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# *EUROPAIRS*

## *Final Report*
## *Period covered: from 01/09/2009 to 31/05/2011*

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End-User Requirements fOr industrial Process heat Applications with Innovative nuclear Reactors for Sustainable energy supply

**EUROPAIRS project** – Grant Agreement no. 232651

***End-User Requirements fOr industrial Process heat Applications with Innovative nuclear Reactors for Sustainable energy supply***

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## Summary

This report is the Final Report of the EUROPAIRS project covering the whole duration of the project (September 1st, 2009 to May 31st, 2011).

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# 1 Final publishable summary report

## 1.1 Executive summary

The development of GENERATION IV nuclear systems and the significant support given in FP5 and FP6 allowed Europe to acquire strong assets in the technology of one of the six GENERATION IV reactor types, namely the (V)HTR.

In line with these assets and with the recommendation of the Sustainable Nuclear Energy Technology Platform, which identifies high-temperature industrial process heat applications of nuclear energy as one of 3 major axes of development recommended for European nuclear R&D, the EUROPAIRS Project investigated a step forward towards industrial application of (V)HTR technology: the objective of the Project was to prepare conditions for the development of an European industrial demonstrator of the coupling of a (V)HTR with process heat applications in a heat (or steam) and power cogeneration mode. Nearly 30 partners from 10 countries (see below) and an overall budget above 800 k€ are the key figures of the Project.

The scope of work of EUROPAIRS covered the following topics and was organised in four work packages:

1. The coordination and organisation of a strong partnership of nuclear industrial and R&D organisations with process heat user industries, based on the joint participation of nuclear and heat end-user partners. A coordination team supported this partnership in achieving a better understanding of and a continuous dialogue between these two communities through mutual information, as well as a sharing of the objectives and of the development programme for the demonstrator.
2. Boundary conditions for nuclear cogeneration have been defined from the points of view of technical feasibility, industrial practicability, sustainability and, as far as reasonable, economic competitiveness supported by a market study. The critical issues have been identified and solutions of viable coupling schemes are proposed and R&D needs pointed out.
3. The safety related impacts of the different normal operating conditions and accidental conditions of each of the two coupled systems HTR and industrial plant on the other system were evaluated, including the safety requirements to be met by the nuclear system.
4. A roadmap for designing and constructing a demonstrator was elaborated, including the developments needed for the reactor, the heat transport system and the process heat applications, as well as the R&D and qualification actions required in support of this programme. A schedule has been proposed as well as an estimation of the costs and a sketch of the business case for further industrial deployment.

EUROPAIRS implemented an extension of the collaboration with end-user industries through an Associated Industry Network (AIN) which included representatives from the Steel Technology Platform. Furthermore EUROPAIRS initiated communication on cogeneration collaborations through an information exchange meeting with the US Industry Alliance for NGNP.

Communication of Project results and achievements was implemented through presentations at various conferences such as ENC 2010 and HTR 2010, at GIF and SNETP meetings and at the Open EUROPAIRS Workshop at the end of the Project.

The EUROPAIRS Support Action terminated in May 2011 after 21 months of successful performance providing a sound basis and a proposal for the way forward for the further development of V/HTR cogeneration technology.


**Figure 1: Consortium composition**

## 1.2 Summary description of project context and objectives

*The objective of EUROPAIRS was to identify the boundary conditions for the viability of nuclear cogeneration systems connected to conventional industrial processes and to initiate the partnership of nuclear organisations and end-user industries,* which would be deployed in a further step to develop a Demonstrator, coupling a (V)HTR with industrial processes. The boundary condition framework defines technical, industrial, economical, licensing and safety requirements for the nuclear system, the processes that can consume the energy generated, and the coupling system.

High and Very High Temperature Reactor ((V)HTR) systems combine advanced safety features with high efficiency. Beyond medium-scale electricity generation, their efficiency in the use of fissile resources and economic viability can be further improved by feeding at least part of the generated heat into those industrial processes, for which both the high coolant temperature and medium-scale reactor power are appropriate. Such new Combined Heat and Power (CHP) applications of nuclear energy would allow saving large quantities of fossil fuel resources and reduce $CO_2$ emissions of industry. Addressing the non-electricity energy market which represents presently 80% of the final energy consumption in Europe, and extending in the future to the production of synthetic oil and hydrogen, nuclear CHP with (V)HTR will therefore bring a unique contribution to the challenges of climate change, security of energy supply and competitiveness as presented in the SET-plan.

EUROPAIRS aimed at adding to the knowledge and experience that has been built up in recent (V)HTR related programmes by the partners of the European High Temperature Reactor Technology Network (HTR-TN) in the $5^{th}$ and $6^{th}$ Framework Programmes, as well in developments performed on national or company bases, the assessment of the viability of a (V)HTR deployment in concrete industrial environments formed by the End-users. End-users are the “clients” of the (V)HTR system, using the electricity and/or other energy products such as process heat and steam. They can be either industrial manufacturers using heat for the production of e.g. chemicals, oil, metal products, engineering companies designing the cogeneration plants or utilities supplying energy services to producers. In this respect, the ultimate goal was to apply the high level knowledge developed by the HTR-TN community to improve the competitiveness of the EU industry, on the basis of “End-User requirements”.

Coupling (*or PAIRing*) directly a nuclear heat source with industrial process heat applications is a challenging but reachable innovation since nuclear cogeneration using current light and heavy water reactors has been industrialised (for district heating, desalination and industrial processes). Ultimately, it will require a prototypic demonstration at an industrial scale, which will be needed both for developing and qualifying the technologies that allow such a coupling and for giving confidence to industry in considering nuclear heat supply as a competitive, reliable and carbon free solution for its energy needs. Such a demonstration could be possible only if a strong partnership was established between nuclear organisations involved in HTR technology development and process heat user industries: the nuclear designers need indeed to know the user requirements for industrial process heat. Moreover nuclear and non-nuclear partners must work together to develop the technologies required for coupling the reactor with industrial process heat applications.

In order to be successful in initiating the partnership between nuclear industry and research and process heat user industries, a common understanding and a sharing of objectives had to be reached by the partners. The following three targets were reached in EUROPAIRS:

- ***To express the end-user requirements and the capabilities of the nuclear heat source***
- ***To assess the viability of combining a nuclear heat source with conventional industrial processes and CHP applications, and identify the boundary conditions for a successful coupling***
- Based on the conclusions and recommendations of this assessment, ***to elaborate a programme for the development of a Demonstrator coupling a (V)HTR with industrial processes that require heat supply.***

The essential involvement of private companies in the form of industrial participation to develop and deploy innovative energy supply systems was thereby established, in line with preferred future cooperation schemes described in the SET-Plan.

EUROPAIRS worked in an international context marked by the existence of industrial (V)HTR projects such as NGNP and HTR-PM and, PBMR (at the Project start). A new interest of large industrial process heat and steam users for these projects such as DOW, CHEVRON, CONOCOPHILLIPS and POTASHCORP grouped in the "Public Private Partnership" for NGNP development in the US (US Alliance for NGNP) has been recognised. EUROPAIRS has endeavoured to cooperate with this partnership in order to benefit from a larger feedback from experience of partnership between nuclear industry and end-users.

### 1.2.1 WP1 Viability assessment

***Objectives:***

- ***Determination of the requirements and characteristics of relevant industrial processes and (V)HTR systems***
- ***Assessment of the viability of connecting a (V)HTR system to industrial processes, from technical, industrial acceptability, licensing and economic viewpoints and identification of the boundary conditions for deployment.***

#### *1.2.1.1 Task 1.1 End-User processes, characteristics and requirements*

The objective of this task was to gather the knowledge on industrial processes that require large quantities of high temperature heat or steam.
For all types of applications, end-user requirements have been defined for the service provided by the heat source. They concern in particular:

- The power (thermal and electric)
- The redundancies of power supply (modularisation)
- The type of heat carrier
- The average and maximum temperature, pressure and flow rate of the heat carrier
- The load variations
- The availability requirements (differentiating planned outages and non-anticipated shut down)
- The expected lifetime
- The cost of hot fluid supply.

Justifications were given to these requirements, allowing the nuclear partners to understand their rationale and the constraints of end-user industries. Depending on the type of application, additional detailed information was provided e.g. with respect to flow sheets of the processes, with data on heat, steam and electricity inputs and outputs if a global optimisation of the coupled nuclear heat source and application processes.

#### *1.2.1.2 Task 1.2 Nuclear system: characteristics and limits*

This task provides a description of the available nuclear system designs and their technological level.
The capabilities of the HTR should answer end-user and licensing requirements: similar parameters to those specified in Task 1.1 should be provided (power, temperature, pressure, transient capabilities, anticipated and non-expected unavailability, lifetime, waste and effluent releases, activation of the secondary fluid, accident behaviour, orders of magnitude of development, investment and production costs, etc.).

Limits of the reactor capabilities were provided in order for the end-users to understand their rationale and the constraints on reactor design. If there could be some flexibility in the capabilities, this was indicated in order to facilitate the matching between the end-user requirements and the reactor capabilities.

#### *1.2.1.3 Task 1.3 Synthesis of the requirements*

This task dealt with the compatibility between energy supply by a (V)HTR and the industrial processes of the end-users involved. The main goal was the improvement of the understanding of the market needs and the identification of possible operating windows for the combined system of an (V)HTR connected to industrial processes, including some preliminary investigations. Although the potential of this combination has always been regarded as high, the viability of coupling a (V)HTR system to industrial processes has not been experienced yet and is still to be assessed. For this assessment, the capabilities of the nuclear system and the requirements of end-users are being matched to identify common operating windows and coupling schemes.

Regarding the technical aspects, the scope included the identification of possible discrepancies between end-user requirements and capabilities of the nuclear heat source. It also comprised the examination of possible solutions for adapting the three systems (nuclear reactor, heat transport system and process heat application) and coupling components (heat exchangers) for allowing them to be operated in a symbiotic way. Furthermore, the development needs for the energy coupling components and energy transport infrastructure, as well as for the adaptation of the nuclear reactor and the application processes would had to be defined. Schemes were to be proposed for the coupling of some prototypic applications. Active participation of both end-user and nuclear industry was required in the definition of the interface and of a schematic chart of the coupled system.

The study of the European industrial heat market showed that industrial activities present very different processes ranging from simple to very complex. EUROPAIRS gathered 13 different end-users (8 of them are heat final consumers), engineering companies and research centres that shared information on large-scale production processes. Information exchange included the characteristics, technological limits and constraints, requirements, adaptability and flexibility potential of both end-user industrial processes and the (V)HTR nuclear system.

The possibilities of adjustment of end-user processes and infrastructure to accommodate the operational limits of the nuclear system and the feasibility of required (V)HTR specifications had to be determined. The feasibility of new components needed for coupling (for instance dedicated heat exchangers for specific application environments) and of innovations in industrial processes (adaptation of the process for replacement of radiative heat supply by convective heat supply, development of processes for giving value to waste products …) had to be assessed. In addition, the economy of (V)HTR deployment in industry as well as its potential for mutual benefit for industrial end-users and nuclear industry had to be considered.
The feasibility of licensing a (V)HTR for combined heat and electricity supply to industrial processes was addressed in the WP2 “Safety”. All along the Project, a close interaction was planned and, indeed took place, between WP1 and WP2.

In addition to the technical evaluation activities, EUROPAIRS partners expressed the need for ameliorating the understanding of the industrial heat market in Europe. Indeed, task 1.1 described qualitatively the different processes operated in heat intensive industries and needed to be complemented by quantitative data. Furthermore, the economic aspects were repeatedly interrogated and required some preliminary clarification.

Two supplementary deliverables were therefore added to the original list: a study on the European heat market and a preliminary study of the economics of nuclear cogeneration; both deliverables were taken over by one of the EUROPAIRS partners, LGI Consulting.

All in all, one can state that the goal of this task was achieved provided the level of information obtained from the other tasks and partners.

### 1.2.2 WP2 Safety and licencing compatibility of the coupled system

***Objective***

- ***Providing safety and licensing aspects of the combined coupled system, based on the system lay-out proposed in work package 1***

The designers of modular (V)HTR systems intend to base their safety demonstration on inherent physical characteristics of the reactor and on the use of passive safety systems for keeping the reactor in safe conditions. They thus consider that the safety approach commonly used for water reactors has to be adapted for (V)HTR systems. The safety approach for (V)HTR systems has already been developed in Europe for the pre-licensing of the German HTR-Modul and reviewed by the German Safety Authorities. Similar approaches were used for licensing in other countries e.g. in China and in the US). The licensing issues related to modular (V)HTR design have been examined again in projects of the 5$^{th}$ Framework Programme (HTR-L) and of the 6$^{th}$ Framework Programme (RAPHAEL) and by industry in recent projects. The assessments made in these frames have been discussed with different Safety Authorities and TSO.

The main scope in this task was the coupling between a (V)HTR and an industrial application: what are the safety related impacts of the different normal operating conditions and accidental conditions of each of the two coupled systems on the other system? What are the safety requirements to be met by the nuclear system for taking into account the fact that it will be located at an industrial site? Another issue addressed was the potential radioactive contamination of the products. These were the kind of questions that Safety Authorities and TSOs involved in WP2 have addressed.

### 1.2.3 WP3 System deployment outlook

***Objectives:***

- ***Assessment of different fuel cycle scenarios assuming significant future (V)HTR deployment in Europe, evaluating (V)HTR resource availability and waste***
- ***Definition of a work programme in the form of a detailed roadmap for (V)HTR deployment in conventional industry, considering the nuclear system, the industrial processes and their connection***

#### *1.2.3.1 Task 3.1 Scenario study*

Solutions are presently developed in Europe and in other parts of the world, particularly through GIF (the Generation IV International Forum), for making electricity generation by nuclear energy compatible with the objectives of sustainable development. If on top of this, a significant penetration of HTR on the market of industrial process heat is assumed, can nuclear energy remain sustainable?

For answering this question, based on the present nuclear fleet dedicated to electricity generation and fuel cycle scenarios and on their possible evolution in the next decades, scenarios of penetration of HTR on the market of industrial process heat were assessed, considering different types of possible fuel cycles for HTR in symbiosis with the fuel cycles used for the remaining of the reactor fleet. Taking into account the results of the HTR-N and HTR-N1 projects (FP5) and RAPHAEL and PUMA (FP6) and CARBOWASTE (FP7), the assessment addressed, in the different possible fuel cycle scenarios, the impact of this HTR penetration on the utilisation of fissile resources and the waste streams.

#### *1.2.3.2 Task 3.2 System deployment roadmap*

Based on the results and conclusions of WP1 and WP2, and task 3.1, a preliminary work programme in the form of a detailed roadmap for the development of a large scale demonstration of the coupling of a (V)HTR with an industrial process heat application and for further industrial deployment of such coupled systems was to be defined, addressing the following items:

- Based on work performed in FP5, FP6 and in various national programs, as well as on the HTR-TN roadmap and SNETP Strategic Research Agenda, and taking into account EUROPAIRS results, the complementary work (design and R&D) for developing a (V)HTR system was to be identified.
- The possible needs of evolution of end user processes for adaptation to the use of a (V)HTR as a heat source had to be expressed and the corresponding developments identified.
- A state-of-the-art of the industrial heat transport technologies available in the range of conditions relevant for (V)HTR industrial applications were to be produced by industrial end-users and potential development needs in this area were to be assessed.
- A schedule for the demonstration project was to be established, based on the assumption that the required resources are available at the right time and that the project will progress at the pace allowed by the necessary duration of all technical steps and by their logical sequencing.
- A rough estimation of the funding needs for the Demonstrator project was to be provided.

### 1.2.4 WP4 Coordination

***Objectives:***

- ***Ensure successful achievement of EUROPAIRS goals***
- ***Facilitate effective communication and information exchange between partners***
- ***Extend the partnership of EUROPAIRS, with other end-user, HTR communities and international initiatives***
- ***Establish a strategic alliance to form the basis for the realisation of combined heat and electricity supply of a (V)HTR to industrial processes***

In order to reach these objectives, the Coordinator was supported by a "Coordination Team", which was to be involved in each work package and task, by which sufficient overview is generated to make sure that any issue is dealt with by the right partner and at the right level in the Project. The Coordination Team was in charge of:

- through the Coordinator with organising the reporting of the Project to the European Commission.
- with the management of the deliverables, assuring that they will be issued following the project schedule and that they will be elaborated following appropriate quality assurance procedures.
- to endeavour developing cooperation with those foreign teams involved in the development of high temperature nuclear systems that are striving to set up a partnership between nuclear industry and process heat end-user industries.
- to organise making deliverables of the Project available to GIF VHTR partners under fair exchange conditions will be included in the Consortium Agreement.
- with the Project dissemination and communication through the public website of the Project, a Newsletter and links with other relevant websites (RAPHAEL, SNETP and other technology platforms of interest, GIF, NGNP…). Students and young professionals will be an important target for communication, in particular through links with the Young Generation.
- To establish a strategic alliance between the nuclear industry and end-users by facilitating communication and cooperation between the different industrial and R&D communities and to take Initiatives in order to learn more about process heat user requirements from industries that are not necessarily represented in the Project which could raise the interest of additional industrial end-users in order to organise a strong partnership. The following measures have been taken:
  - *Contacts with Technology Platforms in relevant areas and with professional associations both at the European and national levels*
  - *Presentations on the prospects of a (V)HTR being used for industrial process heat applications and on the results of the Project*
  - *Organisation of a workshop at the end of the Project, to bring together a larger participation of potential end-user industries and to cover areas that go beyond the current end-user partner participation within the Project.*

- Taking over from the Industrial Users Advisory Group established in RAPHAEL, an informal group of end-users will be organised, if there are end-user industries interested in exchanging information and discussing with the Project, though not wishing a formal commitment in the Project.

## 1.3 Description of the main S&T results

### 1.3.1 WP1 Viability assessment

*WP1 includes individual tasks on the determination of the requirements and characteristics of relevant industrial processes a description of relevant (V)HTR systems and an assessment of the viability of connecting a (V)HTR system to industrial processes from technical, industrial acceptability, licensing and economic point of view and an identification of the boundary conditions for deployment.*

The objective of the first task is to gather the knowledge on industrial processes that require large quantities of high temperature heat or steam. For all types of applications, end-user requirements have been defined for the service provided by the heat source.

The second task provides a description of the available nuclear system designs and their technological level considering end-user and licensing requirements: similar parameters to those of the first subtask are provided (power, temperature, pressure, transient capabilities, anticipated and non-expected unavailability, lifetime, waste and effluent releases, activation of the secondary fluid, accident behaviour, orders of magnitude of development, investment and production costs, etc.). Furthermore the limits of the reactor capabilities are provided in order for the end-users to understand their rationale and the constraints on reactor design.

The third task deals with the compatibility between energy supply by a (V)HTR and the industrial processes of the end-users involved. The main goal is the improvement of the understanding of the market needs and the identification of possible operating windows for the combined system of an (V)HTR connected to industrial processes.

#### *1.3.1.1 Task 1.1 End-User processes, characteristics and requirements*

*The task 1.1 evaluates the need of heat in the industrial world*.

Heat is used in industry for several reasons. The EUROPAIRS partners working in very different industrial sectors were asked to provide their heat requirements (temperature levels and thermal power). The table 1 below sums up these data.

To develop a general description of the thermal energy need in the industry, a classification has been proposed. Three process classes were defined as follow:

- The first is called “the steam class” because heat is transport via steam media or heat is used to remove water. The temperature is between 150°C and 600°C.
- The second is called “the chemical class” because heat is the driver of chemical reactions and is consumed as reaction enthalpy generally at constant temperature. The temperature is between 600°C and 900°C. Heat is supply by fossil fuel burners and marginally by electrical heating.
- The third is called “the mineral class” because heat is used to melt solid or to drive reactions between solids. The temperature is in general above 1000°C.

According to this classification, it is easy to evaluate the market of steam and to evaluate the possible coupling scheme.

| TEMPERATURE\POWER | 10 -150 MWth | 150 - 500 MWth | 500 - 1000 MWth | > 1000 MWth |
|---|---|---|---|---|
| 100-600 °C | Refinery Distillation<br>Steam<br>(heating, process, electricity) | Paper<br>Steam (drying) | | |
| | Steel degassing<br>(process, electricity) | Water desalination<br>Steam (drying) | | |
| | Refinery Distillation<br>Superheated Steam<br>(heating, process) | Soda ash<br>Steam (drying) | Steam as utility<br>for indutrial complex | Steam Assisted Gravity<br>Drainage<br>Steam (process, electricity) |
| 600-700°C | Petrochemicals (styrene…)<br>Reaction enthalpy | | | |
| | Hydrogen<br>Membrane steam reforming | | | |
| | Hydrogen<br>High temperature electrolysis | | | |
| 700-1000 °C | Olefine products<br>Reaction enthalpy | | | |
| | Methane Steam reforming (syngas)<br>Reaction enthalpy | | | |
| | Coal gasification (syngas)<br>Reaction enthalpy | | | |
| | Oxygen<br>Membrane gas separation | Carbon monoxyde production | | |
| | Hydrogen<br>Very High temperature<br>electrolysis | Hydrogen<br>Chemical water splitting | | |
| > 1000 °C | Lime Kiln production | Cement production | | |
| | | Ore sintering | | |
| | | Coke making | Metallurgical processes | |

**Table 1: Heat requirements (temperature and power) synthesis**

#### *1.3.1.2 Task 1.2 Nuclear system: characteristics and limits*

*In the frame of the EUROPAIRS project, the Task 1.2 aims at presenting the characteristics and limits of the HTR nuclear system to make end-users more familiar with this technology and provide the information needed for assessing the coupling. Contributions from several partners were taken into account.*

The HTR technology has already a long historical background with several HTR programs (experimental reactors and operational demonstrators) over the world and, more generally, good knowledge on gas-cooled reactors. The industrials have gained invaluable experience from these past realizations giving them confidence that the High Temperature Gas-cooled Reactor (HTGR) technology is mature. Today HTR, and more precisely 'modular HTR', is considered as an energy alternative for cogeneration and coupling with the conventional process heat market.

The modular concept of the HTR is directly linked to decay heat removal capabilities and safety features of the reactor. Modular HTR is designed in a way that, also during loss of cooling accidents, decay heat can be removed purely by passive means without exceeding predefined temperature limits for fuel and structures. Such a plant design, however, yields limitations on the power output. Thus the optimal design of a modular HTR is a reactor with maximum power limited to 600 MWth which still obeys the temperature limits of fuel during the accidents, but also to the temperature of structures mainly that of the reactor pressure vessel and components. The key attributes of the modular HTR are its fuel, the helium coolant, no concrete but a steel vessel and limited power level and power density favoring inherent safety characteristics (no need of engineered high reliable and redundant safety system). Such simplification in the safety design leads to investments savings.

HTRs (and VHTRs) are commonly associated to heat temperatures as high as 750°C to 1000°C which correspond to the temperatures reachable at the core outlet of the reactor (ROT) and not to the temperatures available for the heat processes. In fact elevated heat temperatures are mainly limited by the properties of candidate materials used for the heat transfer (high temperature strength and corrosion resistance) regarding reasonable expected lifetime. There are thus still important technological challenges to be able to supply a heat process at 800°C.

Currently three main technologies are foreseen for the heat transfer from the core: steam generators (SG), gas-gas Intermediate Heat eXchanger (IHX), and Molten-salt IHX.

The use of SG is the most mature technology as it is already used in most realizations of LWR and gas-cooled reactors. Furthermore, boilers in general are widely used in the industry which gives a very good knowledge on the wearing mechanisms of materials. Sufficient performances already achieved with steam generators, and the expected developments that will allow reaching higher temperatures for both sub-critical and super-critical technologies are presented. The current limitations are related to the resistance to creep damage and corrosion problems.

The second technology for heat transfer presented here is the gas-gas IHX. The use of gas at secondary side of the heat-exchanger allows reaching higher temperatures than with a SG. Major high temperature design, materials availability, and fabrication issues are addressed for plate and tubular IHX concept. The second one is already mature for applications at temperatures around 750°C-800°C. The challenge is to design gas-gas IHX that are sufficiently compact to transfer large thermal power and, at the same time, capable of withstanding creep damage for long lifetimes. Further developments are required to guarantee the performance of the plate technology but it is expected that the technology can gain maturity and become available for HTR realization in the medium term. The Figure below illustrates the concept of plate-type compact IHX.

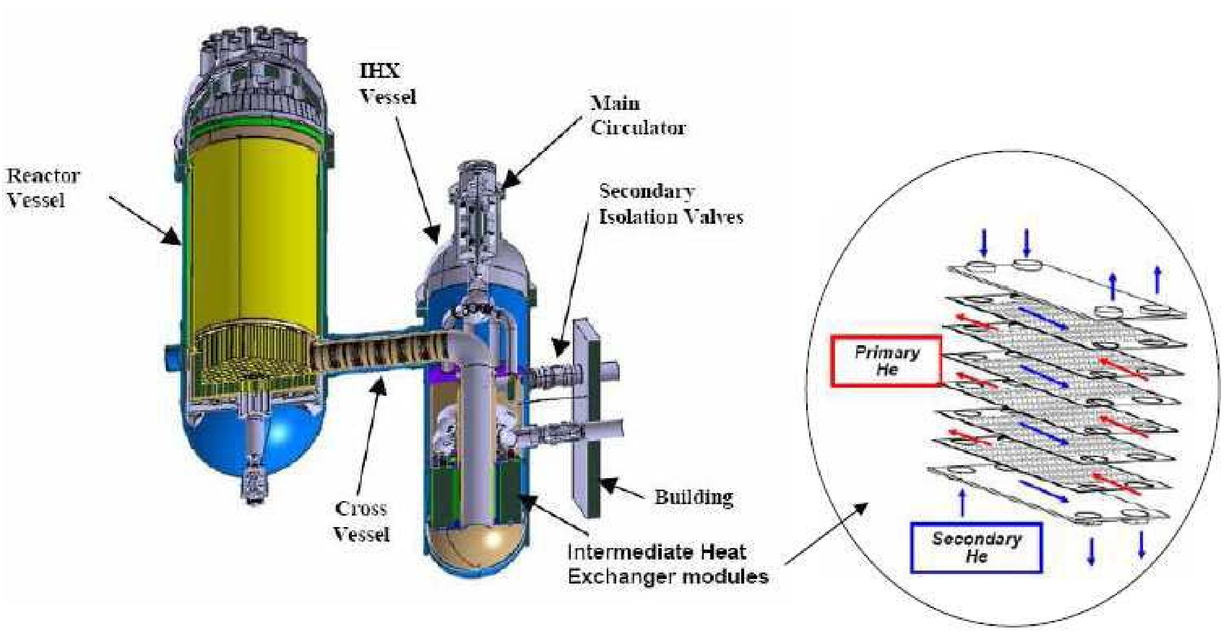


**Figure 2: Concept of plate-type compact IHX**

A third heat transfer technology is the gas to Molten-salt IHX. Molten-salt would allow a more efficient heat transfer and a much higher thermal density, while staying at low pressure in the secondary loop. However, it has its own drawback, mainly corrosion, resistance to pressure differential and risk of freezing. At present, too many uncertainties still exist to consider the coupling with molten-salt IHX as a potential technology in the near and medium terms.

Other key equipment is the primary blower that produces the force circulation of gas in the reactor. The capacity of the blower limits the power that can be extracted by each primary loop as well as the heat exchanger itself. Currently tubular technology presents the same limits as the blower. It is validated that, for a 600 MWth HTR, a design with 4 blowers and 4 SG is feasible.

Transferring heat from the primary circuit to the secondary circuit is not all. Several configurations are possible to do the coupling. The heat process can be directly coupled with the fluid of the secondary circuit, or indirectly by means of a tertiary circuit requiring additional heat transfer equipment. In parallel to the heat process supply, it is possible to have a turbine that generates electricity. The turbine could be either on the secondary or the tertiary circuit, and depending on the temperature required for the heat process, it could be in a bottoming or a topping cycle configuration. The direct coupling between the secondary circuit and the heat process presents the advantages to be very simple. However, it might not be acceptable from a safety point of view and tritium release which may 'contaminate' process heat circuits. The addition of intermediate circuit(s) and a turbine presents advantages, at least for a first realization of a coupling scheme, because it allows more flexibility in the operation of both sides of the coupling (HTR production and heat process consumption). Moreover, the tertiary circuit and a turbine reduce the amplitude of the transients generated by events on the heat process side. The figure below presents a schematic view of an indirect cycle with a SG as heat transport system to a secondary system for heat cogeneration applications.

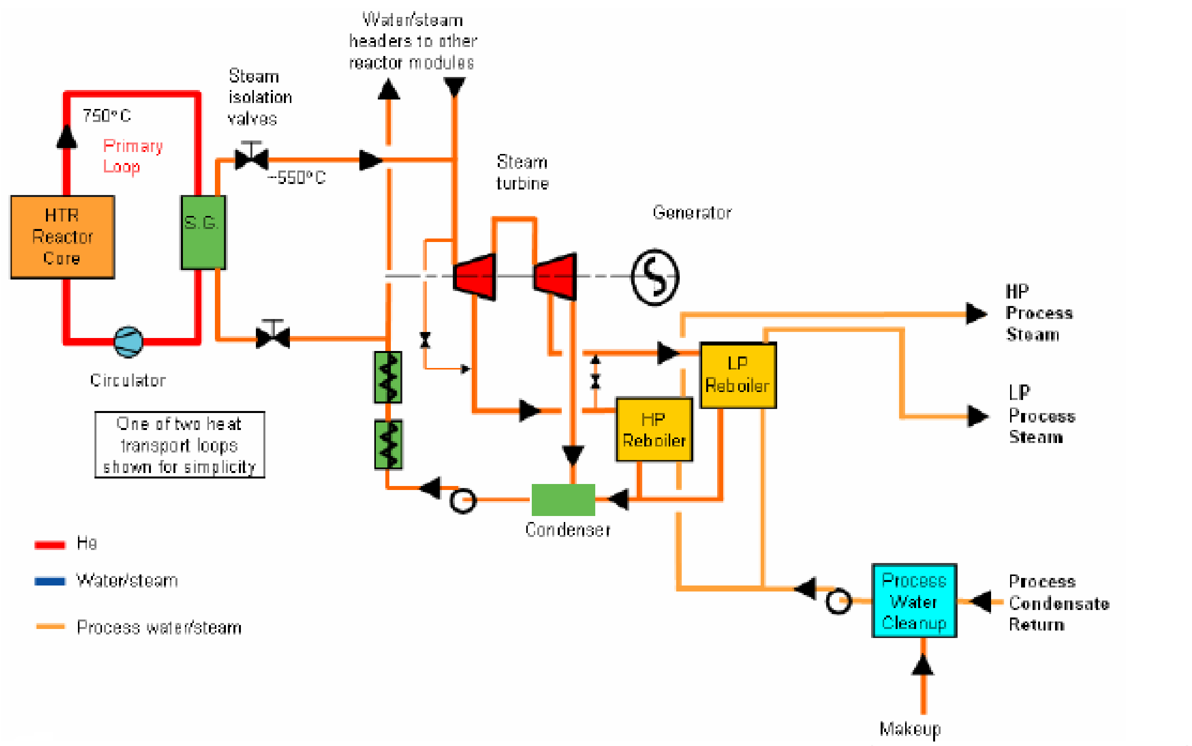


**Figure 3: schematic view of an indirect cycle with a SG as heat transport system to a secondary system for heat cogeneration applications**

Regarding transients and availability requirements the heat transport system should be designed to ensure enough buffering between nuclear and conventional plants to avoid an important interaction between both during their own transients. HTR is designed to withstand a set of design basis transients, as for instance, loss of cooling fluids, loss of forced circulation, and failure of the reactivity controls, which are more stringent than standard transients that can arise from events occurring on the heat process installations.
In conclusion, the results present the operating window of the HTR technology, and how it could be expanded in the future, to clarify for heat consuming industries what the constraints for coupling the HTR with their processes are. The laid out performance window of the HTR technology three different configurations regarding coupling potential are proposed: 'near term', 'medium term' and 'long term' applications that may be proposed by nuclear suppliers during an offer without considering the commissioning of the plant. For near term application it is meant 0 to 5 years, for medium term 5 to 15 years, and for long term applications over 15 years.

#### *1.3.1.3 Task 1.3 Synthesis of the requirements*

1.3.1.3.1 Synthesis of the requirements of Task 1.1 and 1.2

Screening of energy consuming processes

The information shared by the EUROPAIRS end-user, engineering companies and research centres determined (i) the operating window(s) of combined systems, (ii) identified issues to be resolved, and (iii) defined requirements considering infrastructure, coupling system, heat transport, licensing requirements and economics of the coupling.

Resulting from data collected on different processes, three main process families are being proposed (see Task 1.1 for more details). These are the "steam class" with processes using steam as heat transport and heating media that extends from 150°C to approximately 600°C; the "chemical class" where heat is the driver of chemical reactions and is consumed as reaction enthalpy at constant temperature that lies between 600°C and 900°C; and the "mineral class" where heat is used to melt solid or to drive reactions between solids, the temperatures required are usually above 1000°C. This classification provides a high level overview of heat utilization in European industry. The classes were examined to provide the requirements for the (V)HTR for connection to an industrial plant. The maximum temperature of a process is not necessarily the best parameter for comparison; it is important to identify at what temperature the energy is consumed. The screening of the processes should allow distinguishing sensible heat consumed over a range of temperature, from latent heat (of a chemical reaction for example) that is consumed at a specific temperature.

Heat and electricity supply by high temperature reactors

The identification of the operating needs of heat consuming industries is only one aspect of the work. The EUROPAIRS project aims also at determining the operating window of the HTR technology, and how it could be expanded in the future. Heat consuming industries should understand what the constraints for coupling the HTR with their processes are. Over the last years, several companies have achieved important developments to design HTR concepts. But they are all facing the same challenges to improve the technology and make it a viable alternative for heat processes. These challenges are exposed below.

1.3.1.3.2 Coupling of HTR and end-user processes

HTR performance window

Industry has gained invaluable experience from these past realizations giving them confidence that the High Temperature Gas-cooled Reactor (HTGR) technology could be considered mature. But for the alliance aimed in the frame of EUROPAIRS with process heat user industries it is of importance to clearly expose why HTR technology is considered today as an energy alternative for the conventional process heat market. EUROPAIRS has indeed endorsed the role to promote the necessary dialogue to understand which technological barriers must be overcome and how nuclear industry can guarantee the reliability of the HTR technology over industrial plant lifetimes with a modular concept.

One key point of the HTR plant design is the possibility to rely almost exclusively on passive safety features. Not only does it make the HTR concept very safe, but in addition, costs of auxiliary systems could be significantly reduced because these systems do not required high levels of qualification. However, the passive safety features limit the maximum thermal power of a HTR to between 250 and 600 MWth (depending on the core design).

With existing or near-term technology, HTR can deliver process steam at temperatures up to 600°C. But HTR are often associated to temperatures as high as 800°C to 1000°C. Such high temperatures correspond to reactor outlet temperatures not to the temperatures available for the heat processes. These are mainly limited by the properties of candidate materials used for the heat transfer (high temperature strength and corrosion resistance) for reasonable expected lifetime. There are thus still important technology challenges to be able to supply a heat process at 800°C.

HTR are designed to withstand a set of design basis transients, as for instance, loss of cooling fluids, loss of forced circulation, and failure of the reactivity controls. In addition to these standard transients, it will be necessary to study the transient that can arise from events occurring on the heat process installations. In comparison to sole electricity production, the nuclear heat-supply system arrangement is not modified. The power conversion system is adapted to transfer heat to the process unit and to produce electricity (nuclear plant, process unit and grid). Nevertheless, the event of sudden loss of the process heat sink has to be examined. The unit should be capable of sustaining such a situation and continue to produce electricity. At least the heat transport system should be designed to ensure enough buffering or decoupling between nuclear and conventional plants to avoid unacceptable feedback reactions.

Heat Transfer Limitations

As stated above, the temperature available for the heat process is not limited by the maximum temperature at the outlet of the reactor but by the properties of the materials used for the heat transfer to the secondary loop (and to the heat process). One of the tasks of the viability assessment is to identify the limitations of the potential technologies that would be used to carry the heat to the client process. Currently, three technologies are foreseen: (i) steam generators (SG), (ii) gas-gas Intermediate Heat eXchanger (IHX), and (iii) Molten-salt IHX.

The use of SG is the most mature technology as it is already used in most realizations of LWR and gas-cooled reactors. Furthermore, boilers in general are widely used in the industry and much information is available on aging mechanisms but SG design with helium has to be further optimised. The goal in the EUROPAIRS project is to characterize performances already achieved with steam generators and the expected developments that will allow reaching higher temperatures for both sub-critical and super-critical steam technologies. The current limitations are related to the resistance to creep, fatigue and corrosion.

The second technology foreseen for heat transfer is the gas-gas IHX. The use of gas at the secondary side allows reaching higher temperatures than with a SG. Major high temperature design, materials availability, and fabrication issues need to be addressed for plate IHX; the tubular IHX concept is reaching maturity for applications at temperatures around 750°C – 800°C. The challenge remains to design gas-gas IHX that are sufficiently compact for economy and, at the same time are capable of withstanding creep damage for long lifetimes. Further developments are required to guarantee the performance of the technology. It is expected that the technology can gain maturity and become available for HTR realization in the medium term.

A third heat transfer technology is the gas to molten salt IHX. Molten salt would allow a more efficient heat transfer and a much higher power density, while at low pressure. However, it has its own drawback, mainly corrosion, high pressure drop and risk of freezing. At present, too many uncertainties still exist to consider the coupling with molten salt IHX as a potential technology in the near and medium term.

Different configurations of HTR coupling

Several configurations are possible to transfer heat from the reactor as the heat source to the end-user process. This process can be directly coupled with the fluid of a secondary circuit, or indirectly by means of a tertiary circuit requiring additional heat transfer equipment. In parallel to the heat process supply, it is possible to add a turbine for electricity generation, either on the secondary or the tertiary circuit. Depending on the temperature required for the heat process, the turbine could be placed in a bottoming or a topping cycle configuration.

The direct coupling between the secondary circuit and the heat process presents the advantage to be very simple. However, it might not be acceptable from the point of view of tritium release (see section below) and the contamination of equipment of the end-users. The addition of a turbine seems also advantageous, at least for a first realization of a coupling scheme, because it allows more flexibility in the operation of both sides of the coupling HTR production and heat process consumption). Moreover, the tertiary circuit and a turbine reduce the amplitude of the transients generated by events on the heat process side.

1.3.1.3.3 Viability of coupling

Based on the analyses of both energy needs of end-users and characteristics and limitations of the HTR heat supply, it is possible to determine the range of operating conditions in which coupling is feasible and to evaluate the potential that it could represent on the energy market.
The results of this assessment are given in two parts. Firstly, the developments still needed and the roadmap to attain in the near-term prototyping of a full-scale coupling scheme was discussed. "Near-term" means that the construction phase could start within 5 to 10 years. Secondly, we discuss the development required to broaden the range of coupling schemes in order to cover other process heat application with promising market potential.

Near-Term and Long-Term Potentials

The goal to build a prototype in the near future requires that only mature technologies can be used. Economic viability is of course a crucial issue that has to be considered in parallel to technical arguments.

From the analyses of both end-users processes and heat transfer technology for HTR heat supply, it seems obvious that steam coupling would be the most appropriate scheme for a prototype. A near-term coupling scheme is proposed in Figure 4. Design of dedicated steam generators would require limited developments as there is already a market for process steam. The near term assessment determines what would be, with current technologies, the steam temperature available for the heat process as a function of the configuration of the HTR secondary loop and of the distance between the HTR and the end-user facilities. Also the most suitable power size for an HTR shall be assessed depending on the core design (prismatic or pebble-bed) and number of primary loops.

The steam market that would be accessible to HTR supply in the near term already represents a considerable fraction of the potentially achievable CO2 emission reduction potential. The assessment comments on the developments required to make HTR heat supply a viable alternative for further markets. In particular, it could make sense to implement HTRs dedicated to the production of widely used bulk chemicals like hydrogen or methanol. The production of chemical compounds could be at the heart of synthetic fuel production processes and thus reduce dependence on fossil fuels.

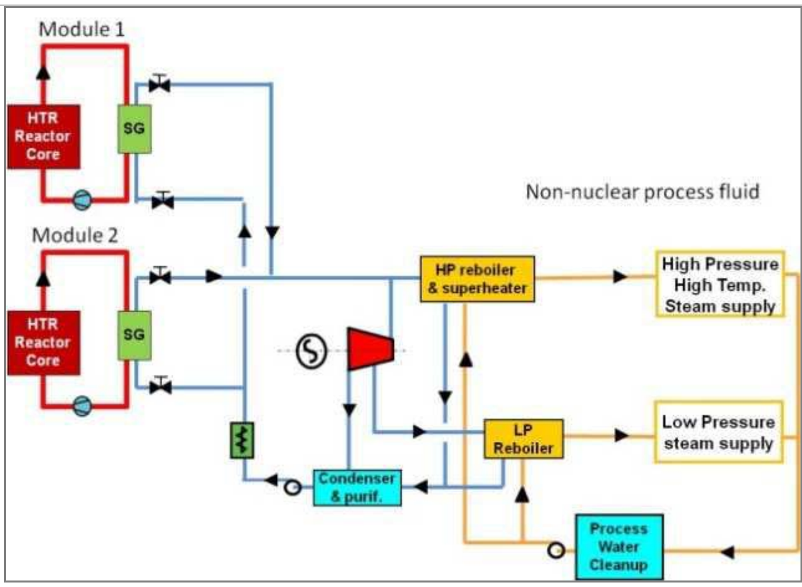


**Figure 4: Near-term coupling scheme with SG**

Safety Analysis

In parallel to the viability assessment, WP2 deals with safety and licensing issues arising from the coupling of the HTR with the heat process: events on one plant of the coupling (nuclear or heat process) will impact the other plant (see WP2 section for details). The study identifies for some cases the specific risks that could arise and then put forward principles and tentative acceptance criteria for the feasibility of the licensing of the coupled system. The main requirement to ensure the safety assessment feasibility is that the safety of the nuclear plant shall not be negatively influenced by the coupling in comparison with stand-alone current nuclear installations. Moreover, the feedback of recent safety assessments of nuclear installations sited close to industrial complexes were used for this analysis.

Of course, the proximity of the HTR to the end-user plays an important role. Principles and criteria for the determination of an acceptable distance – or "safety distance" – between the nuclear plant and the process is being reviewed (chemical attack, fire risk…).

Another item reviewed by EUROPAIRS is related to potential contamination of the heat transport circuit between reactor and end-user by radioactive elements in general and tritium in particular. Indeed, several technical measures enable to reduce radioactive contamination of this circuit below currently applicable effluent limits. Previous experience is available from earlier High Temperature Gas Cooled Reactors (e.g. Ft. Saint Vrain) and from fusion reactor experiments, but construction of a nuclear cogeneration demonstrator will require the formal establishment of contamination limits in heat transport circuits, end-user processes and products.

A review of the technical aspects of tritium contamination management is underway to provide elements on the available countermeasures to efficiently limit tritium contamination of the process. Given the limitations and principles laid down in the European regulation – related to the basic safety standards for the protection of the health of workers and the general public against the dangers arising from ionizing radiation (Council Directive 96/29/EURATOM 1996) – the analysis sketches the requirements to achieve an acceptable safety demonstration.

1.3.1.3.4 Findings on the coupling

The current status of the viability assessment of EUROPAIRS has been presented in the previous sub-chapters. The objective to realize full scale prototyping of a coupling scheme in the near future will require joint efforts from nuclear and end-users industries. The dialogue to understand the needs and the constraints of HTR plants and the heat consuming industries, triggered by the EUROPAIRS project, is paramount. The economic feasibility of the coupling is a crucial issue.

From the technology point of view alone, it appears that process steam production is the nearest term application. However, licensing and siting will require significant effort. Although HTR technology is considered as passively safe, reaching public acceptance may yet be another challenge.

A coupling scheme with steam as heat transfer medium would be a first step with significant impact on the energy landscape. To ultimately exploit the full potential of the technology, developments are required to increase the maximum temperature available for the heat process. The first elements of the analysis indicate that the technology perspectives would broaden significantly if it could supply processes belonging to the "chemical class", i.e. at temperatures between 600°C and 900°C. For such high temperatures, tubular IHX may be available rapidly, but the development of plate IHX is needed to improve the economic viability of the technology. The costs are indeed at the heart of the technological viability.

1.3.1.3.5 Industrial heat market

The heat market of heat intensive industries was analysed and evaluated. No reliable and detailed information was available before the project, except some statistics from OECD/IEA and Eurostat. Yet, although they both use the same information (a questionnaire to Member States), their results differ significantly: 766 TWh in EU27 in 2007 for the IEA against 1 619 TWh in 2007 for Eurostat. The difference can be explained by the sparse information and the not fully reliable statistical treatment. This statistical unreliability made a detailed analysis of the European heat market necessary.

This study was carried out over 7 months. A multiple approach methodology was adopted. The heat consumption was first evaluated indirectly from the greenhouse gases emissions declared in the EU Emissions Trading Scheme. An in-depth analysis was then carried out by sector down to the level of processes, making possible to calculate directly the consumption of steam with a better precision. A market survey was organised from April to September 2010 through confidential interviews with representatives from 12 key sectors in order to better understand their processes and their industrial context.

The study was restricted to Europe. The temperature was segmented in the several classes (100°C - 250°C - 550°C - 700°C – 1000+°C), following an analysis of the heat industrial end-users practices.

Only basic industrial sectors with large productions and massive heat consumption were covered. Industries manufacturing public goods as well as synthetic fuels were not covered by the study.

| Sectors included | | Sectors excluded |
|---|---|---|
| District heating<br>Desalination<br>Pulp and paper<br>Oil refining<br>Chemical industry<br>Soda ash<br>Ammonia and fertilisers<br>Industrial gases | Hydrogen<br>Lime<br>Aluminium<br>Iron and steel<br>Glass<br>Cement<br>Non-ferrous metals<br>Ceramics | Manufactured products<br>Pharmaceuticals<br>Agricultural products<br>Consumer goods<br>Synthetic fuels |

**Table 2: List of industrial sectors included and excluded from the scope of the study**

The heat market could be distributed into two main sub-markets:

- "**plug-in**" covering all combined heat and power plants supplying one or more industrial facilities

- "**extended**" covering all boilers and burners operated internally within an industrial facility and/or embedded directly into the production processes.

The interest of the plug-in market is obvious: the existing cogeneration plant could be replaced by a nuclear cogeneration plant simply by switching the pipes. The extended market relates to a market which may be more difficultly reached today but could yet be interesting in the future for high temperature nuclear steam.

Two additional hypothetical submarkets were considered:

- "**polygeneration**" relates to the co-production of base raw materials beyond the sole cogeneration of heat and electricity such as industrial gases (e.g. hydrogen nitrogen, oxygen) near the cogeneration plant; this market links with the potential of production technologies.
- "**pre-heating**" considers the share that could be technically externalised from the extended market if a low-carbon, competitive high temperature steam was available.

The heat market was found very versatile and should not be approached globally. It differs significantly from the electricity market where all production plants face a global demand, i.e. the power grid. As heat cannot be transported over long distances, the cogeneration plant can only supply a few customers and must be strictly adapted to their needs.

Heat consumption depends on each industry context and operational constraints. The study described these different usages for each industry. The reader is invited to consult the full market analysis for more details.

Most sectors have processes operating at a same temperature range but several sectors, in particular high temperature sectors, may have production phases operating either at very different temperatures (e.g. ceramics, aluminium) or on an extended temperature spectrum.

Nuclear cogeneration from current light water reactors was proven for several low temperature applications (< 150-200°C). Europe has a comprehensive experience in this technology. 13 European nuclear reactors have been and are still producing district heating and process heat for a total of 1 089 GWh in 2006. Beyond Europe, nuclear desalination was established in Japan and Kazakhstan. More interestingly, a large scale industrial park in Canada has been using until 2006 nuclear steam from 8 nuclear reactors at the Bruce Power Station. The plant produced 5 350 MWth of medium pressure steam and supplied a heavy water production plant, a plastic film manufacturer, a greenhouse, an ethanol plant, an alfalfa plant, an apple juice concentration plant and an agricultural research facility.

Europe was found to be an attractive heat market for nuclear cogeneration. First, the European heat market is large, ranging from 2 526 to 3 091 TWh/y, as compared to the 3 367 TWh of gross electricity production in Europe in 2007, of which 1 145 TWh for industry. Second, a good share of the market (25%-30%) is externalised in the form of cogeneration, equivalent to 87 to 89 GWth; the remaining 70% to 75% is consumed in embedded process burners and boilers. The polygeneration market would represent an additional market of 117 TWh/y or 13 GW thermal. The pre-heating market (up to 550°C) could potentially cover a non-negligible part of the extended market up to 361 TWh/y or an equivalent thermal capacity of 41 GW thermal. Third, most industries have increasing concerns on their energy supply and costs and their CO2 emissions. Most of them are looking forward to diversifying their heat production mix with competitive low-carbon technologies.

The heat market was found most significant below 550°C and above 1000°C; very few processes were found to operate between 550 and 1 000°C; industrial gases and lime are the most important sectors in the class 700-1 000°C. The plug-in market is restricted to temperatures below 550°C. The most significant sectors are district heating and chemical industry; the iron and steel plug-in market consumes mainly calorific off-gases. Oil refining, iron and steel and cement are the largest industrial sectors in the extended market; they consume heat mostly via embedded boilers or burners. The sectors with the highest average thermal capacity per site are oil refining, chemical industry, iron and steel, cement. The number of sites where a single cogeneration plant would have a higher capacity than 500 MW would be around 10 to 20 sites (e.g. large complex refineries, large chemical clusters, large integrated paper mills).

The comprehensive information gathered by the study could be used to recommend a best market strategy for nuclear cogeneration, as a preliminary for a future marketing approach.

1.3.1.3.6 Preliminary economic study

This report aimed at introducing the economics of nuclear cogeneration for industry and comparing, on the basis of this preliminary analysis, its economic viability to supply industrial heat-consuming processes against the current reference heat production technology (gas cogeneration plant and gas boiler). For the purpose of this study, LGI has been processing confidential data provided by nuclear industry.

The thermal match of heat production and consumption is the key priority for nuclear cogeneration, since excess electricity can be sold to the market or imported from the grid if insufficient. The cost of a cogeneration plant depends therefore on the cogeneration scheme which is set up, which in turn depends on the industry processes which are to be supplied with cogeneration heat.

The comparison of nuclear and gas cogeneration technologies separately showed that uncertainties do not arise at the same time. Nuclear cogeneration is most risky during construction during which delays and overcosts can occur. Yet, as soon as the plant is commissioned, the risk was found very low except the political and public acceptance risks, which can yet be minimised during the site selection phase.

On the contrary, gas cogeneration faces the greatest uncertainty during the operation period, due to the gas price volatility, the increasing concerns over the security of supply and the CO2 price which all are adding uncertainty.

Beyond the intrinsic risks of any cogeneration technology (whether nuclear or gas), the risk of a cogeneration project depends further on the risk of the site and its surroundings (site characteristics, environmental conditions), the industry requirements and risks (adaptation costs, industrial context...), the related safety measures, the energy context (geopolitics, gas prices, local electricity prices...), the project financial aspects, the general context (inflation, economic growth, industrial production...). All risks are adding to each other so the cost estimation may greatly depend on each project.

LGI Consulting was able to gather confidential economic data and process them in a very short analysis which showed that nuclear cogeneration using high temperature nuclear reactors could already be competitive with gas cogeneration, even at today's gas price ranges. A thorough economic analysis would still be necessary to determine the robustness of this result but this enabled to provide an excellent ground for discussion between all project partners and the community beyond.

### 1.3.2 WP2 Safety and licencing compatibility of the coupled system

After a review of the licensing trend and international standards, two test cases were defined as example of potential short or medium term applications (between ten and fifteen years): steam and electricity production for a chemical complex and a hydrogen production plant (high temperature electrolysis). A simplified analysis of the reciprocal impact of the nuclear plant and the industrial installation has been achieved, based on the safety documents of the chemical site and description of the hydrogen plant found in past studies. Then, tentative acceptance criteria were selected for the main safety functions and major issues and recommendations were outlined which are summarized below.

First it is clear that the nuclear site (as defined in national regulations) should be separated from the industrial site from the point of view of workers access rights, and security management. Each operator (Industrial and Nuclear) should have its own physical area of responsibility. This is to be put apart from separations designed to ensure the protection against external hazards.

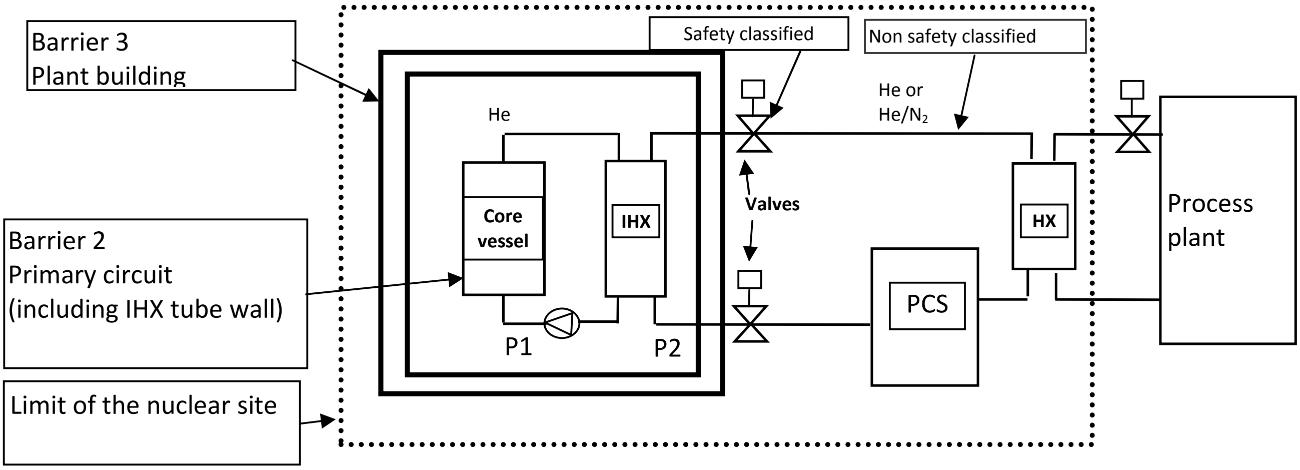


**Figure 5: Tentative scheme of the barriers of the coupled system**

The HTR is designed to have a very low potential impact on the neighborhood in any situation, first because of core power density restriction. This unique feature, if validated in the safety demonstration, is a major point of the feasibility of the safety assessment and licensing of the coupled system because, in case of accident, it is preferable to provide enough delay so that industrial process operators can maintain the installation in a safe condition (practically, they would not have to evacuate the area).

As regards the external hazards, many nuclear sites in Europe are already located in an industrial environment. So approaches and technical solutions for the nuclear site protection have already been implemented to deal with the specific hazards induced by the industrial environment, but rather on a case by case assessment. At an international level, it was noticed that IAEA has proposed a methodology to assess external hazards which would imply several innovative modifications as compared to current approaches (i.e. those developed for EPR assessment). The concept of safe separation distances - which means “distance of no interaction effects” between nuclear plant and industrial process - has been discussed in the study. And examples (like a chemical cluster in the Netherlands) showed that these distances could be relatively short, even considering low probability accidents with high consequences. Moreover, these accidents are often associated with fires or explosions of chemical products storage capacities which can be kept far from the industrial process itself. Finally, three main areas for improvement of technical and methodological aspects of the assessment of external hazards have been proposed in this study: the need for a more detailed analysis of the consequences of the external hazards (probabilities of effects on safety functions, categorization of induced accidental loadings, etc.), the treatment of potential common modes failures and the evaluation of the risk induced by the projectiles.

The nuclear plant availability and the consequences of reactor shutdown are also major criteria for assessment. The nuclear plant safe shutdown, shall always override the operation of the industrial process. Therefore, this will require the assessment of the provisions (systems, procedures) taken in order to avoid the degradation of the industrial equipments with a potential back effect on the nuclear plant.

Concerning the potential contamination of the heat transfer fluid delivered to the industrial circuits by radioactive materials, the effective dose brought to workers by the use of the products of the coupled system should not exceed a fraction of the limit dose of 1 mSv/y. In other words, this means that it is recommended that industrial workers be considered as the general public. In practice, several isolation devices and physical separations between the primary fluid and the heat transfer fluid may reduce drastically the risk of contamination. However, the case of tritium is specific because of its high mobility. In any case, the licensing of the coupled system will be supported by an environmental impact study which will include the specificities of the processes and products. Then, requirements and acceptance criteria to deal with the risk of contamination of End Users products by tritium will have to be discussed with Safety Authorities.

Finally, the licensing process involves the review and evaluation of the efficiency of the emergency planning. Specifically for the coupled system, it has been outlined in the study that attention would have to be paid to integration of the nuclear and non-nuclear risk in a reference emergency planning relevant for the area hosting the nuclear plant and the industrial processes.

### 1.3.3 WP3 System deployment outlook

Firstly the deployment of nuclear cogeneration in Europe and in the world is evaluated as part of the nuclear fleet. The impact but also the potential synergetic benefits, considering waste, resources and infrastructure are evaluated, to determine whether concerns or showstoppers exist when nuclear cogeneration is deployed in its fullest potential. Secondly a roadmap is developed, in which the steps towards nuclear cogeneration deployment are described, based on current knowledge and the information generated in other work packages of EUROPAIRS.

#### *1.3.3.1 Task 3.1 Scenario study*

Task 3.1 aimed at studying a HTR deployment scenario and its impact on natural resources and on waste production. In the study a number of different nuclear futures for Europe and the world are assumed, and the impact and potential issues are identified and evaluated. The scenarios have been selected on what is considered most likely, based on current developments.

The work resulted in the editing of deliverable D31 that was issued in revision 0 at the beginning of July 2011. The main conclusions of this deliverable were that, if all or most of the HTR are fuelled with plutonium or uranium/thorium fuel, their contribution to the world energy needs in industrial heat can be significant. This contribution indeed could reach 10% of world needs for the period [2035; 2100] without jeopardize the nuclear electricity production coming from LWR. On the contrary, if HTR are only fuelled with UOx fuel, their contribution may be limited to a small fraction (a few %) of the world energy needs in industrial heat, due to the uranium resource issue. As for the waste stream, the amount of minor actinides produced by HTR is quite low comparatively with LWR production, especially when HTR are fuelled with UOx or uranium/thorium fuel. This amount can become more significant when HTR are fuelled with plutonium. The scenarios and subsequent conclusions considering future deployment have been described in detail.

#### *1.3.3.2 Task 3.2 System deployment roadmap*

The EUROPAIRS roadmap essentially summarises the findings of EUROPAIRS, in the form of a roadmap that describes the next steps, and the route towards nuclear cogeneration commercial deployment. Different layers of detail have been worked out:

- Level 1: the establishment of a prototype, key to demonstrate technical, financial and licensing feasibility of connecting a High Temperature Reactor to non-nuclear industry. This step essential, and a prerequisite for further industrial commitment to the technology and its application
- Level 2: the global route towards deployment, of which the establishment of a prototype is the first (major) step. Additionally, international cooperation, global licensing, international industrial trends, key medium term nuclear cogeneration applications are included, to provide a wide picture of nuclear cogeneration

- Level 3: Simplified roadmap for communication purposes. This is a one page roadmap, which is entirely based on the underlying roadmaps of higher detail, but focuses on the main assumptions and critical paths, that need to be conveyed to a wider audience. This roadmap is named the 'SNETP Roadmap', as it will be part of SNETP communication considering nuclear cogeneration deployment strategy

Additionally an excel road mapping document in which all levels of roadmap are collected, and a PowerPoint presentation for the SNETP roadmap has been provided.

### 1.3.4 WP4 Coordination

The EUROPAIRS Coordination Team has ensured a clean and efficient management of the project. It monitored the publication of deliverables in due time. Although the consortium was quite large, the management went smoothly and no significant problem should be reported.

In the course of the project, the Consortium was enlarged with 4 new partners (AVN, Alstom, E.ON, AGH), demonstrating the attractiveness of EUROPAIRS. They all brought their expertise to complement the on-going work in the project and to bring specific additional deliverables (AVN, AGH). The Consortium had also to accept that PBMR from South Africa retired due to a government decision. Another South African partner, North West University, was able to take over all the tasks of PBMR so the project was not impacted.

The project seized this opportunity to amend the Grant Agreement and add several new deliverables to the original list. A market study and an economic study were carried out by LGI Consulting. AVN added a deliverable in collaboration with Tractebel Engineering on feedbacks from past HTR project and regulatory trends, and AGH produced a deliverable on nuclear-assisted coal liquefaction.

The project has had a smooth internal communication among all partners. This encouraging frame for dialogue enabled a successful cross-fertilization between the nuclear and non-nuclear industries. The successful internal project communication proves that both communities can discuss very well together and justified the continuation of the work after the project termination.

The Coordination Team organised the collaboration with additional end-user industries not being partners of EUROPAIRS, through an Associated Industry Network (AIN). It liaised with the European Steel Technology Platform (ESTEP).

Furthermore EUROPAIRS started communication on nuclear cogeneration collaborations through an information exchange meeting with the US Industry Alliance for NGNP.

Communication of project results and achievements was implemented by presentations at various conferences such as ENC 2010 and HTR 2010, ICAPP 2011, at GIF and SNETP meetings and at the EUROPAIRS Open Workshop at the end of the project (26 May 2011 in Brussels).

## 1.4 Potential impact

The main impact of EUROPAIRS is to pave the way for future actions concerning "innovative reactor systems" as its objective is to create the conditions for initiating the development of a Demonstrator for the coupling of a (V)HTR (one of the 6 innovative systems selected for their potential by the Generation IV roadmap) with industrial process heat applications, by building a strategic alliance between European nuclear industrial, R&D organisations and process heat user industries.

As a direct impact of EUROPAIRS, the results of WP3 can be used for defining the next steps: the proposal of a new project, in which nuclear and process heat user industries will develop together the conceptual design of an industrial prototype for the coupling of a (V)HTR with industrial heat application(s).

The development of a prototype for heat applications of nuclear energy prepared by EUROPAIRS is therefore in line with the strategic objectives of the SET Plan, which proposes the development of low carbon energy technologies as the main strategic objective for the European development of energy technologies. Addressing heat applications of nuclear energy is indeed one of the 3 axes of the R&D strategy recommended for future European programmes by the vision report of SNETP for innovative reactor system.

More precisely, EUROPAIRS provides basic elements to be able to address at least three of the key technology challenges that the SET plan proposes for developing "a diverse portfolio of clean, efficient and low-carbon energy technologies":

- "Bring to mass market more efficient energy conversion end end-use devices and systems…" "to meet the 2020" target, by developing cogeneration HTR plants with more than 80% efficiency in the form of electricity and industrial process heat supply and "achieve breakthrough in enabling research for energy efficiency: e.g. materials…" "to meet the 2050 vision", by developing the technologies (most particularly the materials and the fuel) that will make the VHTR feasible.
- "Complete the preparations for the demonstration of a new generation (Gen-IV) of fission reactors for increased sustainability" by initiating the strategic alliance between nuclear industry and research on the one hand and process heat user industries on the other hand, which is an absolute prerequisite for the development of one of the most promising types of Gen-IV systems, the VHTR, the main mission of which is precisely to supply industrial process heat, as established in the GIF Roadmap.
- "…create the conditions to enable industry to commercialise hydrogen fuel cell vehicle", by developing the coupling technologies that will in a future step allow using a VHTR for producing in a competitive way large quantities of hydrogen without $CO_2$ emissions.

***International cooperation***, to which the Coordination Team paid a special attention, was initiated by the joint workshop with the US NGNP Alliance.

EUROPAIRS started to launch the development of the demonstrator as an initiative at the European level, but, while establishing the roadmap for the development of the demonstrator it looked for **complementarities with accessible national and international research activities**, in order to build a programme which federates efforts at the European level and at the national or organisation levels. The participation in the Project of partners from 8 European countries (Belgium, Finland, France, Germany, Italy, Poland, The Netherlands and UK) provided information on development activities related to the nuclear and non-nuclear parts of the programme. In addition, the presence of non-nuclear organisations in the Project together with nuclear industry and research allowed to look for synergies – both at the national and European levels – between nuclear and non-nuclear R&D (e.g. materials) and design activities (e.g. development of heat exchangers) to create links between the Euratom projects and relevant non-nuclear European projects. Finally, with direct participation in GIF VHTR projects and Steering Committee of some partners of EUROPAIRS (AMEC, FZJ, JRC and NRG) as Euratom representatives, inputs from this important international cooperation have been integrated in the work programme.

By preparing future actions, EUROPAIRS is also contributing to dissemination and to the construction of the European Research Area (ERA):

EUROPAIRS, as well as the future development of the demonstrator that EUROPAIRS will make possible, contributes to most of the features of the ERA defined in the Green Paper (COM (2007) 161):

- The ERA will need "***well-coordinated research programmes and priorities***, including a significant volume of jointly-programmed public research investment at European level involving common priorities, coordinated implementation and joint evaluation". The development of the demonstrator, the roadmap of which will be proposed by task 3.2 of EUROPAIRS, will be a programme satisfying these criteria.

- EUROPAIRS initiated by its activity "***effective knowledge sharing*** of public and private [nuclear] research and industry" with other research and industrial activities of other sectors of economy, with which the interactions are usually very limited. In the future programme of development of the demonstrator stemming from EUROPAIRS, this knowledge sharing would be even enhanced. This will be true not only at the level of exchanges between organisations, but the ambition of the Project is also to create links at the European level, to generate a strong nuclear and non-nuclear support basis, to be able in the future to mobilize together resources of Euratom and of other parts of the Framework Programmes on joint actions for the development of the nuclear and non-nuclear parts of the demonstrator. This sharing of the knowledge and of research capabilities (competences and experimental equipments) will enhance the potential of European research, in for instance in the fields of materials, of development of high performance heat exchangers, of processing of gases (e.g. development membranes for gas separation that can have both nuclear applications and applications in chemical industry), etc.

- Recommending focusing of the efforts on a programme requiring large advances in R&D, EUROPAIRS will favour the development of "***excellent research institutions*** engaged in effective public-private cooperation and partnerships".

- A key factor for the success of the development of the demonstrator is the availability of experimental facilities in some key areas for the development of the reactor and of its industrial applications. During the definition of the work programme for the development of the demonstrator, a special attention will be devoted to the needs of experimental facilities and proposals will be made for developing or securing "***world class research infrastructures***, integrated, networked and accessible to research teams from Europe and the world" in the areas where they are needed:

- Finally it has been explained in detail how, by giving a high priority to international cooperation, EUROPAIRS will contribute to create "***a wide opening of the European Research Area to the world***".

As the Project is meant at preparing future actions and at calling up the support of stakeholders for a large scale project of strategic interest for Europe, the dissemination of the information it generated, which is of strategic and programmatic nature, is a central objective of the Project and a high priority task of the Coordination Team.
The main supports of the knowledge generated by the project are its deliverables. Therefore for facilitating dissemination, deliverables are either made public, or public versions are released.

The main targets for dissemination and communication are
- The non-nuclear industries in order to develop a strategic alliance between nuclear and industrial process heat users for being able to launch a demonstrator project,
- The European stakeholders (European Parliament members, European Nuclear Energy Forum, European Commission, etc.) in order to get the necessary support for the demonstrator development,
- The possible international partners who could reinforce the alliance or complement the European support to the demonstrator development.

There are also other important target audiences, on the one hand the students and the young professionals; as such an innovative programme like the construction of a prototype should attract brainpower, and one the other hand the general public, the acceptance of which will condition the possibility of industrial deployment. The following impacts are expected:

- A better knowledge in industry of the potential of (V)HTR as a heat source for process heat applications, and as co-generative energy infrastructure
- A better knowledge of European stakeholders of the potential of (V)HTR for reducing $CO_2$ emissions and for being a sustainable solution for that purpose,
- Growth and strengthening of the partnership of industrial process heat users and of international partnership for participating in EUROPAIRS and above all, in the future development of the demonstrator.
- A better information of the public and an involvement of students (e.g. with a larger number of PhD theses than in the 6$^{th}$ Framework Programme) and young professionals in the future development of the demonstrator.

### 1.4.1 WP1 Viability assessment

In accordance with the objectives and the intended impact of EUROPAIRS on the future development of cogeneration in Europe, the viability assessment provides the basis for the safety and licensing considerations of future cogeneration plants and for the implementation of the roadmap towards a demonstrator.

#### *1.4.1.1 Task 1.1 End-User processes, characteristics and requirements*

This task provided a screening of the use of heat in industrial sectors. This document enables the evaluation and the classification of potential industrial heat market. This document show that there is two principles heat provider for the moment: steam for temperature under 370°C and boiler for temperature above 800°C. Between this two temperature levels, there is a gap where new processes (i.e steam methane reforming) can be developed to use new heat source such as nuclear.

#### *1.4.1.2 Task 1.2 Nuclear system: characteristics and limits*

In Europe and in the United State, HTR as nuclear reactor is not focusing on electricity production but also on heat production, and is then a good candidate for coupling with process plant for cogeneration indeed reducing $CO_2$ emissions.
Nuclear industrials acknowledge its unique ability to address growing needs for industrial cogeneration of heat and power owing to its high operating temperature and flexibility.

Based on the HTR information reference document the technical feasibility of coupling a HTR to a process plant for cogeneration is demonstrated. HTR presents available technology for a demonstration in the coming years, economics being set aside. The final conclusions present the available technologies for a HTR demonstration in the coming years.
When HTR development projects are on-going to improve existing technology or deploy new one, a larger range of industrial applications could be envisaged for the coupling in the coming years.
Beside the heat market, there is also the H2 market. In fact ammonia production needs massive volumes of hydrogen, but hydrogen produced from natural gas will be more and more expensive in the coming years (Russia is thinking to double the price of natural gas) and HTR could replace natural gas for Hydrogen production and steam for ammonia production. This market will represent an interesting potential of HTR deployment in the coming decades. A potential explosion of HTR need could be expected in 20 years if demonstration of a prototype is successful.

Regarding the coupling demonstration in a near future and dealing with technological and economical aspects, only power in range of 400-600 MWth should be envisaged. But the market presents lower power needs. Following EUROPAIRS Project the demonstrator must be identified (HTR technology choice and heat application).

#### *1.4.1.3 Task 1.3 Synthesis of the requirements*

The market study has had several strong impacts. First, it has gathered comprehensive quantitative and qualitative information on the market which enables an insightful decision-making from all partners. Second, it has structured a wide community of interest around the Project by approaching multiplier actors like European professional associations. Third, it has clarified the general position on nuclear cogeneration of the different market players so the EUROPAIRS consortium could map clearly its industrial context.

The preliminary economic study has revealed very useful and was widely discussed among partners. The EUROPAIRS Project has indeed achieved outstanding results as regards the technical and licensing aspects but clarifying the economic parameters was a must-do action so that every partner could have a joint and general understanding of nuclear cogeneration. The study further paved the way for future research by recommending the key analysis to carry out.

### 1.4.2 WP2 Safety and licencing compatibility of the coupled system

The study performed within th WP2 is a step forward towards the feasibility of the safety assessement of a prototype of a high temperature reactor based cogeneration system. It is also a tool to estimate the licensing risk associated with the coupled system and to prioritize the tasks needed to suport the safety demonstration. It has enlighted issues that should be discussed with safety authorities prior to the submission of a preliminary safety report, in order to reduce the licensing risks (methodology for assessment of external hazards, contamination limits of the heat transfer fluid, emergency planning requirements). So this study may have an positive impact on the concept accptance by showing path to reduce the licensing risk.

### 1.4.3 WP3 System deployment outlook

Work Package 3 provides a look into the future based on the information available, and the information generated in the other work packages of the EUROPAIRS Project. Making use of the largely known characteristics of High Temperature Technology, end user requirements and TSO requirements regarding licensing, both scenarios assuming large scale HTR deplyment, and the route towards this deplyment have been investigated in Task 3.1 and Task 3.2 respectively.

The impact of this work package is that it provides an overview of the necessary steps and implications of large scale implementation of nuclear cogeneration connected to non-nuclear industrial processes. Special emphasis has been put on the communicative aspects of the outlook provided, to maximize its potential impact to external parties.

#### *1.4.3.1 Task 3.1 Scenario study*

The main impact of the scenario study is that it demonstrates that under the reasonable scenarios that can be assumed with current knowledge, significant nuclear cogeneration deployment can be accommodated with currently known fissile resources. But especially if the ambition for deployment of nuclear systems with improved resource efficiency can be met (i.e. implementation of fast neutron systems for electricity production), a synergy can be foreseen, where fertile and fissile unclear resources are consumed in a most effective way, while meeting not only electricity but also heat demand in a responsible way.

#### *1.4.3.2 Task 3.2 System deployment roadmap*

The roadmap essentially is a summary of current knowledge of High Temperature Reactor deployment, combined with the input from non-nuclear industry. It outlines next steps towards nuclear cogeneration deployment, and sketches the perspectives beyond prototype establishment. Additionally an overview level has been added, specifically for communication purposes.

The well founded way in which the roadmap has been set up in connected roadmaps of different levels of detail, provides both a detailed insight in what is needed for a prototype, and a high level overview on how to work towards deployment.

The report, presentation and roadmap itself, intend to clarify what is needed for nuclear cogeneration to meet its potential. With emphasis on communication, these items will be used to present EUROPAIRS and the nuclear cogeneration perspective to the outside world. The impact of having information in a communicative format is expected to be large, and will support the next steps envisaged by the EUROPAIRS consortium.

### 1.4.4 WP4 Coordination

EUROPAIRS has successfully achieved to trigger an extended dialogue between the nuclear and heat intensive industries – a dialogue which was not straightforward – which enables to continue its action after its end.

By mapping clearly the heat market and the industrial processes, determining the possible operational envelope of a high temperature nuclear reactor with an industrial end-user and the key cost items of such a project, analysing the safety aspects of this coupling and roadmapping the technological RD&D, EUROPAIRS has put all the foundations for a successful deployment of this technology. This is one major achievement and success.

EUROPAIRS has widely communicated externally with the presentations of several of its activities in conferences (ENC 2010 in Brussels on 28 May to 2 June 2010, SNETP General Assembly on 14 September 2010 in Brussels; HTR 2010 on 18-20 October 2010 in Prague, ICAPP 2011 on 2-5 May in Nice) and the final Project workshop on 26$^{th}$ May 2011 in Brussels. A paper was submitted at Nuclear Engineering and Design entitled “EUROPAIRS Prospects For Coupling of HTR with Industrial Processes – Viability Assessment” (authors: N. Delannay, C. Viala, Ph. Muguerra, A. Bredimas, E. Sibaud, J. Ruer, C. Angulo) as well as another entitled “Feasibility study for the safety assessment of a High Temperature Reactor coupled with an industrial process” (authors: O. Baudrand, D. Blanc, V. Noel, J. Segurado, F. Roy, P. Koch, Verfondern, B. Putter, S. Basu, S. Ehster-Vignoud).

In addition to this communication effort, EUROPAIRS has taken numerous contacts with heat intensive industries including technology platforms which were not represented in the consortium, especially through the survey carried out by LGI. This allowed to present the Project activities and to structure a general network around nuclear cogeneration.

All these contacts and bilateral communication actions enabled to disseminate largely the Project results and activities so that most communication targets were reached.

In addition to the useful collaboration of the South African programme, the Project has paved the way for a transatlantic cooperation by inviting the US NGNP Industrial Alliance in a meeting in Paris to exchange information and experience and to agree on future cooperation options. The EUROPAIRS partners appreciate that their links with their US counterparts are now strong enough to pursue the cooperation after the Project termination.

Based on the motivation experienced with EUROPAIRS a majority of the partners are initiating a European industrial cogeneration alliance and the implementation of a **Nuclear Cogeneration Industry Initiative (NC2I)** to promote nuclear cogeneration in the frame of SNETP.

EUROPAIRS partners therefore feel that the Project has reached all its objectives and are very satisfied of its wide impact, which concretizes especially in the continuation of its activities after the Project termination.

## 1.5 Project information

Website address: http://www.europairs.eu/

Project type: Support Action

Project start date: 01/09/2009
Duration: 21 months

Total budget: EUR 1,501,357
EC contribution: EUR 800,000

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**Partners list:**

| No. & short name | Beneficiary | Country |
|---|---|---|
| 1. AREVA-D | Areva NP GmbH | Germany |
| 2. AREVA-F | Areva NP SAS | France |
| 3. AM | ArcelorMittal | France |
| 4. AMEC | AMEC-NNC | United Kingdom |
| 6. FORTUM | Fortum Power and Heat Oy | Finland |
| 7. GRS | Gesellschaft für Anlagen- und Reaktorsicherheit | Germany |
| 8. IRSN | Institute for Radiological Protection and Nuclear Safety | France |
| 9. JRC | Commission of the European Communities –Joint Research Centre – Institute for Energy (JRC-IE) | EU |
| 10. FZJ | Forschungszentrum Jülich GmbH | Germany |
| 11. TKT | Tecnimont KT | Italy |
| 12. LGI | LGI Consulting | France |
| 13. NRG | Nuclear Research & Consultancy Group | The Netherlands |
| 14. PROCHEM | Prochem | Poland |
| 15. SAIPEM | SAIPEM | France |
| 16. TE | Tractebel Engineering (Gdf Suez) | Belgium |
| 17. TUV | TÜV Nord | Germany |
| 18. DSM | Koninklijke DSM N.V. | The Netherlands |
| 19. ZAK | Zaklady Azotowe Kedzierzyn S.A. | Poland |
| 20. AL | L'Air Liquide | France |
| 21. RR | Rolls-Royce Power Engineering plc | United Kingdom |
| 22. BEC | Baaten Energy Consulting | The Netherlands |
| 24. NWU | North West University | Rep. of South Africa |
| 25. SOLVAY | Solvay S.A. | Belgium |
| 26. ALSTOM | Alstom S.A | France |
| 27. AVN | Association Vinçotte Nuclear | Belgium |
| 28. AGH | Akademia Górniczo-Hutnicza | Poland |
| 29. EON | E.ON Kernkraft GmbH | Germany |

## 1.6 D05 - Viability Conditions for (V)HTR Combined Heat and Electricity Supply to Industrial Processes

From the results obtained from the WP 1 and 2 and Task 3.1 it turned out that the viability conditions for (V)HTR combined heat and electricity supply to industrial processes are determined by the economic conditions the system has to meet to enter into the market. The results of the viability assessment are summarised in chapter 1.2 above.

As shown in the EUROPAIRS heat market analysis, small nuclear reactors adapted to cogeneration align well with a very significant fraction of the existing heat-capacity needs for many European process industries (approx. 50–250 MWth) in the chemical/petroleum, industrial, paper, and metal sectors. Nuclear reactors for cogeneration of heat and electricity are thus well suited to support the EU low-carbon society goals while providing stability in production and cost. High Temperature Reactor (HTR) technologies are well suited for the production of “high value” heat by producing for instance steam in the range 200-550ºC, which is a classical product of current fossil-fired cogeneration plants. Future reactor designs could deliver heat potentially beyond this temperature range and further increase the market opportunities for nuclear cogeneration. However, little public information is available on these reactor costs.

Therefore, a study was conducted to develop “target cost” estimates for a range of competitive cogeneration market situations, where nuclear cogeneration would compete against coal and natural gas combined heat and power (CHP) systems, with or without Carbon Capture and Storage (CCS). Parametric analysis was used to develop a cost breakdown of the capital, operating, and fuel cycle costs. Sensitivity analysis was used to understand the impact on competitiveness from key cost variables. For this study, target markets were based on projected 2030 energy technology costs; allowance of this timeframe provides adequate time for this new type of reactors currently in concept phase for design, licensing, and deployment. The costs for all systems used here reflect mature $n^{th}$-of-a-kind (NOAK) systems and are expressed in constant year 2005 Euros.

Parameters included in this study include:

- Thermal efficiency changes from using cogeneration sacrifices some of the electric efficiency to make large amounts of heat available;
- Projected emission allowance costs from the European Emission Trading Scheme
- Cost and performance data for IGCC (“Integrated Gasification Combined Cycle”, for coal-fired CHP) and CCGT (“Combined Cycle Gas Turbine”, for gas-fired CHP) were assumed including the effect of optional CCS (“Carbon Capture and Storage”.
- Fossil fuel cost evolution assumptions for coal and gas (from SEER-2 [1])

Target cost ranges were identified for each market, i.e., coal CHP with and without CCS, and gas CHP with and without CCS, see Figure 1. This range includes the lowest cost up to the value for the high fuel range (e.g., for gas CHP the targeted cost range is 99-177 €/MWh). The large span is mainly due to the large range of projected natural gas prices in 2030. For nuclear cogeneration to be competitive in the targeted markets with the other CHP technologies, the reactor would need to produce a combination of heat and electricity. The primary users of the plant would utilize the process heat and at least a portion of the electrical production. Excess electricity would be sold in small electrical distribution markets or medium transmission markets.

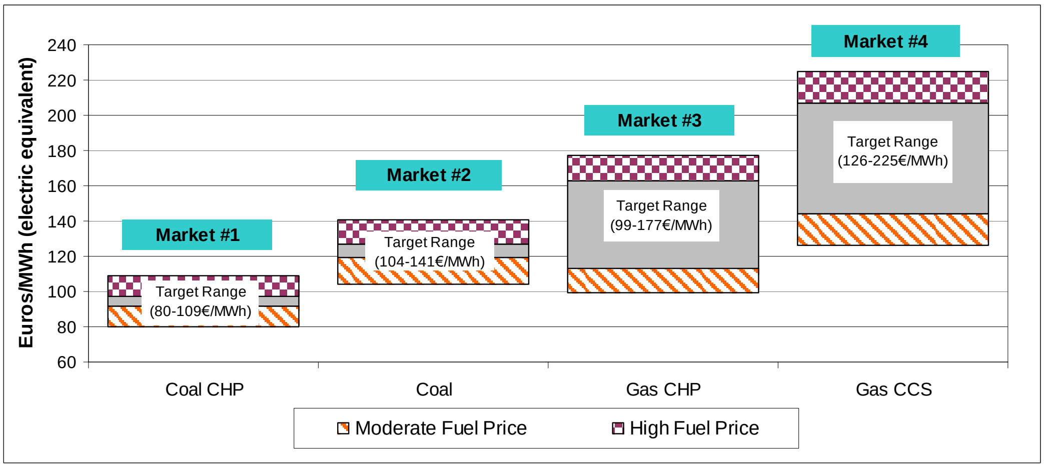


**Figure 1: Overall reactor cost targets (without revenue from heat taken into account) to compete in 4 different CHP markets by 2030.**

In order to develop "target cost" estimates for nuclear reactors competing in each market sector, a cost breakdown structure is needed. The cost structure contains all the costs for the lifetime of the reactor and provides the data at a sufficient level of detail to define useful comparative information (e.g., cost of capitalized equipment, number of reactor operators, annual uranium ore requirements). The cost breakdown structure chosen for this study was the code of accounts (COA) developed by the Gen IV Economic Modeling Working Group [3]. The COA provides a means for consistently placing cost information in explicitly defined categories that are common to most SMR designs and their lifetimes.

The calculation of the "target cost" required the development of a cost breakdown for a representative (non-vendor design specific) nuclear reactor. The developed cost breakdown structure was used as input to back-calculate the detailed cost from the LCOE (e.g., 100 €/MWh). Additional details are also derived from the costs (e.g., overnight capital costs, equivalent number of staff). The detailed costs from the spreadsheet were subsequently input to Gen IV EMWG MINI G4 ECONS model [4] for further sensitivity analysis.

The target cost calculator was used to develop a cost range for each of the four markets described in Figure 1. These target costs represent the reactor capital costs, operations, and the complete fuel cycle. For each market, four data points were analyzed (i.e., bottom and top of the moderate fossil fuel price, bottom and top of the high fossil fuel price) as previously described in Figure 1. In Figure 2, the reference ranges defined on the x-axis represent the range of target overnight capital for each of the markets. For example, the overnight capital costs (in terms of MW electric equivalent costs) for Market #3 ranging from lowest to highest: 5,372 € /kWe (moderate fuel-low carbon) to 5,772 €/kWe (moderate fuel-high carbon); and 9,544 €/kWe (high fuel-low carbon) to 9,944 €/kWe (high fuel-high carbon). Recall that the high and moderate fuel cost ranges were based on the Second Strategic EU Energy Review (SEER-2) data for the four markets. In Figure 2, the target capital costs are given without finance charges (overnight capital costs). As an example, for a small reactor-CHP to compete against coal or gas CHP with moderate fuel costs (and low-high carbon costs), its overnight capital cost would need to be lower than approx. 6000 €/kWe. The allowable ranges for total capital cost, operating costs, number of staff per MWe, front and back end fuel cycle costs were derived using the same approach.

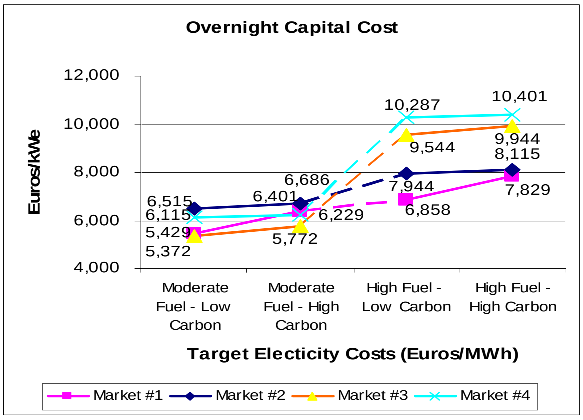


**Figure 2: Target overnight capital by market sector.**

These cost breakdowns can provide reactor developers and analysts with an understanding of the limits for each of the major cost components (capital, operations, and fuel cycle) to successfully compete in future cogeneration markets. The preference would be to develop small reactor-CHP that can successfully compete within the moderate fuel range where there is the greatest market opportunity. However, achieving reactor costs within the competitive high fuel cost range may also be viable for markets that are vulnerable to fossil fuel cost fluctuations and future $CO_2$ costs.

There is no significant difference between the cost sensitivities for small reactor-CHP plants and for larger nuclear power plants. The impact of capital costs and financing rates is largely dominant but somewhat less for small reactor-CHP due to their reduced fraction of total costs. Containing costs from the fuel cycle and operations will be more important for smaller reactors than for LWR.

Another factor to be considered when installing nuclear CHP is that a back-up for downtime (planned and unplanned) is required. The back-up could be another nuclear plant in reserve, a dedicated fossil-fired boiler or a previously used fossil-fired CHP installation which is used as reserve. Since these are site specific issues their economic impacts need to be considered on a case-by-case basis, however they have a non-negligible impact on the economics. In fact, nuclear cogeneration should be installed with priority where there is already fossil cogeneration available. Also, the preferential substitution of large coal-fired CHP (as opposed to gas-fired CHP) with nuclear CHP may be useful, because the gain in reduction of $CO_2$ emissions is almost twice as large compared to replacement of gas-fired CHP. A somewhat higher price for nuclear CHP could be accepted because it would make CCS of the coal-fired system superfluous.

**References**

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[2] D.E. Shropshire, Economic viability of small to medium-sized reactors deployed in future European energy markets, Progress in Nuclear Energy (2011), doi:10.1016/j.pnuene.2010.12.004.

[3] Generation IV (Gen IV) Economic Modeling Working Group, 2007, Cost Estimating Guidelines for Generation IV Nuclear Energy Systems, Rev. 4.2, GIF/EMWG/2007/004, September 26, 2007.

[4] D.E. Shropshire, K.A. Williams, E.A. Hoffman, J.D. Smith, D.J. Hebditch, J.J. Jacobson, J.D. Morton, A.M. Phillips, J.P. Taylor, Advanced Fuel Cycle Economic Analysis of Symbiotic Light-Water Reactor and Fast Burner Reactor Systems, Idaho National Laboratory report INL/EXT-09-15254, January 2009.

# 2 Use and dissemination of foreground

## 2.1 Section A (public)

A comprehensive communication toolkit was created consisting of a logo and a graphical chart, the EUROPAIRS public website (www.europairs.eu) and restricted member area (http://members.europairs.eu), a standard PowerPoint slideshow, a Project presentation, and a poster.

Over the Project duration, the website has had 480 visits, with each visitors viewing on average 7,25 pages (out of 10-12 pages) and 8 minutes average time spent on the site. The bounce rate has been of 33,54%. Therefore, the website has attracted targeted visitors which browsed completely the website.

### An industrial network was built around the HTR technology

- Beyond the industrial companies involved in the EUROPAIRS consortium, EUROPAIRS has raised the industrial awareness on HTR technologies by taking numerous contacts with heat intensive European industries, mostly represented by their European representative associations (pulp & paper, iron & steel, oil & gas, aluminium, coal, synthetic fuels, ceramics, glassmaking, chemicals, fertilisers, industrial gases, lime, cement, cogeneration). European associations are demultiplyers of the communication reach of EUROPAIRS so the number of companies in direct and indirect contact is potentially high.

- An Associated Industry Network was set up, gathering different European heat intensive industries. This network constitutes an important network of industrial contacts which could be interested in HTR technology in the future.

### International relations were strengthened

- A leading meeting with representatives from the Industry Alliance for the US NGNP programme was organised in Paris on the 13th and 14th October 2010. This meeting has enabled to exchange information on both European and US HTR programmes and to prepare a potential transatlantic cooperation. Important links were made and will make possible to dialogue and organise both programmes at best.

- The South African HTR programme, represented in the EUROPAIRS Project by PBMR (which retired from the Project due to the financial crisis) and Northwest University, was closely involved in every activities of EUROPAIRS. Both programmes may further cooperate on the demonstration of high temperature nuclear cogeneration coupled to advanced applications such as hydrogen or synthetic fuel production.

### EUROPAIRS results were disseminated

- The EUROPAIRS results were presented at the final workshop to a diverse audience of 50 persons. Participants came from research and engineering in various fields (energy, coal, nuclear, oil sciences) as well as the nuclear industry at large (vendor, safety organisations). Heat consuming industries were represented (chemical, paper, lime, industrial gases, fertilizers, oil & gas industries) and other industries in the Project networks could not participate in the workshop but asked to be kept informed (glassmaking, ceramics, synthetic fuels, cogeneration, oil and refining). Finally utilities with a strong experience in operating nuclear power plants, in particular in cogeneration mode, were also represented.

- All presentations were made public on the website of the EUROPAIRS project:

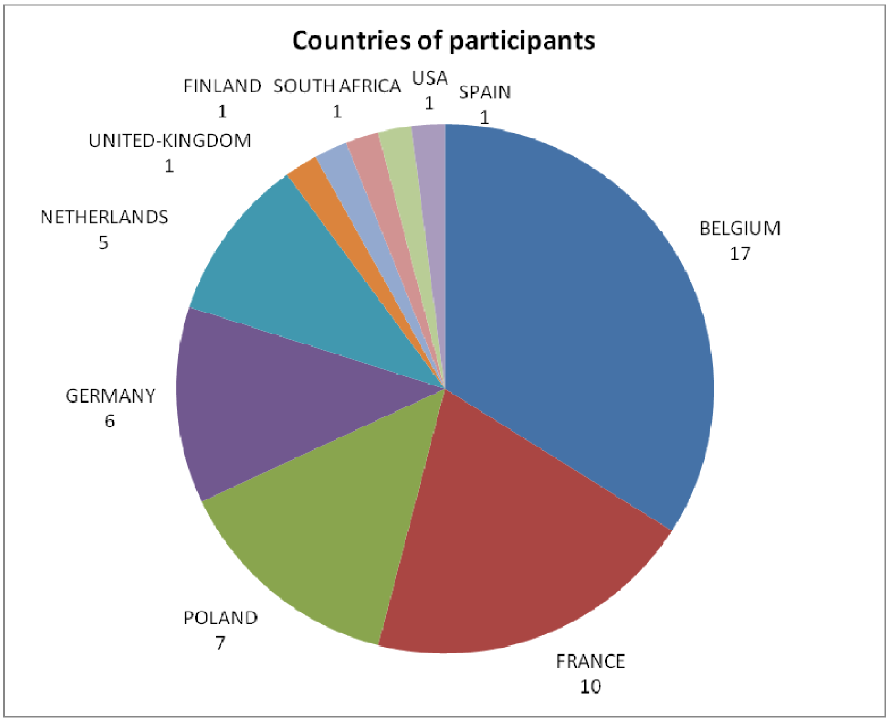


**Figure 6: Countries of participants to the EUROPAIRS Workshop**

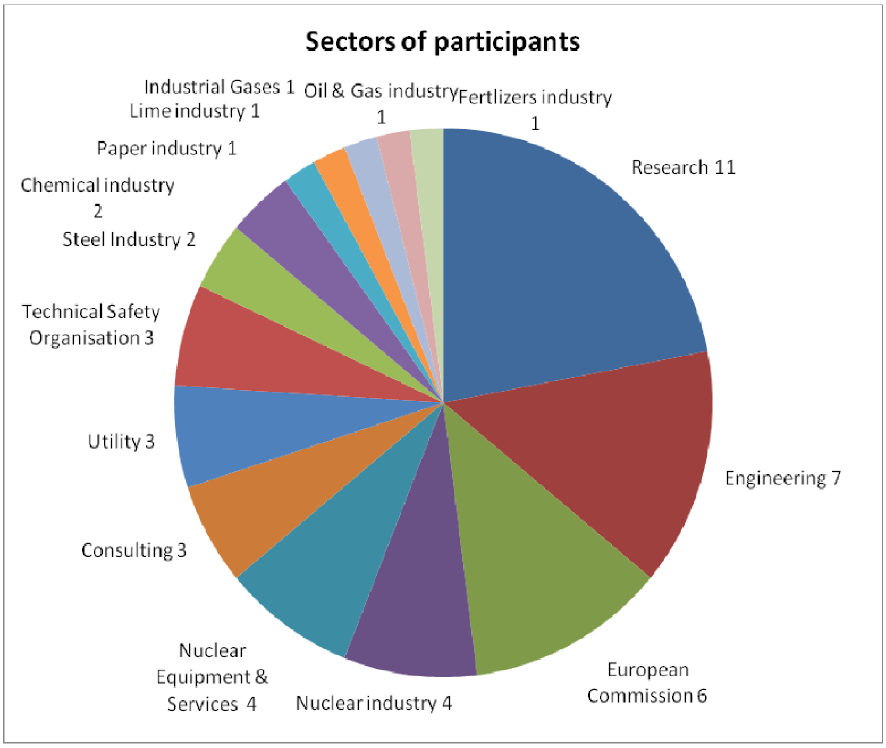


**Figure 7: Sectors of participants to the EUROPAIRS Workshop**

- Some confidential deliverables were further adapted in a public version (e.g. the study on the European industrial heat market) or through journal papers (e.g. in Nuclear Energy Design)