1 Final publishable summary report

1.1 *Executive summary*

Nuclear reactors are a source of large amounts of electric energy, with very small CO_2 and other noxious emissions associated to it. In the quest for a low-emissions economy currently undergoing in the EU, decarbonisation of electricity generation is only one part of the solution.

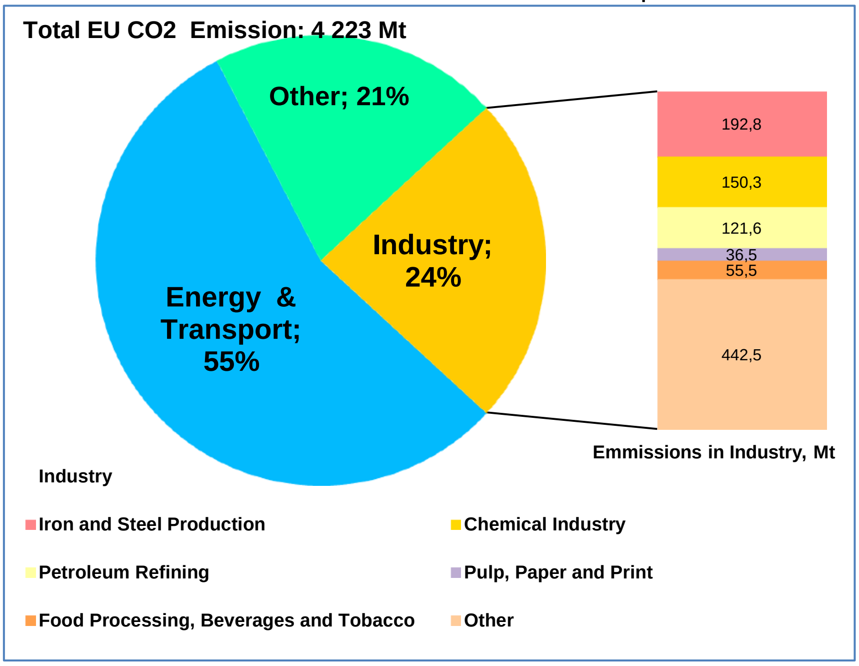

Figure 1 Total EU CO_2 Emission in 2014

Another very important source of emissions is the industry, responsible for about 24% of EU's consumption of fossil fuels and similar proportion of CO_2 emissions. The industry sectors, including those responsible for the production of iron and steel, for food processing, the chemical industry, ceramics and glass wares and machinery producers, they all present intensive energy needs currently provided by fossil fuel combustion.

The average level of CO_2 emission in the different EU industries remains at about 37 Mt. However, in some Member States such as Germany, France, United Kingdom, Italy, Netherlands, Romania or Poland the level is much higher, presenting levels between 50 and 200 CO_2 Mt.[1]. With regard to the climate policies in countries where the industrial plants represent still a strategic importance, their main target represents the reduction of the CO_2 emission. This focus comes as a next step after the cut in the Energy Sector. Henceforth, for any serious attempt to curb the overall emissions, the emission level must also correspond to the industry share.

[1] Data retrieved from the National Inventory Reports for all EU Member States, UNFCCC National Inventory Submissions accessible here

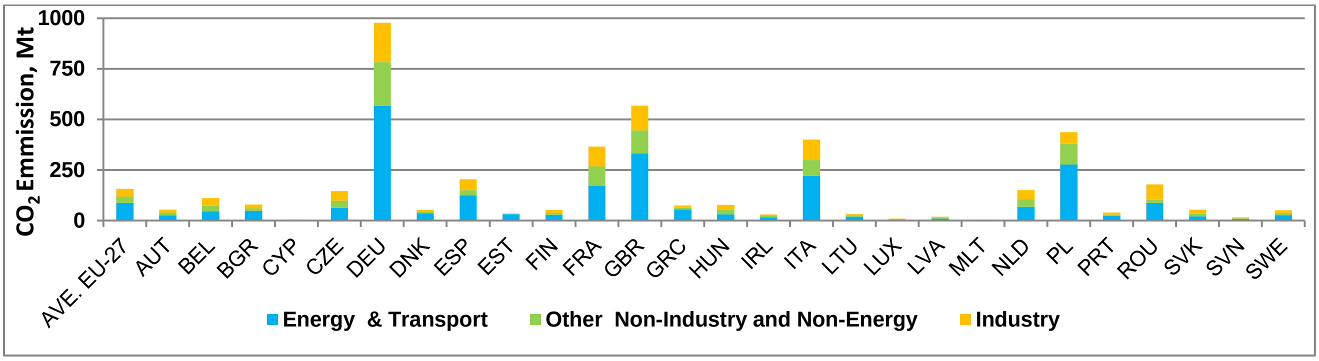

Figure 2 CO_2 Emission in 2014

This goal creates very significant economical and societal challenges. While industry may be forced to reduce emissions through a system of various CO_2-taxes, the most likely result of such a system, as already noticed, is the escape of industry to countries with less stringent environmental requirements.

This effect diminishes tax incomes of EU-countries and raises unemployment seen in many of them to unacceptable levels. Moreover, the relocation of industry to other countries (so-called "carbon leakage") merely changes the geographical location of their origin, but does not reduce emissions.

As a result, emissions from the production and transport of industrial goods purchased by an end customer do not diminish, on the opposite. The only apparent benefit would be the statistical reduction of emissions in a particular country.

Apart from emissions, the absence of alternatives to fossil fuel consumption leads to often unacceptable geopolitical dependence on supply countries (energy security). This phenomenon is particularly seen in Central and Eastern Europe as highlighted by the Ukrainian crisis.

Therefore, it is desirable that nuclear reactors start providing not only electricity, but also other forms of energy (heat, cold) for industry on a much wider basis than today. This mechanism is called cogeneration of heat and power. While globally there are more than 750 reactor years of experience with nuclear cogeneration of heat and power, the range of applications was mostly limited to rather low temperatures such as steam production for the paper and pulp industry, district heating and seawater desalination. Nuclear cogeneration has been shown to be highly efficient: it can raise power plant efficiency from approx. 35% up to 80%, concomitantly reducing the need for cooling, an important aspect for arid regions.

Expansion of nuclear power in this new market would provide substantial environmental, economic and societal benefits, as well as geopolitical ones which go way beyond pure classical economic analysis, e.g. in the form of LCOE.

However, before deployment at a significant scale, the demonstration of nuclear cogeneration has to tackle a number of challenges. In this undertaking the NC2I-R has built upon the previous EUROPAIRS project, which was concluded in 2011.

NC2I-R project was an "executive" project of SNETP/NC2I, in line with SNETP SRIA, and sharing information with GIF and the IAEA.

1.2 Summary description of project context and objectives

WP1 – *Structuration of NC2I*. This Work Package aimed at providing hints on the optimum method for implementing the nuclear cogeneration from organisational and legal points of view. The main goal of WP1 was to address all governance issues in order to prepare the evolution of this initiative. NC2I-R thus aimed to provide all elements to support strategic decisions by the NC2I Task Force, in order to launch the implementation phase of the European nuclear cogeneration initiative. For this purpose, NC2I-R built on a solid base including the network of research partners involved in several ongoing European and national programmes, the industrial network established in the frame of EUROPAIRS, and the official support already enacted by several national and regional authorities.

WP2 – *Infrastructures and competences.* The purpose of WP2 was to draw an inventory of all infrastructures and competences which are crucial for the establishment of new nuclear cogeneration, both at the scale of demonstration and of industrial deployment. This stock taking spanned in particular the EU, but also reached out to selected countries overseas where use of nuclear cogeneration was/is industrial practice or planned for the future. For non-EU countries, the IAEA, OECD/NEA and GIF were solicited to establish the necessary contacts. Past, present and envisaged future projects were screened through literature reviews, a questionnaire was formulated and distributed, and complementary interviews (by phone and face-to-face) were conducted with a variety of involved stakeholders. The explicit intention was to include collections of non-technical information and advice, for instance on the employed business models or on communication with the civil society and political decision makers. The interviews helped this project to discover new aspects which were insufficiently addressed in earlier nuclear cogeneration projects. The feedback compilation and analysis received the highest emphasis in terms of manpower and number of involved project participants and turned out to be excellent support for the ensuing tasks. The information on infrastructure and competences was mapped and analysed such that recommendations for future priority work were deduced. The mapping was structured topically (by subject) and topologically (by geographic situation).

WP3 - *Safety and Licensing.* The main objective of WP3 was to advise and support the establishment of the general technical specifications of a nuclear co-generation demonstrator. For this purpose, WP3 provided input to WP4 regarding the licensing process, safety requirements and R&D needs to support the safety demonstration of a nuclear co-generation system.
As a first task, WP3 partners have gathered and reviewed the experience gained through the licensing of existing and past nuclear facilities with co-generation capabilities.
Then, a tentative roadmap for the licensing of a co-generation system has been written, which aimed at giving a starting point to some European countries foreseen as potential hosts for a future demonstrator. The feedback of the WP3 partners related to past projects (HTR-Module, PBMR, etc.) provided the backbone of this work. The partners have also reviewed the recommendations made in the frame of the high temperature reactor program developed in the US.
To complement these guidelines, the partners drafted the specific safety requirements associated with the co-generation systems selected in WP4. A review of the main R&D supporting the safety demonstration has been made, taking into account the outcomes of the FP7 projects EUROPAIRS and ARCHER.

WP4 - *End-users focus & Deployment scenarios.*
The purpose of WP 4 was to identify and to model demonstration and deployment options for nuclear cogeneration, then evaluate and rank those options according to the usefulness for

both industrial and policy-driven interests and finally to propose an optimised deployment strategy for the most promising options..
EUROPAIRS has provided some cost data on High Temperature Reactors, and preliminary economic analyses. This data was considered as a first input to develop more detailed economics analyses, including factors influencing the economics & financing, and conditions of economic viability for nuclear cogeneration. Additionally, the partners executed sensitivity analyses on the cost of nuclear energy against a number of factors such as gas, oil, coal prices, and carbon taxation, among others. This provided boundary conditions for the economic viability of nuclear cogeneration.
This Work Package built on the experience feedback from cogeneration (collected in WP2) and technical and safety requirements (collected in WP3), to draw general specifications for a demonstrator program. Generic requirements for sitting were defined, and a mapping of the most promising chemical sites in Europe was performed. The compilation of all these data supported the elaboration of a roadmap for a first project.
A SWOT analysis of this technology, after a thorough review by stakeholders and potential customers, was conducted to appreciate the cost/benefit of nuclear cogeneration with respect to economic and policy-related objectives, and criteria was developed to establish priorities.
The network of companies and associations already involved in NC2I-R strengthened with potential users (chemical companies, oil refiners, fertiliser producers…) in a so called "End-User
Group (EUG)" was built, to support the development of nuclear cogeneration beyond the project.

WP5 - *Communication & Interactions.*
The purpose of WP5 was to group all activities related to dissemination: interactions with European and non-European audiences, which included ongoing projects on nuclear cogeneration, as well as industrial research actors from nuclear and conventional industry, safety organisations, international institutions, and the general public.
WP5 established a 'community communication' in order to contribute to the structuring of the nuclear cogeneration community in Europe; 'international communication' in order to allow for a structured dialogue between NC2I and its counterparts such as the US NGNP and other programmes, and international institutions (IAEA, OECD/NEA, GIF); and finally 'public communication' in order to promote the work and perspectives of NC2I to a wider audience.
A detailed dissemination plan was established at the beginning of the NC2I-R project, in line with the general communication strategy of the NC2I. NC2I-R is expected to generate unique results to prepare the demonstration of nuclear cogeneration, with market and economic research, licensing preparation, and capability analyses. In order to maximise the impact of the project, most findings of Work Packages 2 to 4 were made public and widely disseminated, at least in a summarised form.
It is recalled that the NC2I-R project represents a coordination action and not a research project; scientific communication and education/training actions were thus not covered here, but in the frame of the ARCHER project, closed in January 2015.The project latter reminded had contributed to the scientific basis for the development of nuclear cogeneration in Europe.

1.3 A description of the main S&T results/foregrounds

1.3.1 Main S&T results/foregrounds of WP1

D1.11 identified and analysed a number of governance schemes for technological platforms or networks, by sector, operating at European level.

D1.12 report has taken into account the work performed in the European projects on deployment conventional cogeneration and support mechanisms. It presented a short summary of the current status of nuclear cogeneration in Europe and in Poland. Until now there was no specific organisation in Europe which decided to implement nuclear cogeneration. The lack of strong and continue interest in nuclear cogeneration projects on national government level resulted in the weak support from the European and national structures. As long as there is no real commitment from the government, there will be no interest from potential industrial users.
Basing on some experiences of the promotion of "conventional" cogeneration, it was possible to accelerate the deployment of nuclear cogeneration in Europe. A long term solution for competitive energy market was the adoption of common rules for cogeneration focused on the results – availability and total emission, not on sources.
As a result, the stimulation of new initiatives on nuclear cogeneration materialised into a Joint cooperation entitled the GEMINI Initiative. This initiative had accelerated the deployment of HTGR technology for process heat cogeneration for the industry in the USA as well as in Europe. HTGR reactor technologies were included in SMR technologies, which were to be applied for the cogeneration, as well as other technologies for lower temperatures. It had opened the perspective of cooperation between NC2I, NGNP and the UK.
D.1.21 report has analysed some of the legal forms available among legislations of chosen EU Member States that potentially might be exploited by NC2I for the purpose of obtaining a legal personality. The suggested legal forms for NC2I were based on the assumption that project had decided for one of the presented paths and had also obtained its legal capacity in one of the EU Member States. This legal capacity was obtained in compliance with the adequate national laws; NC2I would become a pan-European organisation founded on EU law or establishes an international association.
D1.22 report has analysed some of the legal forms available among legislations of chosen EU Member States that potentially might be used for the purposes of the Demonstrator programme. The suggestions on possible legal forms for the Demonstrator programme focused on limited liability companies, associations and foundations, which existed in different forms in every EU Member States and were formulated based on their national laws.
In conclusion, both reports presented above recommended that the final decision regarding the legal forms of the NC2I and of the Demonstrator has to be drawn after careful consideration.
D1.23 is a review of financial resources relevant to technology development and prototype building within the context of the NC2I.

1.3.2 Main S&T results/foregrounds of WP2

In **Task 2.1** operational feedback was collected from previous, existing and planned nuclear cogeneration projects in a number of countries with the aim of identifying a most complete set of boundary conditions which led to successful projects in the past. Stakeholders consulted include in particular utilities and end-users. The scope encompassed technical and non-technical information (organisational structure, financial aspects, public relations, etc.) and specifically experience on licensing gained from these projects. The information was collected by a questionnaire and additional face-to-face interviews.

The questionnaire was formulated to cover 9 categories of in total 56 questions for 38 identified projects: Motivation and initiative, Role of key players, Organisational structure, Technical aspects, Safety and licensing, Financial aspects, Timing, Public relations, General experience feedback.
From the 38 identified projects worldwide, 23 from 10 countries have provided feedback on a variety of applications such as district heating, seawater desalination, paper and pulp industry, petrochemical industry, coal gasification or salt processing. This is a surprisingly positive response considering that several of these projects date back to the 1980s and many of them were performed outside Europe.
A report was drafted to summarise and analyse the received information and to deduce from there which boundary conditions are favourable for the construction of new nuclear cogeneration projects. As in 2014 some further feedback from China and Japan was received, a second version of this deliverable was issued.
The most common applications were:

- district heating (HU, CH, CZ, SK, S, ROC, FIN, RU)
- seawater desalination (KZ, JA)
- process steam
- paper and pulp (N, CH)
- salt refining (D)
- reforming of gas and coal (D)
- (petro-)chemical) (D, CAN)
- nuclear processes (UK, CAN)

The IAEA is currently preparing 3 extensive Tecdocs which summarise most possible applications. It must be noted that several participants in NC2I-R contribute to these IAEA Tecdocs either as editor, author or reviewer.

The table below lists the positive and negative experience from this exercise.

+	-
Response to questionnaire better than expected Few confidential answers Risk acceptable for stakeholders No licensing issues (!) No safety issue (contamination) Many projects considered positive and successful Sometimes unexpected side benefits (noise, traffic…) Most projects started when economy was strong and when oil was expensive	Collection of information has taken much longer than anticipated (date for interviews) Interviews beyond utilities and end-users takes a strong effort So far rather weak information on financial aspects and licensing (forgotten, not considered important, wrong contact point, confidential, outdated…) Current economic context less favourable for large long-term energy infrastructure investments (?) Limited value of answers from paper studies?

The following bullet list summarises preliminary lessons learned from the other nuclear cogeneration projects:

- There is no general recipe, for success, but similarities!
- Past cogen applications did not experience licensing issues; still applicable?

- Support from government (local, federal) is essential
- Decision making process strongly depends on local circumstances (commercial, ex-socialist, grass-root democrats, local environmentalists)
- Psychology is important: e.g. perceived threat to consumer autarchy
- CAPEX/OPEX of the cogeneration installation (pipelines + heat exchanger station) is negligible compared to CAPEX/OPEX of NPP
- Economics = f(temperature, consumer density, distance, load curve…)
- Warmer winters, improved insulation, alternative "green" heating methods (geothermal, heat pumps, woodchips etc.) negatively impact seasonal load curve and economy of district heating;
- District cooling would be profitable only with very high consumer density
- Back-up is a must
- Recommended risk minimisation strategy: multiple investors - multiple customers;
- Typically PPP with up to 80% public (Beznau), but fully commercial projects (Stade) and fully state-owned projects (ex-socialist states) also exist;
- Permanent PR effort is beneficial to maintain local support during service life: "open days" for residents; school/university visits;
- Experience with existing projects is technically and economically so positive that two NPP (Paks, Bohunice) envisage extension of district heating system;
- Nuclear phase-out has stopped expansion plans in CH against local support;
- Switzerland will ultimately replace Nuclear Cogeneration with a mix of geothermal, wood chips and fossil (very local solution);
- High technical and consumer satisfaction (cost, reliability, simplicity…);
- Financial success requires high consumer density;

Task 2.2 has started with the collection of topical reports and material in conference proceedings (especially the HTR conference series and the HTR track of ICAPP where the WP leader is actively involved) and from publications. Papers from European industry and R&D organisations are used as an indicator for the identification of R&D and industrial infrastructure and competences. More detailed information will be collected by contacting the authors of these papers.

Specifically, AREVA has delivered 8 topical reports on the following past experience from Germany:

- Tribology and Corrosion
- ADAM/EVA energy storage/heat transfer concept
- PNP project
- HTR cost analysis
- IHX and isolation valves
- Turbomachines
- KVK Test loop
- Tritium

Obviously, also the partners of the two most recent FP6/7 technology projects (RAPHAEL and ARCHER) were contacted. The networks of SNETP and AK VHTR in Germany were used, in particular to capture industrial infrastructures and competences.
The HTR 2014 conference (October 2014) was used to meet European experts involved in AVR and THTR who are experienced in technical details for design and construction, can

help with licensing difficulties, the preparation of a commissioning plan of a demonstrator or the definition of demonstration plan.

Finally, in **Task 2.3** an analysis was performed to identify the gaps in industrial infrastructures and competences for R&D which needs to be bridged prior to licensing and construction of an HTR demonstrator. Emphasis was given to existing industrial infrastructure and R&D competences in Europe.
Based on the valuable results of the German HTR development program up to the late 1980s, significant progress has been made by a several European FP5-7 R&D projects which obtained further leverage through the collaborative participation of European organisations in international projects (NGNP, PBMR, HTR-10…) and in GIF. The most outstanding examples are in the areas of fuel production and qualification, the qualification and coding of high temperature structural materials and new graphite grades (incl. through irradiation testing), component development (e.g. turbomachines, heat exchangers), helium technologies and licensing-relevant modelling (e.g. reactor physics, thermo-fluid dynamics, mechanics, tritium transport, source term calculations, system code integration). In addition, significant improvement was achieved in understanding the market and end-user needs so as to design a power plant accordingly. The European System Integration studies in ARCHER and in NC2I-R, the ANTARES and SC-HTGR projects performed by AREVA, and several other industrial designs worldwide reflect this development.
For the preparation of a demonstration project, further work is required in the areas of system design based as much as possible on proven technologies. As part of the GEMINI initiative between the European NC2I Task Force and the US NGNP Industry Alliance, maximum design convergence for a demonstrator is intended allowing for differences where licensing requirements or market needs impose them. For successful demonstration, a functioning and stable licensing framework is required at an early stage as part of the infrastructure. This will guide the conceptual design (safety option report) and possibly required targeted R&D. This licensing framework must be capable of taking into account the specific safety approach of modular HTGR based on inherent safety features of the system and addressing the coupling with industrial processes.
The state of R&D infrastructure is reflecting the available budget and has shown its flexibility. Due to the time gap between the last running HTR reactor and the HTR "revival" in 1999, some facilities had been shut down, mothballed or refurbished to support other projects and developments. A number of them could be recovered and have produced significant results. Examples are the facilities for fuel production (CEA), quality assurance (AREVA), irradiation (HFR), post-irradiation (NRG) and safety testing (JRC) or the large-scale facilities to simulate air and water ingress accidents (FZJ). The situation is similar for graphite qualification.
What should not be underestimated is the time and effort required for qualification. Assuming that the currently ongoing international collaboration towards fuel and materials (metals, graphite, composites) qualification are confirmed successful, there is still work ahead in view of licensing related to computer codes and to large-scale test facilities for the qualification of components. These include steam generators, heat exchangers, circulators with magnetic bearings, isolation valves, control rod mechanisms, instrumentation and others. Specific qualification test rigs will be needed, like the Helium Test Facility built in South Africa for the PBMR program. Comparable large scale Helium loops are not currently available.
In parallel to the design efforts, the supply chain for components must be analysed and, where necessary, rebuilt. An example is the steam generator for which design tools are

available in Europe but where there is no supplier worldwide with the required manufacturing capability.

1.3.3 Main S&T results/foregrounds of WP3

Review of the licensing feedback gained on past projects and existing nuclear cogeneration installations

WP3 has provided a tentative analysis of the feedback of nuclear cogeneration, based essentially on European facilities and project plants.

The review has showed that that no cogeneration specific safety issue was raised during the licensing and operation of these installations which were mainly dedicated to low temperature water/steam production for district heating and industrial use.

According to the operators contacted by WP3, no specific safety case related to cogeneration has been documented in the safety reports. Nevertheless, the implementation of cogeneration usually goes along with the study of external hazards associated with tertiary installations (turbines, stream generators, etc.) and nearby back-up boilers. The impact of the heat demand variations on the nuclear installation has also to be taken into account.

Finally, operators of the reviewed installations generally demonstrate that they have precluded the risk of radioactive contamination of the heat carrier fluid delivered to customers.

Moreover, the strategy applied by the designers is to eliminate any potential impact on the neighbourhood in any situation.

To be able to apply the above mentioned approach, it is recommended to design rather indirect coupling systems than using directly the primary heat in an industrial process. As an example, the coupling scheme envisaged in the past in the PNP-3000 project, where flammable gases were produced inside the reactor building, sounds today a challenging design. Such configuration would not be consistent with the present trend in licensing. Indeed, for direct coupling design, the potential economic advantages would certainly be jeopardised by the cost of the engineered protections and subsequent operational constraints (constraints on maintenance, in service inspection, radioprotection, etc.).

In past HTR based cogeneration projects, indirect coupling schemes using an intermediate helium/helium heat exchanger were also envisaged. Specific risks associated with this kind of application were addressed in the task 3.2.

Considering the heat supply through process steam, as studied with the HTR-Module concept, the pre-licensing procedure of the late 80s provides a significant experience in terms of risk identification. In practice, the production of process steam has not required a specific licensing, at that time. In other words, taking into account the cogeneration capability of the HTR-Module would have been possible using standard safety approach.

Based on these considerations, It appears that the licensing of new prototype of HTR with cogeneration capability would essentially require to the detailed study of the associated safety cases and definition of up to date assessment criteria.

Orientations on a licensing procedure applicable to a nuclear co-generation system

The study performed in WP3 provides some licensing guidelines based on the partners' feedback to the licensing of past projects (especially Hungary, Lithuania, Germany and Czech Republic). It should be noted that, initially, the recommendations expressed at a European level by WENRA were intended to be integrated in the WP3 work, but their review has revealed no potential impact on the licensing of a near term nuclear cogeneration project.

The screening of past and recent co-generation applications with a nuclear heat source reveals no specific licensing issues beyond the standard licensing requirements of the NPP. Indeed, for some standard requirements a higher effort will be needed to address specific co-generation related aspects (e.g. evaluation of external hazards by nearby industrial facilities, fast isolation options for transfer lines out of the NPP site). Regarding other standard requirements the specific safety features of modular HTR will lead to a significant improvement of the nuclear safety (e.g. reduced exclusion zone possible because of limited radioactive releases even during beyond design basis events) and of the economic conditions (maximum achievable temperature level).

While limits for emissions or releases of radionuclides from nuclear facilities are in general documented in the respective national regulations, for co-generation applications the aspect of a product free (related to international or national limits) from artificial radioactive contamination will be even more in the focus of the public. This specific care should be met by promoting the radionuclide barriers already applied in modern NPP for normal operation and design based accidents and the additional advantages given by the HTR technology.

The tritium contamination issue related to gaseous primary coolant circuit has been discussed within WP3. Tritium, as well as hydrogen, is able to diffuse through the metallic walls of heat exchanger tubes or sheets and therefore the contamination of the secondary coolant circuit with tritium has to be considered in the radiological assessment. The partners' review of numerous studies and design features dedicated to tritium management in HTRs shows that He purification systems proved good efficiency and that additional contamination of the secondary circuit through leaks could be avoided by maintaining the secondary circuit overpressure. Moreover, an additional barrier against the contamination of product stem or product gas by tritium could be provided by a tertiary circuit. Such an additional circuit, as already proposed in the project EUROPAIRS, would also be supported by the WP3 in order to minimise the effort for the licensing process of the prototype HTR, although recent investigations in the ARCHER project indicate that reasonable limits of tritium contamination in process steam might also be met without a tertiary circuit.

To effectively support the licensing of HTR based co-generation application and in particular a prototype facility, the partners recommend that the following activities should be conducted in addition and in advance (if possible) to the standard licensing procedure:

- in a pre-application phase, early discussion of the safety features specific for a modular HTR (e.g. passive decay heat removal, "vented containment") with the regulator of the country hosting the Demonstrator with the aim to achieve clarity about their consideration in the licensing process;
- a demonstration that co-generation or process heat application issues are covered by the licensing procedure;
- a gap analysis for further R&D needs under consideration of the results achieved in the gap and SWOT analyses in the ARCHER project.

The licensing of the HTR shall follow the general licensing procedure covering the main aspects as:

- Definition of the nuclear facility, its activities and the respective boundary conditions (e.g. dose and discharge limits, action levels)
- Siting and site evaluation
- Safety and environmental impact assessment
- Safety demonstration of the proposed technology for all operation stages and accidental conditions
- Public inquiry
- Construction
- Commissioning
- Operation
- Decommissioning

Because of the prototype issues and the strong interface to the local public, the partners of the WP3 estimate that a road map should include an extended pre-licensing phase with a strong public involvement to promote a positive acceptance level in the local public. An extended environmental impact study should also be included.

The licensing process of a HTR powered co-generation installation should be supported by the typical actions for a NPP addressed in a PSAR. For the co-generation systems and components and in particular for the interface to the local public infrastructure or the conventional end-user facility the licensing issues are covered by the nuclear standard regulations. But because of the larger and more visible interface outside the nuclear site, it seems essential that a simple and understandable overall description of the facility should be available to the public in an early stage of the project.

General safety requirements and R&D needs for the specifications of a demonstrator program

Based on the operational feedback of HTR and the recent studies performed within ARCHER and past European projects, the partners of the WP3 have identified a few technical domains which shall require significant R&D effort. In addition, the partners of the WP3 have chosen to extend their review to the qualification requirements envisaged for a prototype HTR. This review and the conclusions were drafted on the assumption that a future demonstrator would only require minor adjustments of its technical specifications to be used as a nuclear cogeneration plant. In this frame, the study outlines several remaining questions such as:

- the evaluation of the fission product transfer coefficients in the fuel coatings and graphite matrix,
- the means to evaluate the fuel temperature in standard and accidental operation,
- the achievement of a suitable radiative emissivity of the core barrel,
- In service inspection of the primary structures including graphite structures, fuel elements (blocks) and steam generator tubes,
- the evaluation of dust behaviour, distribution in the primary pipes and components (potential for accumulation, plate-out, etc.), resuspension and dust bound fission products phenomena and, in general, the development of a complete chain of computer codes for the modelling of source term in case of depressurisation scenarios.

In relation with the main safety requirement associated with the HTR concept, i.e. the passive decay heat removal capability, qualification of the cavity cooling system is also an essential step in support of the safety demonstration. It would also allow for further improvement of the safety margins provided by the passive decay heat removal feature of the HTR.

Licensing is backed mainly by the evaluation of normal and abnormal transients relying on tests and computer codes. A rather complete set of codes is already available, but shall require R&D efforts to be validated. Finally, development of specific design rules would also require R&D efforts (extension of existing ASME or RCC-M applicability).

Regarding the licensing of a demonstrator, it is to be noted that remaining uncertainties, like those affecting the assessment of the accidental radioactive source term, could be outweighed by a conservative approach in the studies of the safety cases and by provisional mitigation measures (confinement, filters, monitoring systems, etc.).

Considering the potential for further developments of the HTR concept (VHTR), the R&D for support of the safety demonstration are assumed to be needed essentially in the field of development of high temperature resistant fuel and material together with an effort to enhance of the fuel quality control and reduce uncertainties on safety parameters (fuel maximum temperature and burn-up).

As a conclusion, regarding the licensing of a co-generation installation, a few specific requirements can be outlined which need some more attention for an HTR co-generation application:

Minimum Distances

The HTR and the conventional end-user facility shall not influence each other in particular in case of severe accidents as explosions or release of corrosive materials. The safety related risk induced by external hazards as defined in the SAR, shall be independent from the cogeneration components and the end-user facility. While this is usually covered for a standard NPP because of the requirement “as much as possible away from any external hazards”, for cogeneration applications, a limited distance to the end-user facility is

mandatory for economic reasons (investment for the transfer line). Therefore any external hazard for the reactor by the end-user facility has to be evaluated in particular.
Regarding the potential impact of the reactor on the end-user facility, it should be noted that because of the passive safety characteristics of HTR's, the low power density and the consequential elimination of scenarios comparable to LWR core melting,, the derived HTR exclusion zone would be smaller than for other NPP types, allowing a closer distance to the end-user facility or other public infrastructure (schools, stadium, etc.). Demonstrated by investigations on the size of the exclusion zone, this area may be limited to the NPP/industrial site itself.

Radionuclide release limits
Radionuclides may be transported by the transfer medium in constant concentrations over a longer distance than usually considered within standard release scenarios. Therefore the radionuclide release scenarios have to consider this release pathway option adequately (at HTR conditions). This will usually result in technical measures to quickly isolate the transfer line in case of accidental contamination.

Thermal hydraulic feedback/transients
For HTR process heat applications, heat production would represent the major part of the thermal power delivered by the nuclear plant. Varying operation conditions at the transfer system or at the end-user side will generate feedback/transients to the HTR. These feedbacks and transients have to be considered in the safety analysis report of the HTR and covered by corresponding safety systems (e.g. compressor chambers).

1.3.4 Main S&T results/foregrounds of WP4

A suitable industrial sector for the nuclear co-generation is the process industry which requires constant heat and electricity to its processes. The chemical industry presents the best opportunities for the implementation of high temperature nuclear cogeneration.

The sector is suitable as:
- It already uses cogeneration with long operating experience records
- The required temperatures correspond to the output of an HTR
- The power capacity of several parks is large enough to be compatible with the size of an HTR alone, or used in plants of several modules
- There is a strong willingness to decrease the CO_2 emissions.
- Energy cost is generally a large part of the costs. Long term predictability is therefore a strategic objective.

The project has evaluated the potential of nuclear cogeneration for different industries, based on current trends and technology evolutions:
- In the steel industry many processes require high temperature steam above 700°C. The development of innovative processes in the steel industry has been delayed due to the decreased sales and production of the steel industry in Europe.
- The hydrogen production mainly uses the Steam Methane Reforming (SMR) process, which is a possible application for high temperature nuclear cogeneration. Research is ongoing and budgets will be allocated to projects developing the innovative processes: HT electrolysis and cater splitting (thermochemical cycles).
- The CTL (Coal To Liquid) and the CCS (Carbon Capture and Storage) technologies were identified as potential applications for high-temperature nuclear cogeneration. CTL requires temperatures between 450°C and 800°C which are compatible with

HTR's output temperature. CCS technologies could be applied to highly-emissive industries such as the chemical, steel, cement and refining industries.

The economic assessment evaluated the competitiveness of an HTR when producing electricity (competition with hydro, coal or large nuclear power plants) or heat (competition with gas, coal and oil), for different scenario of fuel and CO_2. The most critical aspects that affect the feasibility are the availability of the plant, the interest rate, investment costs, and heat prices.
Design adaptation and licensing costs may challenge the viability of a HTR cogeneration project. A HTR project alone would not be profitable if it needs to support large costs for design and licensing. However, cost related to site adaptation and a significant part of the licensing cost could be covered. A licensing process based on a generic design assessment should strongly favour such project and therefore a standardisation of regulation and licensing procedures should be one of the main priorities when developing the HTR concept further.

At the moment the coal price is quite low, as well as emissions allowance prices. This means that the alternative ways to produce heat with conventional fuels is still quite cheap which weakens the profitability of nuclear cogeneration. Therefore changes in the prevailing market conditions that increase the economics are needed. Those changes would be an increase in fossil fuel prices and/or increase in CO2 prices and increase in electricity prices. Other aspects (e.g. job creation, energy independence…) were not evaluated in this assessment but would also bring value.

The best near-term opportunities can be found from HTR powering a chemical park. Integration of nuclear actors downstream in the value chain as Energy Manager would mean that the counter parts for a chemical park would be less numerous and it could concentrate on its core business.
Following this economic assessment, the following task was to localise and characterise chemical and petrochemical sites within Europe which can be a potential market for deployment of the HTR's.

The main processes compatible with HTR capabilities are:
- refinery distillation steam,
- refinery distillation superheated steam,
- petrochemicals - reaction enthalpy,
- steam as utility for industrial complex,
- paper steam (drying)

Mapping of industrial sites was conducted in a manner allowing describing the heat market and distinguishing industrial sites located in Europe. Depending on availability of information sites were described in terms of:
- Rated thermal power
- Electric power production and usage
- Fresh steam parameters (temperature, pressure, mass flow)
- Process steam parameters (temperature, pressure, mass flow)
- Current power production unit characteristics (size, age, fuel)
- And others (e.g. environmental factors, regulatory framework etc.)

In total 132 sites were identified within Europe, 57 provided data related to their needs.

A significant share of the sample sites uses less than 100 MWth – 20 sites. About the same proportion needed between 100MWth and 250 MWth. The last significant category was about 500 MWth, in this category include 9 sites. The electrical power demand is distributed somewhat in more uniform manner. The smallest demand – up to 50 MWe was reported by 20 sites. Each of next categories, respectively 51-100 MWe, 101-200 MWe and 201-400 MWe, reported between 4 and 6 sites.

Thanks to the results of the economic studies and site mapping, different end-user configurations have been tested in order to define key parameters for a demonstrator in Europe.

For chemical complex with a thermal need lower than 200 MWth, profitability is challenged under the current market conditions. Therefore, additional revenues shall be considered though additional load (e.g. supply district heating needs in the vicinity of the chemical complex) or valuation of parameters not considered in the study (e.g. energy independence...).

Coal-To-Liquid process, based on the conditions of Secunda West plant (South Africa) and potential improvement of the current processes, is hardly competitive with the current market conditions. Substitution of coal generated process steam and electricity offers the best opportunity for nuclear cogeneration, when compared to all other coupling configurations. However, the challenge remains its high cost and the impact of such on the profitability of the conventional CTL route.
Advanced process operating at higher temperatures, modelled in the SYNKOPE project showed that nuclear cogeneration plants represent a solution for continued use of coal and lignite even if stricter EU CO2 emission targets are imposed on the energy sector.
Grid stabilisation aspects by balancing the heat and electricity production have been evaluated. The valuation of energy shifted during intraday variations is quite marginal and therefore unlikely to compensate capital costs of a dedicated plant. Energy storage in existing processes (e.g. storage under the form of hot water in district heating systems, variation of the production volume...) and other financial arrangement (e.g. contract with the Transmission System Operator for modulation or shadowing or reserves) is to be investigated on a case-by-case basis.

A roadmap for the deployment of a first HTR cogeneration roadmap was constructed, including the following key elements:

- The key requirement towards commercial application of a cogeneration HTR is the deployment of a demonstrator.
- The main challenge towards an HTR cogeneration demonstrator is to bring together the different stakeholders, and their different relations that are needed to take the technology forward. In order to demonstrate HTR cogeneration the ‘chicken and egg’ issue of proving the feasibility of the HTR technology, of developing a new business model for the (nuclear) stakeholders involved, and of getting the end-user interested by proving the HTR cogeneration reliability and affordability.
- The key decision points are selecting the demonstrator application and location and fixing the demonstrator requirements based upon that.
- The main technological challenges are the design and manufacturing of the reactor pressure vessel and the industrial fabrication and qualification of the fuel.
- The US - European initiative Gemini will facilitate and target the development of an HTR cogeneration demonstrator.

An objective of the project was to maintain a communication between industrial companies and associations which have demonstrated interested in nuclear cogeneration, since the constitution of the EUROPAIRS Industry Advisory Group. Introduction to the concept of Business Group, description of the base for formation of the Business Group, communication tools, selected communication outcomes were developed and used for communication with end-users. Main recommendations for further development of the Business Group

- To further enlarge the Business Group, NC2I partners will be invited to contact directly their own professional network and set up face-to-face meetings
- When NC2I is not yet recognised among potential BG members, well-known NC2I partners especially from industry (vendors, utilities) should be visible.
- The Business Group activation should take place when the conditions for initiating a successful demonstration programme are met begin (government commitment, reference design selection, and visible long-term strategy).
- During the discussions, key figures were missing such as the cost of electricity and steam as well as financing schemes. The WP4 (deliverable D4.11) and WP1 (deliverable 1.12) now provide such information. It should be incorporated into further communication materials.
- It is suggested to invite professional or sectoral associations to take part in the Business Group.

1.4 The potential impact and the main dissemination activities and exploitation of results

The NC2I-R project has allowed to:

- Improve knowledge about nuclear cogeneration, its strengths and weaknesses, based on experience gathered in Europe and elsewhere.
- Provide knowledge about safety of nuclear cogeneration plant, focused on potential licensing issues.
- Create clear path towards constructing a specialised cogeneration plant.
- Provide links between nuclear community and industrial end-users of heat and electricity. These links will be beneficial for launching the demonstrator programme.

The project also contributed to clarify the road-map, requirements and steps toward the licensing of a HTR powered cogeneration system. It has also drafted a list of R&D items to be dealt with in priority to support the safety demonstration and to ensure project acceptance by safety Authorities and the public. The reviews performed within WP3 have contributed to bring elements to gain more insight into the licensing risk associated with HTR systems. These reports might be used by the designers to build up a preliminary version of the safety analysis report of the prototype (or “safety option file”).

In addition, the project identified the Key Success Factors (internal, related to the demonstrator project, or external related to the energy market, competing technologies, political environment, public support etc.) which condition the economic viability of nuclear cogeneration.

The project also identified large potential customer sites for nuclear cogeneration plants within Europe which would benefit from the deployment of HTRs, and maintained or created contacts with them.

Moreover, the project has shared its insights with a wider community on several occasions:

- SNETP Nuclear Days and SNETP meetings
- Meetings with potential customer companies
- HTR 2014 conference
- ICAPP 2015 conference
- SMR Summit 2015 conference
- ARCHER Eurocourse
- IAEA SMR seminar
- GIF Meetings (VHTR System Steering Committee, GIF Experts Group)
- GIF-IAEA/INPRO meetings
- GIF – OECD/NEA meetings
- NC2I-R final workshop

Last but not least, the project has enabled a new collaboration between Europe and the USA with the so-called GEMINI initiative aiming at common demonstration of nuclear cogeneration.

Like other nuclear installations, nuclear cogeneration plants do not have a short-term profitability goal but, instead, must be considered as strategic long-term investments in the future of Europe's energy infrastructure. NC2I-R has allowed to more precisely formulate the economic value of nuclear cogeneration in terms of Levelised Cost of Energy. However, it is obvious that this technology additionally creates significant positive externalities (emission reduction, energy security, enhanced nuclear safety, re-industrialization, tax income, jobs etc.) which are considerable, yet difficult to quantify in classical economic terms.

Regarding European energy policy, nuclear cogeneration can address, in a timely manner, simultaneously several of the recently published ten SET Plan Integrated Roadmap Actions for the Energy Union (COM(2015) 6317 Final). These include:

- **(4) Increase the resilience, security and smartness of the energy system:** Nuclear cogeneration decreases the need to import fossil fuel and can help accommodate variable renewable electricity generation.
- **(6) Continue efforts to make EU industry less energy-intensive and more competitive:**
  Nuclear cogeneration reduces the carbon footprint for the production and transport of many everyday products in industrialized countries.
- **(9) Step up research and innovation activities on the application of carbon capture and storage (CCS) and the commercial viability of carbon capture and use (CCU):**
  CCS and CCU can only work credibly when their high energy requirements are met by a low-carbon energy source such as nuclear. In addition, most CCU techniques require a large source of hydrogen which is ideally produced with HTRs in nuclear cogeneration configuration.
- **(10) Maintaining a high level of safety of nuclear reactors and associated fuel cycles during operation and decommissioning, while improving their efficiency:**

  Nuclear cogeneration very significantly enhances efficiency. The use of inherently safe HTR technology should be considered a serious opportunity to enhance nuclear safety in the European nuclear reactor fleet.

The NC2I-R project consortium expects that the sum of this positive potential impact of nuclear cogeneration will be recognized at the level of the EU Commission, Member States and industry as a solid low-carbon contribution to building the European Energy Union.

Website address: www.nc2i.eu

Project partners:

- National Centre for Nuclear Research (NCBJ), Poland
- Joint Research Centre (JRC), European Commission
- Nuclear Research and Consultancy Group (NRG), The Netherlands
- Technische Universitaet Dresden (TUD), Germany
- Areva Gmbh, Germany
- Institut de Radioprotection et de Surete Nucleaire (IRSN), France
- E.ON Kernkraft Gmbh, Germany
- Fortum Power and Heat Oy, Finland
- PROCHEM S.A., Poland
- LGI Consulting, France
- AGH University of Science and Technology, Poland
- Lietuvos Energetikos Institutas (LEI), Lithuania
- Noordwes-Universiteit (NWU), South Africa
- VUJE AS, Slovakia
- Budapesti Muszaki es Gazdasagtudomanyi Egyetem (BME), Hungary
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