



# GEMINI+

2021



## HTGR, A CLEAN ENERGY FOR INDUSTRY & TRANSPORT

# BOOK LET

At the heart of research carried out in the Horizon 2020 project GEMINI+, nuclear cogeneration through High Temperature Gas Cooled Reactors (HTGRs) matters today to achieve the European energy transition.



# WHY THIS BOOKLET?

As partners of the GEMINI+ project of the Euratom H2020 Programme, we defined the design basis of a High Temperature nuclear Reactor (HTR) that enables not only electricity generation, but also heat supply for industrial processes without CO<sub>2</sub> emissions. Moreover, with this high temperature heat, “green” hydrogen, also important for decarbonisation of industrial processes and transport, can be produced in large quantities.

We are convinced that to comply with the ambitious Green Deal objectives of decarbonisation of Europe, addressing CO<sub>2</sub> emissions of electricity generation is not enough. Industry and transport are responsible for even more emissions. Nuclear energy can contribute to decarbonise these activities, not with present electronuclear plants, but with reactors operating at higher temperature. The solution we propose in GEMINI+ is likely one of the nuclear solutions that can be implemented the most quickly. And it is not only a theoretical view: in Europe, Poland, which participates in GEMINI+, plans to make a demonstration of the use of HTR for industrial heat needs on the basis of the results of this project.

With this booklet, we want to give the general public, the stakeholders from the political spheres, from industry and from financial institutions, the information necessary to understand our project and its importance for Europe and possibly to support it. If you have any questions or if you need more information, please visit our website and/or contact us: [secretariat@snetp.eu](mailto:secretariat@snetp.eu)

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# THE POTENTIAL OF HTGR TECHNOLOGY

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## Nuclear supplies clean energy

Based on fission of uranium, nuclear energy does not emit CO<sub>2</sub> and other pollutants (microparticles, NOX, etc.). About 25% of electricity in Europe is generated by nuclear plants avoiding 790 million tons of CO<sub>2</sub> that would be emitted if that electricity was generated by coal-fired power plants, and still 215 million tons, if generated by modern combined cycle natural gas-fired power plants.

Nuclear produces little waste: a 1000 MW nuclear plant produces about 16 tons of irradiated fuel per year (approximately 1,5 m<sup>3</sup>). For comparison, a 1000 MW coal plant rejects about 400 thousand tons (approximately 150 thousand m<sup>3</sup>) of ashes per year, containing toxic and radioactive products, plus toxic microparticles (with a death toll of 23 thousand people per year in Europe).

The radioactive waste of nuclear plants can be safely buried deeply underground in stable geological formations, where it has been scientifically shown that it will remain captured. The radioactivity of this waste will disappear progressively over time, contrary to that of certain chemical waste (in particular the type found in coal ashes).

Moreover, the large reserves of nuclear fuels' raw materials are much less vulnerable to geopolitical instabilities than fossil fuel. This provides an excellent contribution to the long-term sustainability and security of energy supply in Europe.





## **Electricity represents a small fraction of consumed energy**

Only 23% of the energy is consumed in Europe in the form of electricity while the need for heat in industry is much higher. This is nearly fully reliant on fossil fuels. Therefore, decarbonising electricity generation with nuclear and renewables is only a small part of the solution to tackle global warming.

## **Can nuclear contribute to decarbonise non-electricity energy consumption?**

A large part of the energy produced by any thermal electricity generation machine is wasted. Using a thermal machine to deliver both electricity and heat (cogeneration) is more efficient.

Cogeneration is widely used on industrial sites to produce both the electricity and heat/steam needed by the site. Usually, cogeneration is performed with fossil fuel-fired plants, very rarely with nuclear plants. In here lies a great opportunity for the newest generation of nuclear power plants.

Today's electro-nuclear plants operate at about  $300^{\circ}\text{C}$ , where the heat can be used for district heating, desalination of seawater, and a few other low temperature industrial applications (for instance the paper industry). Unfortunately,  $300^{\circ}\text{C}$  is inadequate for most industrial processes, which require higher temperatures (between  $300$  and  $550^{\circ}\text{C}$ ).

For such high temperature nuclear cogeneration applications, other types of reactors are required. Such reactors already exist: the Generation IV systems. The most mature of these reactors can be deployed early enough to curb CO<sub>2</sub> emissions in the short-term. These are the High Temperature Gas-cooled Reactors (HTGRs).

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## What is a High Temperature Gas-cooled Reactor (HTGR)?

A High Temperature Gas-cooled Reactor (HTGR) is a helium-cooled, graphite, moderated nuclear reactor, which has been demonstrated to operate with proven technologies at a temperature up to about 750 °C. In the longer-term, with advanced materials, 900 to 1000 °C could be reached.

The helium heated in the core of the reactor, boils water in a steam generator. A turbo-generator that supplies electricity can be operated with the steam produced in the steam generator. However, this high-quality steam is now of a sufficient temperature that it can also **provide heat to an industrial steam network**. In addition, it can **supply steam to a district heating network for households**. This is where the HTGR adds its highest value to the energy system for the future.

The HTGR uses a special fuel called TRISO fuel. TRISO fuel is made of **1 mm particles**, in which a fissile kernel (the source of the primary energy) is wrapped by three refractory coating layers. These layers keep in any condition – normal or accidental – full leak tightness to the radioactive products that are formed in this kernel during operation of the reactor. Thanks to this fuel, there cannot be any significant radioactive release to the environment, in any circumstances.



## For which kind of applications?

In addition to the applications that are already accessible by today's water-cooled reactors, HTGR can supply high quality (up to 550 °C) heat/steam to industrial processes, mainly in chemical and petrochemical industries. The market for these applications is significant: they use 87 thousand MWth in EU, presently (exclusively) produced by burning fossil-fuel.



Currently, heat is in many cases already provided by conventional cogeneration plants or boilers through steam distribution networks, HTGR can therefore be “plugged-in” into existing networks, substituting older cogeneration without any other modification in the existing infrastructure of the industrial site. This will be HTGR's entry market.

Later, once HTGR heat supply has proven to be economically attractive, other applications below 550 °C through new steam networks will form the next market. Also, HTGR can easily perform pre-heating for processes above 550 °C, reducing their CO<sub>2</sub> emissions.

In due course, HTGR can also be used to boost clean, high-efficiency production of hydrogen from thermo-chemical and high-temperature



electrolysis processes. Hydrogen has already a large, growing use in industry for replacing carbon as a reducing agent to suppress CO<sub>2</sub> emissions of chemical processes (today 8% of total CO<sub>2</sub> emissions in the EU).

Moreover, HTGR will also address the needs of reduction of CO<sub>2</sub> emissions in transport (25% of total emissions), either directly through the direct use of hydrogen, or through the production of synthetic fuels. CO<sub>2</sub> free heat supply is only the start for reducing CO<sub>2</sub> emissions in industry and transport.

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## High Temperature Gas-cooled Reactor (HTGR) is very safe

Heat cannot be transported over long distances. The source of heat must be located close to its uses. HTGRs can be located close to urban centres or large industrial sites because of their outstanding safety characteristics.

This very high safety level, addressing the most stringent international safety standards, is made possible by combination of several inherent features of HTGR, a large thermal inertia provided by the hundreds of tons of graphite in its core, which makes possible temperature excursion very slow, a negative effect of temperature increase on core reactivity, which immediately stops nuclear fission, as soon as the temperature starts to increase, and finally the robustness of the TRISO

fuel, which keeps radioactivity tightly enclosed in the fuel up to more than 1600 °C. These features make HTGR a very forgiving reactor.

Moreover, based on the above mentioned inherent physical features, if a HTGR is limited to a few hundred megawatts, **the reactor (then called a modular HTGR) can be designed in such a way that its safety is fully passive.** This means that even without any active safety system - or human - intervention, the fuel cannot exceed 1600 °C (i.e. cannot reach melt-down temperatures), preventing significant radioactivity release to the environment in any accident conditions.

And finally, the TRISO fuel is not only more robust than other types of nuclear fuel now in operation. It also keeps its outstanding robustness in final disposal conditions. Its coating layers provide a **robust barrier to migration of fission products from a deep geological repository to the biosphere.** ●





# BUILDING THE TRANSITION

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## **The EU truly committed to reduce its greenhouse emissions**

Within the 2015 Paris Agreement, the EU pledged to reduce of at least 40% its greenhouse gas emission by 2030. In order to make a global energy transition, the Commission set up the 2016 Clean Energy Package for all Europeans. It covers five dimensions: energy security, internal energy market, energy efficiency, decarbonisation of the economy, and research, innovation and competitiveness.

More recently, the European Green Deal has reinforced the EU ambition of achieving climate-neutrality by 2050. According to Ursula von der Leyen, President of the European Commission, this set of new regulations and policies "is our new growth strategy. It will help us cut emissions while creating jobs." One of its main targets is to decarbonise the energy sector by cutting at least 55% of carbon emissions by 2030.



## Contributing to the European Green Deal objectives

Investing only in renewable sources is not enough to tackle global warming. For instance, in industrial heat uses renewables cannot sensibly replace fossil fuel-fired plants. HTGR technology can, however, provide a CO<sub>2</sub> clean solution here, and can also be a source for green hydrogen production at a relevant scale.

HTGR technology is mature and already available today. The growing number of HTGR projects worldwide include China's HTR-PM, an industrial prototype which will likely start operation in 2021, and Canada's micro-HTGR to be built in Chalk River Laboratories before the middle of



the 2020s. Europe also has ample experience with HTGR technology. In addition to many R&D programs, the Euratom projects from the 4<sup>th</sup> Framework Programme, end of in the 1990s, till Horizon 2020, and many design projects up to 2000, the UK has built and operated one of the first experimental HTGR reactors, DRAGON. Germany followed with another test reactor, AVR, and an industrial prototype, THTR. Thanks to this



experience and the competence of its nuclear scientists and engineers, Europe is well positioned to exploit its know-how in nuclear energy not only for the decarbonisation of electricity, but also for reducing the greenhouse gas emissions of industry and transport by high-temperature heat supply from HTGRs.

Investing in the development of HTGR cogeneration plants will therefore contribute to the Green Deal objective of decarbonisation of Europe. It will also secure Europe's energy supply and will help to stop "carbon leakage" of industrial production to countries with less stringent environmental regulations and will therefore contribute to keep industrial jobs in Europe.

## **Building an industrial tool thanks to the GEMINI+ project**

HTGR can contribute significantly to the decarbonisation of European industry in a time frame compatible with the Green Deal agenda (carbon neutrality of EU by 2050). No further significant R&D programme (that could delay implementation) is required to start designing and constructing the nuclear systems for CO<sub>2</sub> free energy supply to industry.

A solid base of technical development, design and feedback from operations is available to support a fast emergence of HTGR systems that can satisfy the performance expectations of industry and the safety requirements of the regulator.

A challenge for developing a system adapted to the energy needs of industry is that it must be flexible enough to address the versatile needs of industry and nevertheless standardised enough to be competitive. But contrary to electro-nuclear plants that deliver a single product (electricity), **each industrial sites require tailored power**, as well as tailored balancing and optimisation between process steam and electricity generation, with each site having different requirements in terms of load transient capacity, etc.

How to design a standardised nuclear plant that must satisfy the versatile energy needs of its customers? **In the framework of the Euratom H2020 Programme, the GEMINI+ project (2017-2020)** developed the main design options for a HTGR plant that brings such flexibility, while keeping a standardised design. This is a prerequisite for cost moderation. The plant does not supply electricity to an external customer. It only supplies steam at 540°C, 138 bars, to the customer's steam distribution network. It can be used primarily for process heat supply, but also, if needed, partially, for electricity generation.

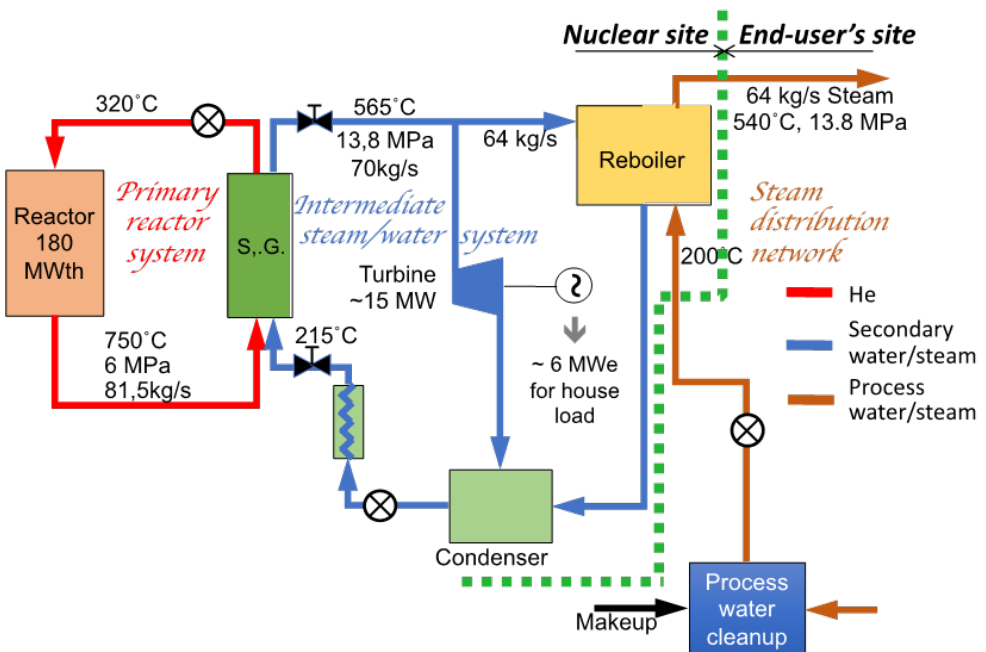


The power delivered in the form of steam to the customer is unitised at 165 MWth. By choosing a relatively small power for each unit and adapting the number of units to the needs of the industrial site, the modular design philosophy allows a **systematic use of modular manufacturing and construction techniques**, which should further reduce cost. Also, the

incorporation of an intermediate steam/water circuit, between the nuclear reactor and the customer's steam distribution network, introduces an additional barrier to radio-contamination of the customer's facilities.

The preliminary cost evaluations performed at the very early stage of design of the GEMINI+ project show that competitiveness with natural gas for high temperature steam supply should already be achievable today with a system implementing the design options of GEMINI+, all the more since the cost of carbon emissions is increasing in Europe. ●

## Configuration of the GEMINI+ nuclear boiler



# THE NEXT STEP

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## **Paving the way for a high temperature cogeneration demonstration**

Because the HTGR technology is mature, there is no need for significant new technology development. However, a few residual R&D needs for consolidating the safety case, remain.

Civil applications of nuclear energy were mainly focused on electricity generation, with a few experiences of cogeneration at low temperature ( $\leq 250^{\circ}\text{C}$ ) for district heating or particular industrial applications that did not require high temperature (paper industry). These applications have been quite successful and did not raise safety issues. Nevertheless, until now, there has been no industrial application of nuclear energy for supply of high temperature heat to industrial processes with HTGR.

Therefore, before any possible large-scale industrial deployment, a demonstration is necessary to show to potential industrial users that:

This type of nuclear heat supply is reliable in an industrial environment and can satisfy industrial requirements (e.g. imposing no constraints on the operation of industrial processes, with in particular the ability to face typical load transients imposed by normal process operation, and no radio-contamination of facilities or products).



The licensing of a HTGR coupled to industrial process heat applications will be acceptable by regulators and will not impose new regulatory constraints to the operation of the non-nuclear industrial processes.

The economic competitiveness can actually be achieved.

Lastly, a demonstration will be the opportunity to initiate the development of a reliable supply chain for the components and systems of the reactor, some of which will require the development of specific manufacturing processes that will have to be qualified for nuclear applications.

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## **Towards industrial deployment and hydrogen production**

The demonstration has the objective of initiating industrial deployment, which will be based on the replication of the design and technology options selected for the demonstration and will not require new developments. However, two significant topics, not part of the demonstrator itself, are essential for industrial deployment of HTGRs, and must be addressed at the same time as and in parallel with the demonstration project:

### **European HTGR fuel development**

The industrial production capacity of the very specific TRISO fuel used in HTGRs, is limited to facilities existing in the US, in China and in Japan. Taking into account the long duration for the development of a fabrication facility and qualification of its fuel, the fuel for the demonstration plant will be procured from the international market. However, in order to face the growing needs of a successful industrial deployment afterwards and to secure fuel supply, a fuel manufacturing capability will have to be developed in Europe. This development should start as soon as possible to be ready to enable and supply a future commercial market.

## Fostering green hydrogen production

Low-temperature electrolysis is more expensive than standard industrial hydrogen production by steam-methane reforming. Most  $\text{CO}_2$  free hydrogen production processes by water splitting, now in development, require much higher temperatures than a steam network can provide ( $< 600^\circ\text{C}$ ) while some require electricity supply in addition.



Coupling this technology with a reactor like the one defined in the GEMINI+ project might nevertheless be possible, without waiting for longer-term development of higher temperature reactors. Nevertheless, the coupling scheme with the reactor will be different from the simple coupling with a steam network.

It is necessary to start selecting the most suitable hydrogen production process to work with an HTGR and develop the specific coupling scheme required for this application, without delay. This will enable massive nuclear hydrogen production when cogeneration HTGRs are commercially deployed. ●



# THE POLISH OPPORTUNITY

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## **A national priority enhancing an early demonstration**

In Poland, in addition to the replacement by nuclear power of coal power plants responsible for nearly all electricity generation, the HTGR technology itself has been placed by the government among the national top priority projects in its 2017 Strategy of Responsible Development. This may considerably reduce natural gas imports, which represent, with coal, the basic heat source for the chemical industry. Indeed, the energy roadmap for Poland presented by the Ministry of Energy included both large light-water reactors and HTGRs.

The high dependency of Polish industry on coal as its primary energy source together with its aging fleet of coal boilers, rising CO<sub>2</sub> emission prices and increasing difficulties of mining domestic coal are strong incentives for such evolution. This evolution was confirmed in 2019 by the Ministry of Entrepreneurship and Technology (now Ministry of Development), which put HTGR in the list of National Smart Specialisations. A new version of the national strategic energy program (PEP2040) is in preparation, and includes the development of HTGR for industry energy needs.





## Public opinion support and large national industrial market

In addition to the Polish government's commitment, the support of public opinion to nuclear energy in Poland remains high: 69% of Polish people living near a site foreseen for nuclear power plant construction are in favour of nuclear energy (according to a survey commissioned in 2018 by the Polska Grupa Energetyczna Energia Jądrowa 1 (PGE EJ1), the nuclear subsidiary of the Polish company Polska Grupa Energetyczna S.A).

On the other hand, Poland is a major consumer of hydrogen and producer of nitrogen-based fertilisers, whose production processes are compatible with HTGR steam supply. The GEMINI+ project identified an amount of 7047 MWth produced presently by conventional fossil fuel-fired boilers and cogeneration plants for chemical facilities in Poland, which represents almost 43 HTGRs with an output of 165 MWth, of the type developed in the European project.

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## Towards early implementation

The GEMINI+ project is coordinated by the National Centre for Nuclear Research (NCBJ), which allowed not only to adapt the design options selected by the project to the needs of Polish industry, but also test the conditions to be met by a demonstration project on an actual Polish case: acceptability of the site, appropriate funding and business schemes,

industrial and technological readiness, readiness of the system and component supply chain, spent fuel management, etc.

The NOMATEN Centre of Excellence has received 7 years (2018-2025) of joint financial support (€37M) from the Foundation for Polish Science and the European Commission on the development of novel materials, specifically those designed to work under harsh conditions – radiation, high temperatures and corrosive environments.



In the frame of the national strategy program GOSPOSTRATEG, the National Centre for Research and Development funds a project (2019 – 2022) for the preparation of law, organisation and technical instruments to deploy the HTGR.

Finally, on the basis of national public funding sources, a budget has been released for starting the programme for the design, construction of a small experimental HTGR, EUTHER, the aim of which will be to demonstrate the technologies that will be deployed later on industrial reactors, as well as the feasibility of coupling with industrial processes.

These initiatives of governmental authorities make presently the Polish HTGR programme the most promising opportunity for an early demonstration of nuclear high-temperature industrial cogeneration in Europe. ●



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During 36 months, GEMINI+ partners worked together towards the demonstration of high temperature nuclear cogeneration with a High Temperature Gas-cooled Reactor (HTGR).

Launched in September 2017, this European Horizon 2020 project funded under the Euratom programme provided a conceptual design of a high temperature nuclear cogeneration system to supply process steam to industry, a licensing framework for this system and a business plan for a full scale demonstration.

Coordinated by the National Centre for Nuclear Research (NCBJ), in Poland, the GEMINI+ consortium gathered 26 partners from across Europe and included partners in Japan, South Korea and the United States.

The GEMINI+ project has been initiated by the European Nuclear Cogeneration Industrial Initiative (NC2I), one of the three SNETP pillars. NC2I aims at demonstrating an innovative and competitive energy solution for the low-carbon cogeneration of heat and electricity based on nuclear energy. The targeted outcome is the commissioning within 10 years of a nuclear cogeneration prototype to deploy this low-carbon energy technology in several energy-intensive industries.



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