nuclear Cogeneration Industrial Initiative

NC2I VISION PAPER

September 2023



www.snetp.eu/nc2i

This document has been prepared by the
Nuclear Cogeneration Industrial Initiative
established within the European
Sustainable Nuclear Energy Technology Platform.

Core contributors

Józef Sobolewski
Dominique Hittner
Michael Fütterer

Józef Sobolewski

Chairman of NC2I

Foreword

It is well known that the prosperity of societies is strongly correlated with their access to reliable and affordable energy. Energy plays a vital role in various aspects of human life, such as enabling effective food production, ensuring clean drinking water, providing lighting, heating and cooling for homes and buildings, supporting industrial processes, facilitating transportation, enabling communication, and enhancing entertainment options. As the world population continues to grow rapidly, access to energy is increasingly recognized as a fundamental human right.

With the acceleration of climate change, European citizens and politicians are becoming increasingly aware of the negative impacts of continued reliance on fossil fuels for stable energy supply and as feedstock for essential products of chemical and petrochemical industries. Moreover, the war in Ukraine has evidenced that the large dependence of Europe on fossil fuel imports is weakening its economy thus challenging Europe's geopolitical weight. Therefore, the urgency of implementation of solutions to limit the use of fossil fuel in Europe is becoming widely recognized, and included in the objectives of the Net Zero Industry Act (NZIA).

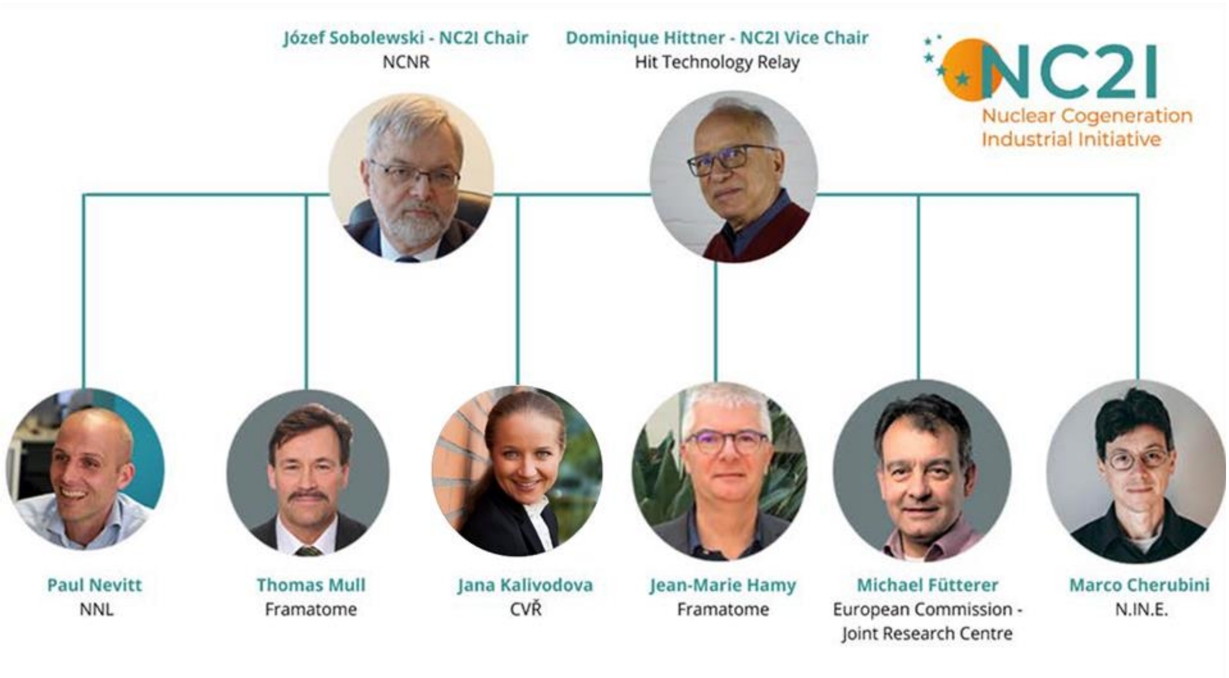
Among the different sources of energy, nuclear is one of the most efficient, and the one with the lowest lifecycle greenhouse gas emissions. Nuclear reactors produce nearly 1/4 of the electricity in Europe today. Nuclear technology, however, has not yet said its final word. If we compare the evolution of combustion from a fireplace to supercritical boilers, I would place Generation I and II nuclear reactors at the level of a tiled stove. There is a need and there is room for many improvements and innovations. In order to explore these paths, major European nuclear stakeholders set up the Sustainable Nuclear Energy Technology Platform (SNETP).

When talking about energy, most people mean electricity. But if we take into account the total final energy consumption per capita in the EU, electricity is less than 1/4 of the total consumption, the rest comes from fossil fuels. We should bear in mind that approximately the same amount of primary energy is used for heating/ cooling and for transport as for thermal electricity generation. Physics dictate that electricity generation from combustion or from nuclear reactions always leads to large quantities of waste heat.

However, through cogeneration of heat and electricity we can turn this "waste" into a valuable resource. Applying cogeneration to nuclear energy may significantly change the European landscape and economy. No more CO_2 emission, but rather clean and affordable energy to heat or cool our buildings, with a nuclear technology that will also deliver high temperature heat needed by industry.

In addition to heat, nuclear energy can produce large quantities of clean hydrogen either by using simple electrolysis at room temperature or more efficient high temperature processes. This is in stark contrast to the presently dominating hydrogen production process, Steam Methane Reforming of natural gas (releasing about 8 times more CO_2 by weight than the produced hydrogen. Clean hydrogen or hydrogen derivatives can play a key role for decarbonization of industrial processes and of transport, which are responsible for twice the greenhouse gas emissions of electricity generation. Developing the production of nuclear heat and hydrogen are indeed the goals of the Nuclear Cogeneration Industrial Initiative - one of the three pillars of SNETP.

NC2I Coordination Board



Marco Cherubini, Nuclear and Industrial Engineering (N.IN.E.), Italy
Michael Fütterer, European Commission - Joint Research Centre (JRC), Europe
Jean-Marie Hamy, Framatome SAS, France
Dominique Hittner, Hit Tech Relay (HTR), France – Vice-Chairman of NC2I
Jana Kalivodová, Research Centre Řež (CVR), Czech Republic
Thomas Mull, Framatome GmbH, Germany
Paul Nevitt, National Nuclear Laboratory (NNL), UK
Józef Sobolewski, National Centre for Nuclear Research (NCBJ), Poland – Chairman of NC2I

Declared NC2I Members

CEA	Commissariat à l'Energie Atomique et aux Energies Alternatives	France
Chalmers	Chalmers University of Technology	Sweden
CVREZ	Centrum vyzkumu Rez s.r.o.	Czech Republic
EDF	Electricité de France	France
EDF Energy	EDF Energy Nuclear Generation Limited	UK
Energorisk	Energorisk, Ltd.	Ukraine
ES Group	ES Group Europe s.r.o	Ukraine
Fortum	Fortum Power and Heat Oy	Finland
Framatome (F)	Framatome SAS	France
Framatome (D)	Framatome GmbH	Germany
HTR	Hit Tech Relay	France
IFE	Institute for Energy Technology	Norway
IZFP	Fraunhofer Institut IZFP	Germany
Jacobs	Jacobs	UK
JAEA	Japan Atomic Energy Agency	Japan
JRC	European Commission – Joint Research Centre	EU
LEI	Lithuanian Energy Institute	Lithuania
MTA EK	Center for Energy research, Hungarian Academy of Science	Hungary
NCBJ	National Centre for Nuclear Research	Poland
NINE	N.IN.E Nuclear and Industrial Engineering S.r.l.	Italy
NNL	National Nuclear Laboratory	UK
NRG	Nuclear Research & consultancy Group	The Netherlands
Nucadvisor	NucAdvisor	France
Nuccon	Nuccon GmbH	Austria
SSTC NRS	State Scientific and Technical Center for Nuclear and Radiation Safety	Ukraine
Tractebel	Tractebel Engie	Belgium
UJV	ÚJV Řež, a. s.	Czech Republic
VTT	VTT Technical Research Centre of Finland	Finland
Westinghouse	Westinghouse Electric Sweden AB	Sweden

The Nuclear Cogeneration Industrial Initiative aims to make a significant contribution to European energy security and decarbonization targets by facilitating the deployment of nuclear cogeneration plants and new nuclear technologies for clean and competitive energy beyond electricity.

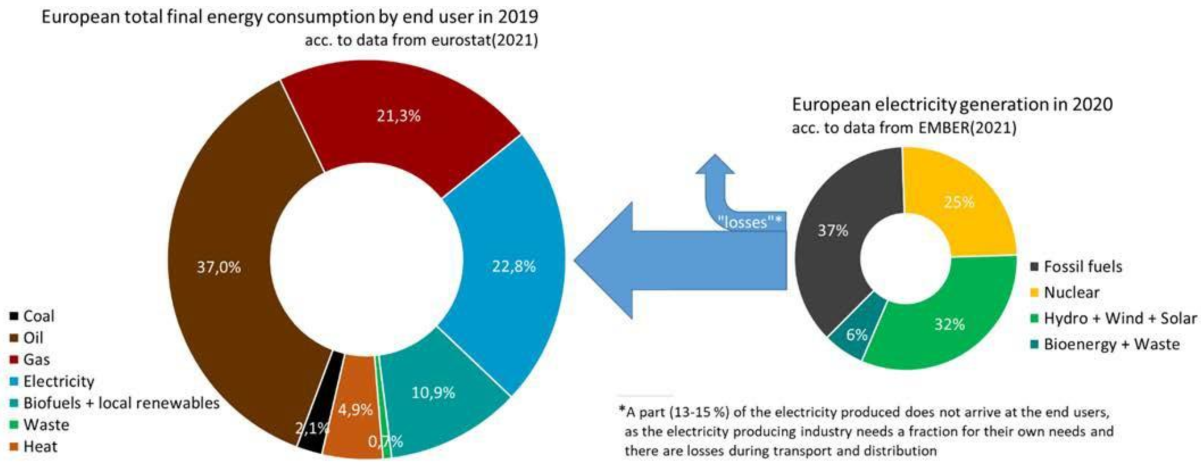
NC2I Mission

In the present period, the acceleration of climate change and the high vulnerability of the European economy to the energy crisis are major concerns in the European Union The urgency of finding solutions not only for low- carbon electricity generation, but also for full decarbonization of industry and of other non-electric energy needs (presently responsible for CO_2 emissions four times higher than electricity generation [1]) has become evident. Such solutions should be affordable, deployable in the short- term, and should enhance the security of energy supply in the EU.
The Nuclear Cogeneration Industrial Initiative (www.snetp.eu/nc2i) was established as one of the three pillars of the Sustainable Nuclear Energy Technology Platform (SNETP – www.snetp.eu). Its mission is to accelerate the development of solutions for non-electric applications of nuclear energy in line with the objectives of the Green Deal to reach Net Zero in 2050. While nuclear is not included in the Net Zero Industry Act, the technologies proposed by NC2I are destined to help decarbonize industry at large scale in those countries that choose to include nuclear in their energy mix.

As stipulated by Commissioner Gabriel and major European stakeholders [2], they offer flexibility of use for process heat in energy-intensive industries and for producing hydrogen.

Need of Clean and Competitive Heat

Nuclear power is a reliable technology for electricity production without harmful emissions. Today's industrial nuclear power plants produce 26% of all electricity [1] and 52% of energy from non-combustible sources in Europe. However, electricity represents only 24% of the European energy consumption, while heating and cooling for residential and industrial uses account for 50%. Almost 100% of derived heat originates from combustion and only 0.2% from nuclear reactors. This implies that an effective European energy strategy has to address this sector with high priority although it is merely invisible to the public. The expected political and socio-economic benefit is very significant.



Electricity generation with its CO_2 emission structure in quantitative relation to other CO_2 sources, in terms of final energy consumption, European view (graphics based on Eurostat data [4] (left) and EMBER [5] (right))

NC2I Strategy

1. Low Temperature Cogeneration

In addition to electricity generation, heat from present industrial nuclear reactors is already being used up to 240°C in several European countries and worldwide, e.g. for district heating, seawater desalination or various needs of process heat in the paper and pulp industry. As confirmed by related studies (EU projects [3], [6], [7], IAEA [8]), the significant existing experience in nuclear cogeneration of heat and power has shown that nuclear energy can substitute fossil-fired cogeneration without drawbacks in terms of compatibility with end-user needs, performance, reliability and safety, and even with advantages in terms of economic aspects such as competitive cost and price stability, emission reduction, and customer satisfaction. Plans like those in Finland considering construction of Light Water SMR for district heating are opening perspectives in this respect.

2. High Temperature Process Heat

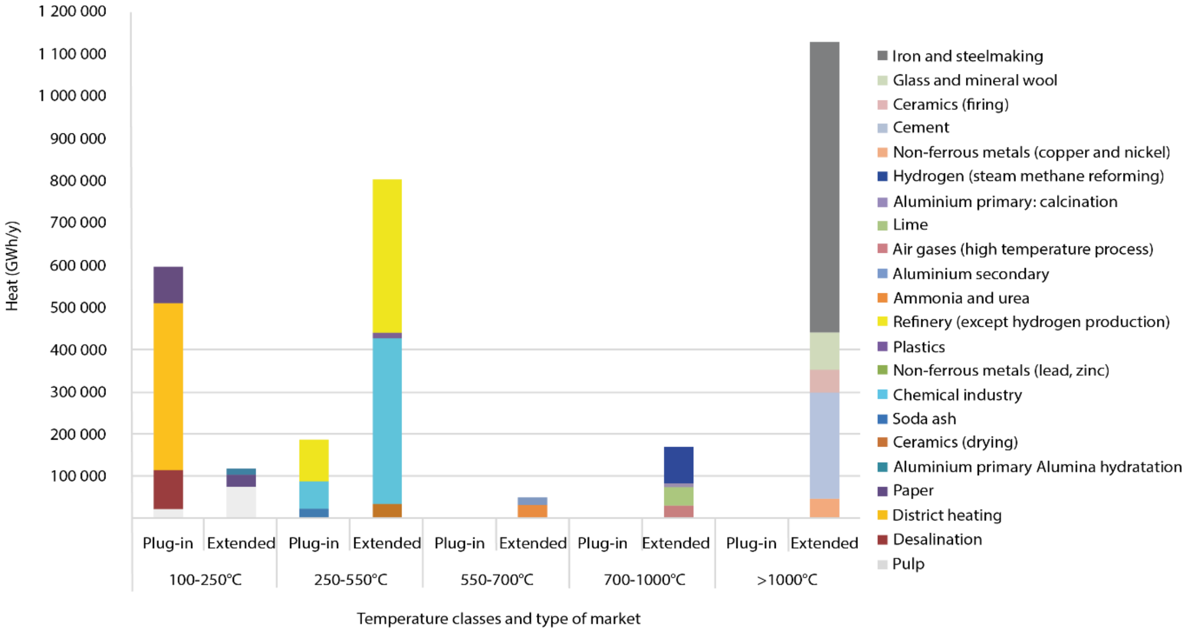
Approx. 90% of process heat in most industrialized countries is characterized by high energy intensity at > 250°C (see figure below, data from [5]). This, coupled with absolute dominance of fossil fuels in heat production, results in high emissions, not only of CO_2, but also of fine dust, heavy metals, NO_x, SO_3 and others. Consequently, many issues concerning public health, environment, energy security, geopolitics, socio- economics etc. are at stake. As long as no commercially viable alternative exists, fossil fuels remain the sole option for most high-temperature processes that power industry.

In Europe, about 50% of the process heat market is found in the temperature range up to 550°C, today mainly in the chemical and petrochemical industry, with perspectives for the production of hydrogen, steel, cement and other hard-to-abate applications [6], [7].

To advance broader applications of nuclear cogeneration to industrial processes requiring heat at high temperature, international technology developments are focusing on nuclear reactor types designed to deliver this high temperature heat. Depending on the customer's needs, various reactor concepts can be considered, e.g. the well-known Generation IV International Forum concepts, including modular High Temperature Reactors (HTGR) and their long-term evolution towards very high temperatures (VHTR), Super-Critical Water Reactors (SCWR), Molten Salt Reactors (MSR) and different Fast neutron reactor concepts cooled by either Sodium (SFR), Lead (LFR) or Gas (GFR).

However, for competitive nuclear solutions delivering process steam up to 550°C to be deployed as soon as possible to curb industrial CO_2 emissions while maintaining energy-intensive industry in Europe despite the present energy crisis, the HTGR featuring the most mature technology for high temperatures, is currently the only option, ready for early deployment and covering the broadest range of temperature. The expected experience feedback from HTGR operation will later facilitate deployment of other advanced reactor types for nuclear cogeneration once these can deliver high temperatures, become mature enough and present certain advantages in comparison to HTGR.

Modular HTGR designs feature unique simplicity owing to their intrinsic passive safety concept and to the unique property of its fuel that can withstand temperatures above 1600°C without losing its integrity and releasing its radioactive content. Combined with relatively low power output and low power density, such features make a core meltdown impossible. The modular HTGR safety concept is therefore a clear advantage for siting in proximity to industrial end users. As it also makes expensive redundant and active engineered safety systems superfluous, it is an asset for competitiveness, a prerequisite for any industrial deployment.



Distribution of the European heat market by temperature class and sector [6].

The "plug-in market" is the part of the market in which heat is supplied to industrial processes by steam distribution networks in the temperature range 100 - 550°C. Today, steam is produced by fossil fuel fired cogeneration plants or boilers, which can be substituted by nuclear plants delivering steam with the same characteristics, without changes to the existing steam distribution infrastructure. The remaining heat market is the "extended market". In the range 250 - 550°C, the European heat market represents more than 100 GWth. This includes a large part of industrial applications requiring steam at significantly higher temperatures than what Light Water Reactors could deliver.

3. Industry needs Hydrogen and Heat - together

Emissions of CO_2 from industry are not only resulting from fossil fuel burning for process heat supply. Certain processes themselves generate a significant part of the CO_2 released by industry. Chemistry, steel industry, present hydrogen production from steam-methane reforming etc., use carbonated agents, which are responsible for significant CO_2 emissions. These could be avoided by substitution of carbonated agents by hydrogen stemming from water splitting processes. Any nuclear reactor can produce hydrogen through water electrolysis, but only HTGR can produce at the same time high temperature process heat and hydrogen required by industry.

In addition, the high temperature heat produced by HTGR allows the use of high temperature thermochemical processes or high-temperature steam electrolysis for large-scale hydrogen production. These processes achieve much higher efficiency than low-temperature alkaline electrolysis. Hydrogen or hydrogen derivatives such as synthetic hydrocarbons or ammonia could also be employed for energy storage or hard-to-abate transport purposes. Therefore, the use of HTGR could not only clean up many industrial processes, but also contribute to the decarbonization of road, air and maritime transport, as well as to energy storage. When including electricity generation, industrial process heat applications and hydrogen production for industry and transport, nuclear energy has the potential to cut about 75% of human CO_2 emissions.

NC2I Strategy

In line with the ambitions of the Green Deal to reach Net Zero in 2050 and to complement actions foreseen in the Net Zero Industry Act (NZIA), NC2I endeavors to provide a timely nuclear contribution to the European demand for low- carbon heat and transportation fuel. NC2I aims at unlocking and using the potential of nuclear cogeneration to substitute at large scale fossil fuels in industrial and residential heat applications and to produce hydrogen for decarbonizing multiple applications in industry and transport. Hence, NC2I focuses on:

- collecting and developing data and know-how needed for industrial deployment of nuclear cogeneration;
- demonstrating the technical and economic viability of this technology for process heat and hydrogen;
- licensing of nuclear cogeneration systems.

4.1 Low-Temperature Cogeneration

Although the experience with low temperature cogeneration using LWRs has been largely positive, up to now such installations at the scale of a few tens to several hundred MWth remain scarce, as there were no incentives in a context of cheap and abundant natural gas and in absence of CO_2 taxation. Now that the geopolitical energy landscape is drastically changing, based on the analysis of existing experience and of its so far limited market penetration, NC2I is supporting initiatives to facilitate new deployment of low-temperature nuclear cogeneration, and of reactors dedicated to heat supply. In particular, NC2I is following the present development of Integrated Light Water Small Modular Reactors (LW-SMR) that might offer new prospects for low-temperature cogeneration: the power delivered by these systems often matches well with end-user needs in several EU countries. Their safety design, based on systematic use of passive systems might exclude massive radioactive release in accidental conditions. Consequently, the construction of such reactors in close vicinity to agglomerations or industrial sites might be acceptable, thus avoiding high costs for long-distance heat transport and the resulting heat losses. Such LW-SMRs could substitute fossil-fired boilers or cogeneration plants to deliver hot water or steam to existing heat networks without requiring changes to these heat distribution infrastructures. They could also provide chilled water for cooling of buildings in summer. These applications are limited to the market sector with applications up to approximately 250°C, unless they use temperature boost techniques (electric superheating, chemical or compression heat pumps), which, however, have a negative impact on exergy efficiency.

4.2 High-Temperature Process Heat

For the much larger market of industrial processes requiring steam up to 550°C, NC2I considers HTGR technology to be the most appropriate in the short/medium term, because HTGR can rely on significantly higher readiness levels than other concepts: in Europe, extensive technology developments have been performed, including projects of recent Euratom Framework Programmes. Two test reactors (DRAGON in the UK and AVR in Germany), as well as an industrial prototype (THTR in Germany), were built and operated. China has started an industrial prototype plant with 2 reactors of 250 MWth each, and 2 high temperature test reactors are operated, one in Japan and another one in China. Several other countries and private companies are also running HTGR development projects, e.g. in the US, Canada, Japan, Korea, Poland, UK and elsewhere.

Moreover, the present energy crisis has put energy security high on the political agenda. In Europe, HTGR are competitive with natural gas above a price of the order of 15-20 US$/MBtu.

The skyrocketing prices attained by natural gas since the beginning of the Ukraine war have demonstrated the unacceptable vulnerability of European industry and society to gas price volatility and the resulting disruptive impact with its long-reaching consequences such as further de-industrialization and carbon leakage. Already now at a gas price that has dropped back to 11.6 US$/MBtu in late summer 2023, HTGR with its price stability can immunize industry against unpredictable gas prices and ever increasing CO_2 taxes.

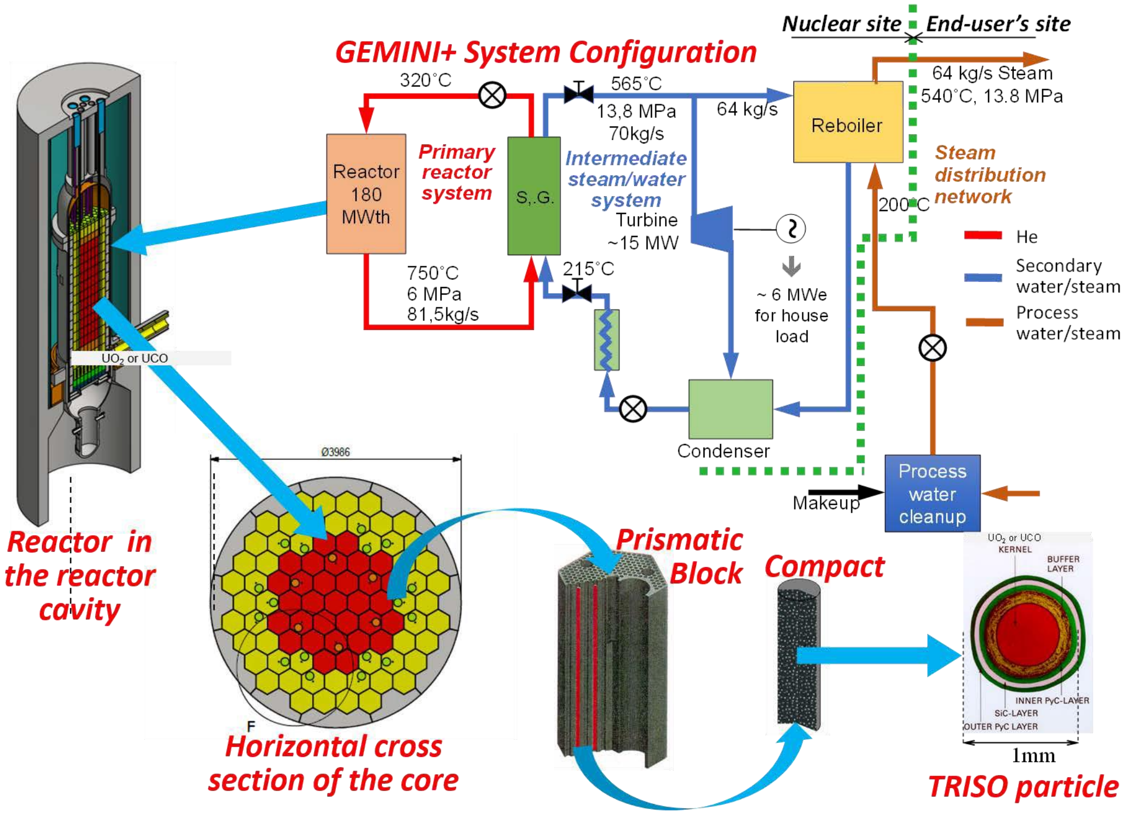
Based on the high HTGR readiness levels in terms of technology, market, and licensing, the next step is near-term demonstration of the coupling between a nuclear reactor with an industrial site for heat supply at relevant scale. This will be a major innovation, because so far electricity has been the main product of the nuclear industry. While several low-temperature heat applications have been implemented until now, they were mostly by-products of electricity generation.

Such demonstration shall confirm that the operation of an HTGR is competitive and can match the needs of industrial customers. There shall be no unacceptable constraints from the nuclear plant on the customer operations and vice versa. It shall also verify that the licensing of such a coupled facility does not raise new issues. Most of all, demonstration will be a lighthouse project for industry and investors to raise interest in HTGR as a solution with acceptable innovation risk to achieve profitable business results while meeting their energy and environmental targets.

Conventional industrial cogeneration is practice on many industrial sites across Europe for production of steam at or below 550˚C. This steam is distributed as heat carrier or chemical reactant to processes through large steam networks.

For temperatures above 550˚C, the heat required by applications is currently produced in-situ by combustion of fossil fuels. No technology for heat transport at this level is industrially available, except for few applications using molten salts up to 650˚C. For short-term demonstration, the objective of NC2I is, therefore, to demonstrate nuclear cogeneration at a high temperature level. Like any major innovation, this comprises certain risks (technical, financial, scheduling, licensing, competitiveness and others). To mitigate these risks, NC2I proposes for this demonstration the use of proven HTGR technology and to add it to a conventional cogeneration plant for steam supply to an existing steam distribution network (“plug-in” application). The existing plant could then continue to be used as back-up to the nuclear plant in case of outages.

In addition to early demonstration, NC2I also encourages longer-term development of HTGR technology and of the interface with end-user processes. Without ignoring the evolution of many of these applications towards lower temperatures owing in particular to new catalysts, advanced materials should be developed and qualified to extend the field of application of HTGR towards the many non-electric applications that will continue to depend on heat at temperatures beyond the reach of current technology.



GEMINI+ concept for process steam generation.

A prismatic block type HTGR is producing primary helium at 750˚C, which is converted to secondary steam at 565˚C. A small fraction of this steam is transformed via a small turbine to electricity to cover the house load of the system. The largest part of the energy is sent to a reboiler producing tertiary steam at 540˚C, thus physically separating the nuclear facility from the end-user product. The system delivers the equivalent of 165 MWth to an existing steam network thereby matching the power output of many standard fossil-fired boilers.

NC2I Actions

For demonstration of nuclear cogeneration at industrial scale as soon as possible, NC2I partners, in cooperation with authorities in target countries and in synergy with other SNETP pillars, are working to facilitate:

- any European initiative towards demonstration of nuclear cogeneration; presently, these are most particularly the Polish HTGR-POLA programme to develop HTGR for testing industrial applications, and projects with similar objectives in the frame of the UK AMR programme and the France 2030 competition;
- definition of the most appropriate technical options of a commercial reactor design addressing the needs of end-users, competitiveness and updated safety requirements, while minimizing project risks; this is done by performing Euratom funded projects; the most recent was GEMINI+, which proposed the principles of a standard design for adapting to versatile cogeneration needs of different industrial sites; the new project GEMINI 4.0 (started in 2022) is examining the potential of the GEMINI+ design to cogenerate electricity, high-temperature heat and hydrogen;
- preparation of the above mentioned Euratom funded projects of an updated licensing framework for a modular cogeneration plant including the highest recent safety requirements, in particular taking into account the European Nuclear Safety Directive;
- support from political and economic stakeholders, as well as the awareness of citizens about the benefits for Europe to develop the use of nuclear cogeneration for low- and high-temperature heat supply and hydrogen production, in particular, but not only, through the efforts of Euratom funded projects and other initiatives, e.g. the upcoming SMR Partnership;
- in line with the European Commission Declaration EU SMR 2030, the inclusion of early demonstration and deployment of HTGR for industrial non-electric applications in the frame of the European SMR Partnership [9];
- development of international cooperation around the project, so as to let it benefit from activities of international organizations, such as OECD/NEA, IAEA, and GIF, as well as other industrial and research capacities.

References

[1] All data for energy 2015 EC28 http://ec.europa.eu/eurostat and http://heatroadmap.eu/.

[2] Commission Declaration on “EU Small Modular Reactors (SMRs) 2030: Research & Innovation, Education & Training”, 4 April 2023. https://research-and-innovation.ec.europa.eu/system/files/2023-04/ec_rtd_eu-smr-declaration-2030.pdf

[3] C. Auriault, O. Baudrand, M.A. Fütterer, Experience Feedback from Nuclear Cogeneration, 2015 International Congress on Advances in Nuclear Power Plants, ICAPP’15, Nice, France, 3-6 May 2015.

[4] Energy statistics - an overview - Statistics Explained (https://ec.europa.eu/eurostat/statistics-explained/).

[5] C. Redl, F. Hein, M. Buck, P. Graichen, D. Jones, Agora Energiewende and Ember (2021): The European Power Sector in 2020: Up-to-Date Analysis on the Electricity Transition, 202/02-A-2021/EN, January 2021.

[6] A. Bredimas, Market study on energy usage in European heat intensive industries, EUROPAIRS project, FP7, Deliverable 131, 27/05/2011.

[7] A. Bredimas, Results of a European industrial heat market analysis as a pre- requisite to evaluating the HTR market in Europe and elsewhere, Nuclear Engineering and Design, Vol. 271, p. 41-45 (May 2014).

[8] Advances in Nuclear Power Process Heat Applications – IAEA-TECDOC-1682 (May 2012).

[9] Information on the EU SMR pre-Partnership and draft Workstream reports: https://snetp.eu/2023/07/17/european-smr-pre-partnership-launches-stakeholders-consultation-on-work-performed-to-date/

9 782919 313372

www.snetp.eu/nc2i