NC2I-R

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Summary

Construction of a roadmap for the deployment of a system is a tool which helps obtaining an overview on the timing and dependence of the various activities required to establish the end goal, i.e. the deployment of the system. Within the EU FP7 Europairs project, a first HTR cogeneration roadmap was constructed. The aim of the current effort is to update this roadmap with the most recent information and validate the roadmap with industrial and international input.

The resulting NC2I-R roadmap will subsequently serve the NC2I platform, SNE-TP, the European Commission, and the European and international HTR community at large to structure follow-up activities.

In order to construct this NC2I-R roadmap, input from the NC2I-R activities on sites mapping, deployment scenarios and demonstrator requirements is used and their main conclusions are summarized in this report.

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NC2I-R

Roadmapping towards
Demonstrator

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The next chapter will explain the different types of roadmap to be constructed and presented in this report and how they interact and depend on each other. Chapter 3 describes the input used to construct the NC2I-R roadmaps. After that, the international developments with respect to HTR are discussed in chapter 4. Chapter 5 sketches the cogeneration market based on NC2I-R input, chapter 6 the HTR demonstrator specifications based on NC2I-R input, and chapter 7 the technology gaps based on input from the EU FP7 ARCHER project. Finally, in chapter 8 the NC2I-R HTR technology, the NC2I-R HTR deployment, and the NC2I-R roadmap are explained and presented.

2 Roadmap Types

2.1 Technical Roadmap

The technical roadmap is the basis for the demonstrator aspects and planning in higher level roadmaps such as the deployment roadmap and eventually the NC2I-R roadmap. The roadmap has been constructed by estimating time, costs and risks of all aspects of the demonstrator. Counting backwards from a targeted commissioning date in 2027 as envisaged by Gemini (2014).

2.2 Deployment Roadmap

Based on the detailed technical roadmap for the demonstrator a higher level roadmap is set up for the deployment of this demonstrator. This roadmap starts from the technical roadmap, but includes information on the international developments and foreseen deployment schedules. In Europe, a demonstrator project can potentially be funded in a public private partnership construction in SET-plan framework as an industrial initiative. Therefore the entire demonstrator project is an industrial initiative until commissioning, and is presented as such. In 2014, the European nuclear cogeneration community started a collaboration with the US nuclear cogeneration community which provides important input to this deployment roadmap. More details will be explained in chapter 3.

2.3 NC2I-R Roadmap

The highest level NC2I-R roadmap is intended for communication purposes, and highlights the most relevant and important aspects of European HTR nuclear cogeneration deployment in the framework of NC2I-R, but avoids distracting details. However, all planning and timing aspects rely fully on the underlying more detailed deployment and technical roadmaps. As such, the timing and duration of developments presented in the NC2I-R Roadmap have a solid basis, are checked, and should be considered ambitious but realistic.

3 Roadmap Input

The starting point for the NC2I-R Roadmap has been the Europairs roadmap as presented by De Groot & Roelofs (2011), an update of which was presented by De Groot et al. (2013) at the FISA conference in Vilnius (see figure 1). Within the current NC2I-R project, this roadmap has been updated and elaborated taking into account the latest knowledge and developments. Validation of the duration of various developments within the technical roadmap has been achieved with the input of industrial partners within the NC2I-R project. Additionally, the detailed technical roadmaps (INL, 2008 and Venter & Koekemoer, 2008) produced in 2008 within the framework of the US NGNP project have been used to verify the durations and timing of various developments within the technical roadmap.

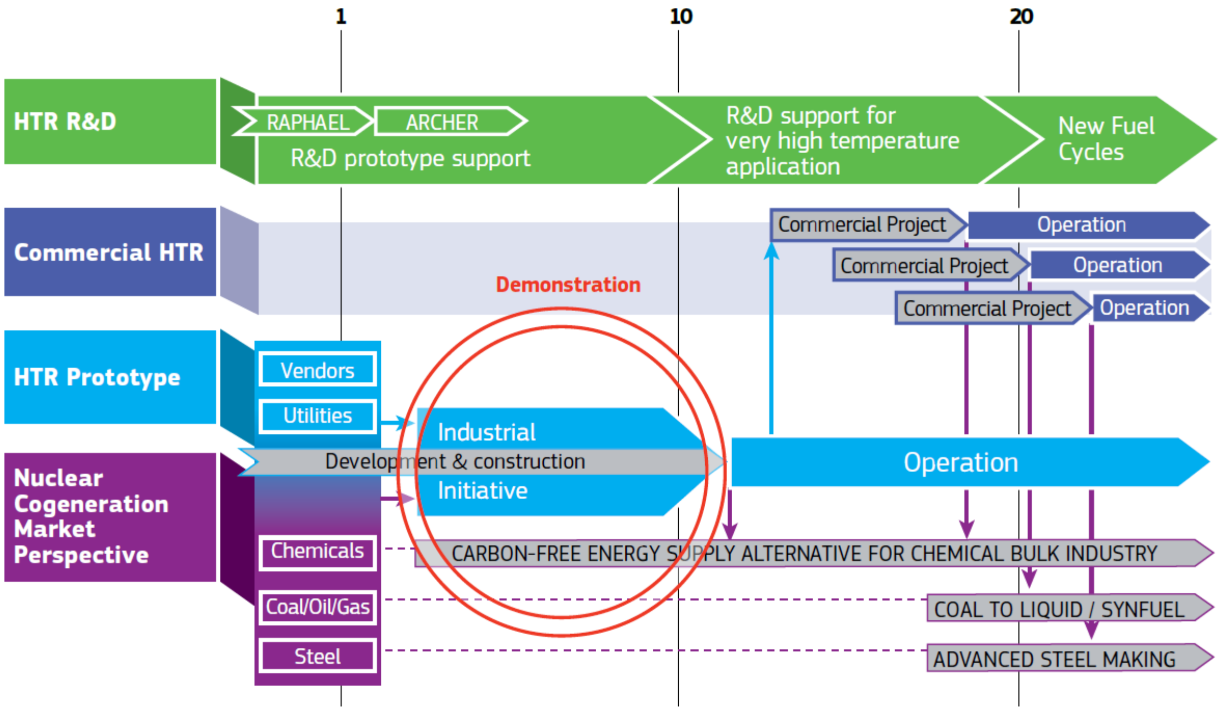


Figure 1: The EUROPAIRS Roadmap with the essential step of the demonstrator highlighted (De Groot et al., 2013)

The Gemini initiative, formed in 2014, is a Trans-Atlantic Partnership to Accelerate the Development of High-Temperature Gas cooled Reactors (HTGRs). These types of reactors are immune to extreme natural disasters because no electric power sources, cooling water or operator intervention is required to prevent core damage and significant radioactivity release. The initiative combines the forces of the European Nuclear Cogeneration Industrial Initiative, NC2I (www.nc2i.eu) and the US Next Generation Nuclear Plant Industrial Initiative, NGNP (www.ngnpalliance.org). They promote and work on the commissioning and the deployment of this nuclear reactor. The main timing of the demonstrator has been updated with the timeline presented in The Gemini Initiative Vision Document (Gemini, 2014). This document considers the following steps in the HTR development:

- **2014 –2015**: NC2I and NGNP Industry Alliance work with potential demonstration sites in the US and EU to develop a proposed development partnership. In addition, initial discussions begin with the US and EU governments on how to move forward will be taking place.
- **End of 2015 – mid-2016**: Project structure and partners largely determined. Substantial non-government cost share will have been determined.
- **End of 2016**: Agreement with US and EU governments on cost sharing and moving forward on project scope.
- **January, 2017**: Necessary contracts implemented, project oversight mechanisms in place and work on design and licensing requirements in both the US and the EU begins.
- **January, 2023**: Completion of design and licensing requirements in both the US and EU.
- **Beyond GEMINI: 2023 – 2027**: Construction of HTR prototype(s) in the US and EU.
- **Mid-2027**: First operation

The NC2I-R Roadmap should be in-line with the vision of the NC2I platform as expressed in the SNE-TP Deployment Strategy (SNE-TP, 2015) which is under public consultation (see figure 2).

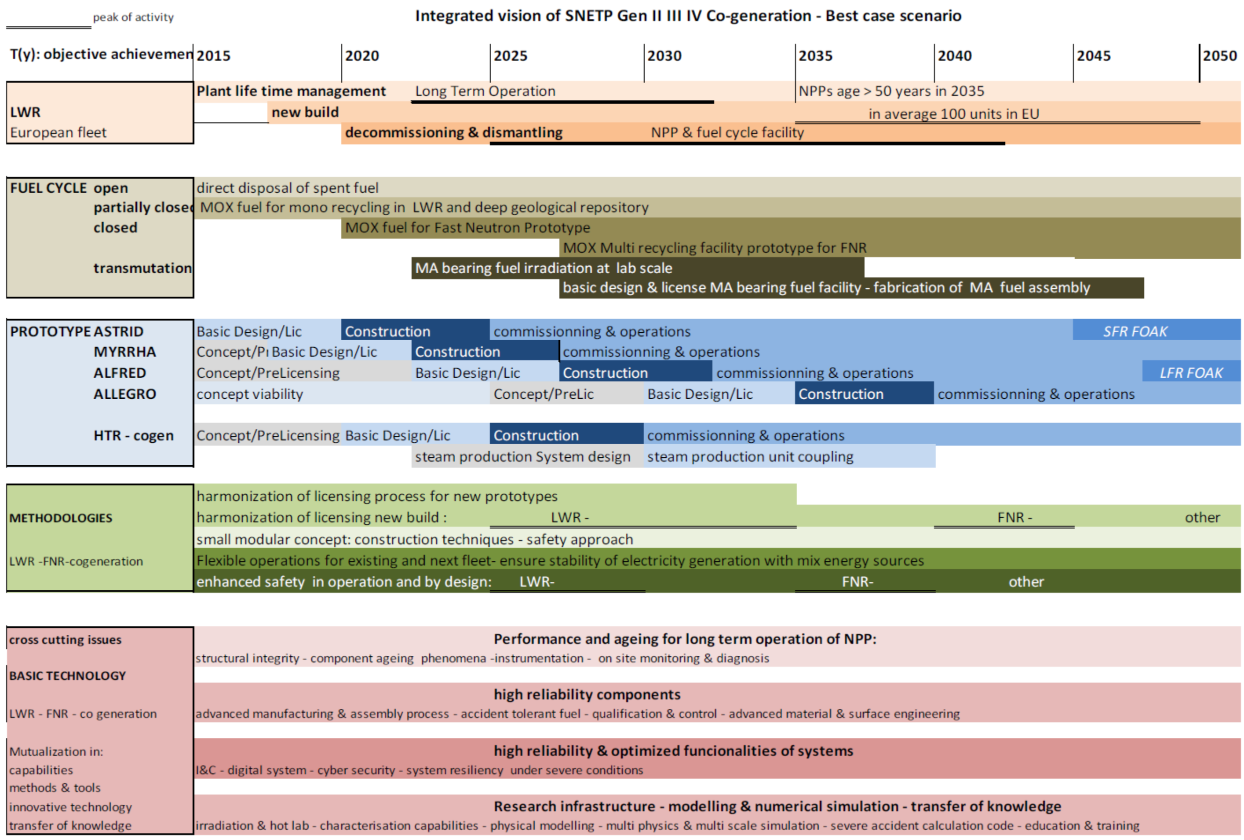


Figure 2: SNE-TP tentative roadmap (SNE-TP, 2015).

4 International HTR Activities

This chapter shortly introduces the international HTR activities and initiatives. The information collected provide the European activities an international framework and show that activities are not limited to Europe and the US only. It also shows that demonstrator projects are being planned all over the world with different ambitions and purposes.

4.1 Historical Perspective

In his overview of the HTR concept and technology status for industrial nuclear cogeneration, Hittner (2015) shows the history and experience with HTR reactors summarized in a single figure. This is shown in figure 3.

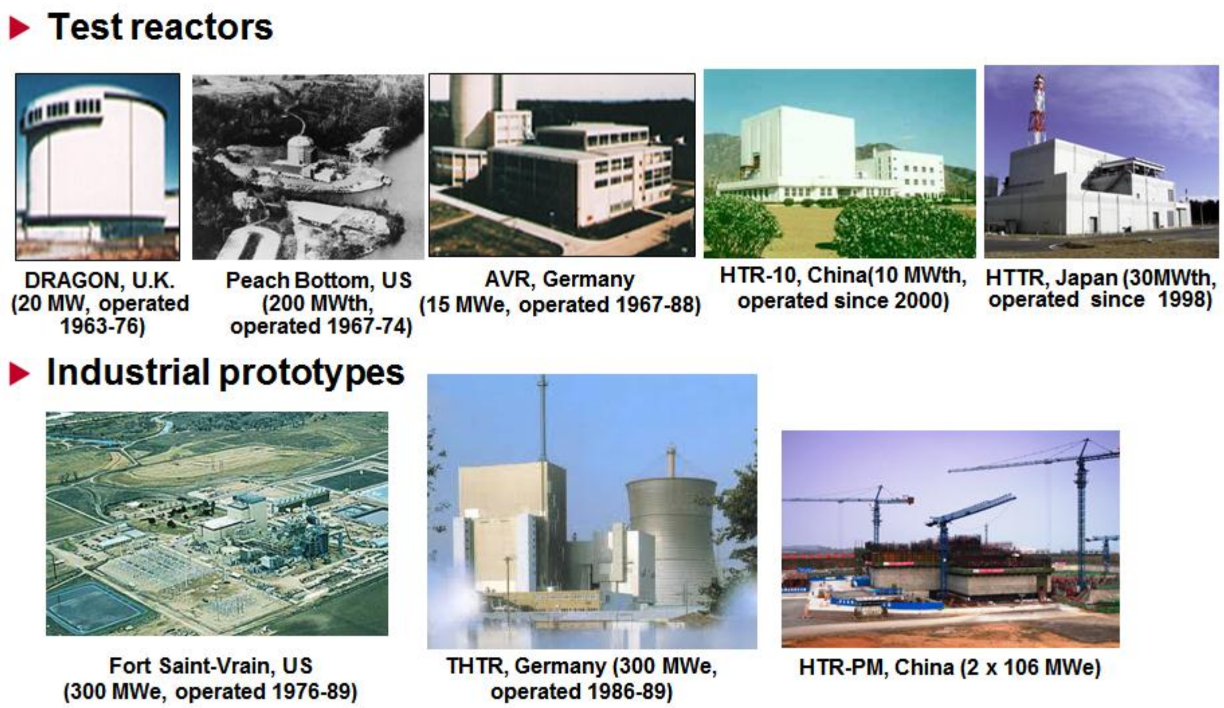


Figure 3: Overview of The HTRs built and operated in the world (Hittner, 2015)

Starting from this overview of projects which have actually been constructed, the historical perspective sketched in figure 4 is constructed. This overview starts on the left with the reactors which have been or are still operated. On the top left, the pebble bed designs are shown, amongst which the AVR, HTR-10, and HTTR are test reactors, whereas the THTR was a demonstration reactor. At the bottom left, the prismatic block designs can be found, such as the test reactors Dragon and Peach Bottom and the demonstration reactor Fort St. Vrain. In the next column, based on the design and operating experience of these reactors, new and optimized designs are shown, like the HTR-Modul, the GT-MHR and Antares which were developed in the past decades. More recently, these designs have been the basis of new international developments. The PBMR and NHDD initiatives in South Africa and South Korea have been developed more or less in parallel to the GT-MHR and Antares designs. More recently, new start-up companies were formed which try to promote their HTMR, Xe-100, and StarCore designs. However, ambitious as these projects may be, none of them has come to realization yet. The only HTR project which is currently under construction is the Chinese HTR-PM reactor. The following sections will provide more detail on the international developments.

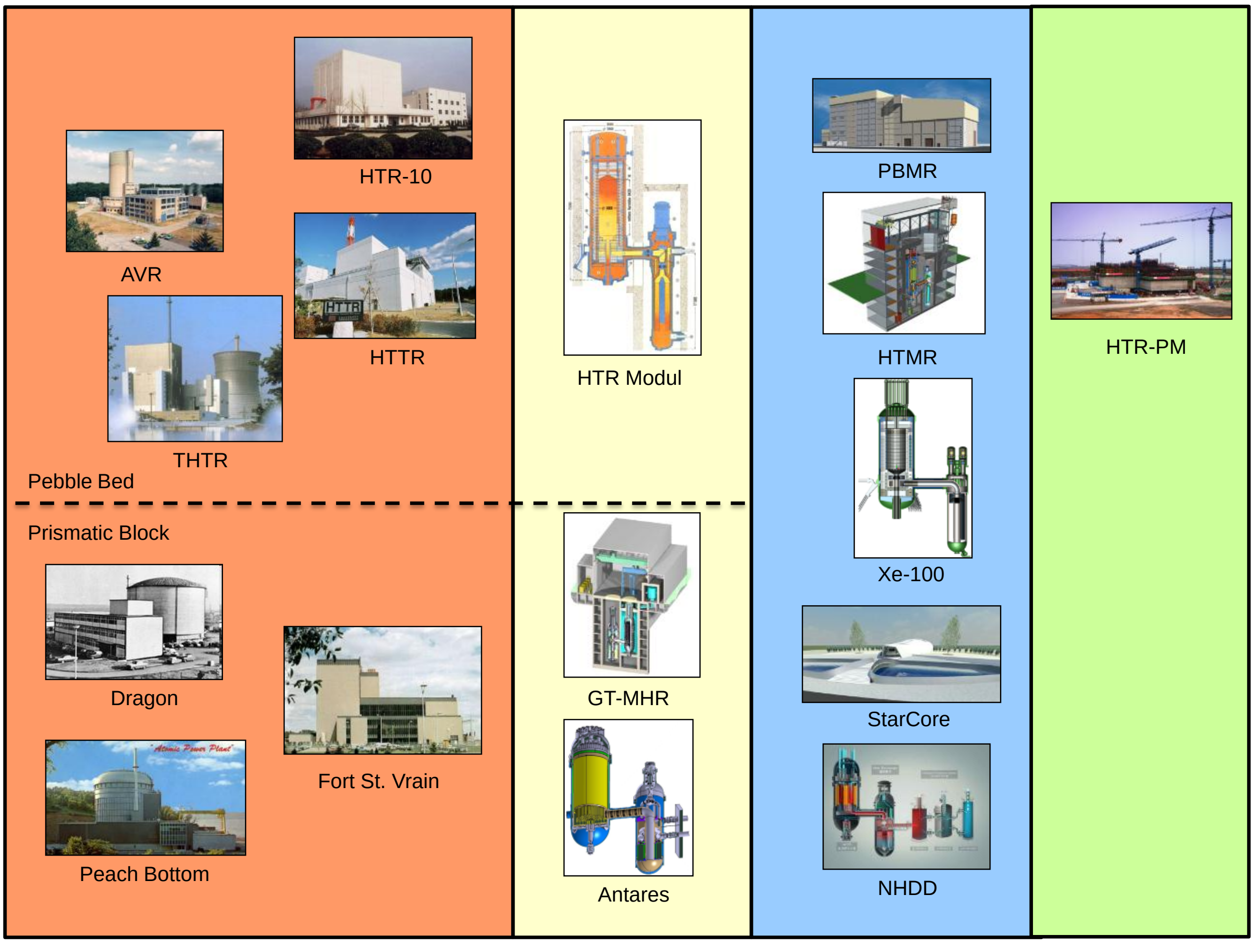


Figure 4: Historical perspective of HTR reactors

4.2 China

HTR-10

The HTR-10 test reactor is operational since 2000 with the purpose of verification and demonstration of the HTR technology in China. It is a 10 MWth pebble bed test reactor in which a.o. the unique safety features of an HTR are demonstrated. Approximately 16 000 pebbles form the nuclear core of the reactor.

HTR-PM

HTR-PM is a 2x250 MWth, 200 MWe pebble bed twin unit under construction (NECE, 2015). The design is largely based on the German HTR-modul design. The main target of the system is electricity production via a conventional steam cycle. Only in a later stage of HTR-PM development, cogeneration tests might be envisaged. The nuclear core will consist of approximately 500 000 pebbles. The HTR-PM is currently under construction in China. First concrete was poured end of 2012. In the end of 2014, irradiation test of fuel pebbles performed in Petten (Netherlands) was successfully finished. The target date to connect to the grid is 2017. The technical project objectives are (Dong, 2015):

- Demonstration of inherent safety features
- Demonstration of cost competitiveness
- Standardization and modularization
- Confirmation of proven technologies

4.3 France

Antares

Antares (AREVA New Technology based on Advanced gas-cooled Reactors for Energy Supply) is the AREVA design for HTR (Areva, 2005). The goal of the Antares developments is to create a commercially competitive Advanced High Temperature Reactor to meet future industrial demands for electricity generation and process heat supply. The Antares development program of Areva includes considerations for improvements in power output and outlet temperature. These considerations have led to a 600 MWth design employing prismatic blocks and an indirect cycle.

4.4 United States

NGNP & Piketon

The NGNP (Next Generation Nuclear Plant) R&D project in the USA targets the establishment of a Very High Temperature Reactor (VHTR) for hydrogen production. In parallel, the US end user industry targets an HTR for steam and electricity production. Interested US industrial stakeholders have been organised in the US Alliance. Although the US NGNP program brought a lot of improvements for HTR technology, limited design work was done. End of 2014, the NGNP entered discussion with managers of the Piketon site as a potential location for a demonstration plant. Simultaneously, discussion with the European counterparts resulted in the Gemini initiative explained in more detail in chapter 3.

X-Energy

X-Energy’s mission is to build and profitably sell nuclear reactors (X-Energy, 2015). Aiming for commercialization in the mid-2020’s, the Company sees extensive U.S. and international market opportunities for their Xe-100 in government and commercial applications. They envisage a small HTR with 125 MWth and approximately 48 MWe. The core will comprise about 170 000 pebbles. For security and safety reasons they propose to construct the reactor completely underground. Design certification is planned around 2024 with commercial deployment scheduled late 2020's.

4.5 Canada

StarCore

StarCore aims at a very small, 10 or 20 MWe, reactor for local, affordable electrical power and thermal energy with a 5 year life span (StarCore, 2015). Customers only pay for electricity as delivered and are not responsible for nuclear operations or safety. They envisage a plant which is buried 30 m underground, is fully automated and monitored by satellite by StarCore. It only requires on-site personnel to manage the electricity generation and distribution of thermal energy.

4.6 Japan

HTTR

In Japan, the events at Fukushima have given new attention to HTR thanks to its excellent safety features. The new strategic energy plan approved in 2014 mentions facilitation of R&D for high temperature reactors (Sakaba, 2015). Japan possesses the HTTR test reactor. This test reactor of 30MWth is operational since 1998 and uses prismatic blocks. Like all nuclear facilities in Japan it shut down after the 2011 earthquake. Restart of the test reactor is scheduled in 2015.

4.7 South Korea

NHDD

The Nuclear Hydrogen Development & Demonstration design is under development in Korea, scheduled for deployment late 2020's (Kim, 2015). In parallel, a Korean Nuclear Hydrogen Alliance was established in 2009 with participation of nuclear industries (vendor, utility, engineering companies, and research institute) and potential end users (steel, oil refinery, petro-chemistry, and motor companies). They established a memorandum of understanding with the US NGNP Industrial Alliance in 2013.

4.8 South Africa

PBMR

During the second half of the 1990s the South African utility Eskom embarked on a feasibility study regarding the possible development and demonstration of the Pebble Bed Modular Reactor (PBMR). In 2010 the South African Government decided to terminate its funding of the project and essentially to mothball it for later reconsideration. The company has documented the considerable intellectual property and expertise developed in the project (Ellis, 2015). It has also developed strategies for the preservation of this body of knowledge for use in the future. PBMR is currently in a state of Care and Maintenance. PBMR now has a register of more than 200 patents, with nearly 40 still in the application stage. Four Trademarks are also in the process of being registered worldwide. PBMR is continuing the quest of ensuring that the PBMR Intellectual Property (IP), created during the nine years the project was running, is secure, accessible and retrievable. The future of PBMR remains unclear.

HTMR

The private company Steenkampskraal Thorium Limited (STL) has launched a new HTR initiative in South Africa aiming at deployment of the High Temperature Modular Reactor (HTMR). They made two designs, a 25 MWth and a 100 MWth design which should be licensable within a few years. They target at international markets with cleaner, safer, and sustainable nuclear power.

4.9 Indonesia

As outlined in NC2I-R deliverable 5.42 (Mull, 2015), first ideas for HTGR deployment in Indonesia were made in 1989 in the context of oil refinement on Sumatra. A joint assessment of Indonesian bodies together with German KWU (nowadays AREVA GmbH) had suggested a total of four HTR-Modul reactors to cogenerate steam (up to 4000 t/h) and electricity (up to 300 MW), plans which obviously were not followed up to their end. Recently, Indonesian representatives reintensified their contacts to the HTGR community. The National Atomic Energy Agency of Indonesia (Batan) is taking decisive steps today to introduce nuclear energy into the Indonesian electricity infrastructure. Besides conventional LWRs on some larger and more developed islands, they intend to build Pebble Bed HTGRs with electrical outputs of up to 100 MWe for provision of electricity and process heat (e.g. for seawater desalination and possibly H2 production) on smaller islands (WNA, 2015).

Before constructing power reactors, Batan is presently preparing to build a small HTGR-based Experimental Power Reactor which is referred to as Multi Purpose Power Reactor (MPPR) as outlined by Sunaryo (2015). The MPPR project does not only employ technical objectives but also incorporates social objectives as it is aiming at an increase in public acceptance for commercial NPPs. In parallel, Batan is starting R&D on fuel and high temperature materials. A decision for a pebble bed core for the MPPR was taken in the first semester of 2015. This experimental reactor is intended to have a thermal power of only 10 MW. Construction time is estimated to be 4 years. A conceptual design phase was started in April 2015 by award of a contract to a Russian-Indonesian consortium and it will last 8 months. The result of this conceptual design will be a lean safety assessment report. The German consultant BriVaTech is involved. For the beginning of 2016 a call for tender is expected for an EPC-contract.

5 Cogeneration Market

This chapter summarizes the work described the NC2I-R deliverables 4.21 (Gradecka et al., 2015), 4.31 (Stahl, 2015), and the South African WP4 contribution (NWU, 2015).

5.1 Cogeneration Processes

The main processes compatible with HTR cogeneration are (Gradecka et al., 2015):

- refinery distillation steam
- refinery distillation superheated steam
- petrochemicals - reaction enthalpy
- steam as utility for industrial complex
- paper steam (drying)

Note that NWU (2015) clearly evaluates that hydrogen production is economically not attractive in South Africa. Instead, substitution of coal generated process steam and electricity offers the best opportunity for nuclear cogeneration.

5.2 Locations in Europe

Possible sites in Europe for application of nuclear cogeneration are identified by Gradecka et al. (2015). Mapping of industrial sites was conducted in a manner allowing describing the heat market and distinguishing industrial sites located in Europe. They identified 132 possible sites. Of those 132 sites, they provide quantitative information for 59 sites spread over Europe and shown in figure 5. Of those sites, 40 are located in Eastern Europe, 15 of which in Poland. Furthermore, 16 sites are located in Western Europe (where it should be noted that some of them are located in countries with a non-nuclear perspective like e.g. Germany and Belgium), and 3 in Southern 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.)

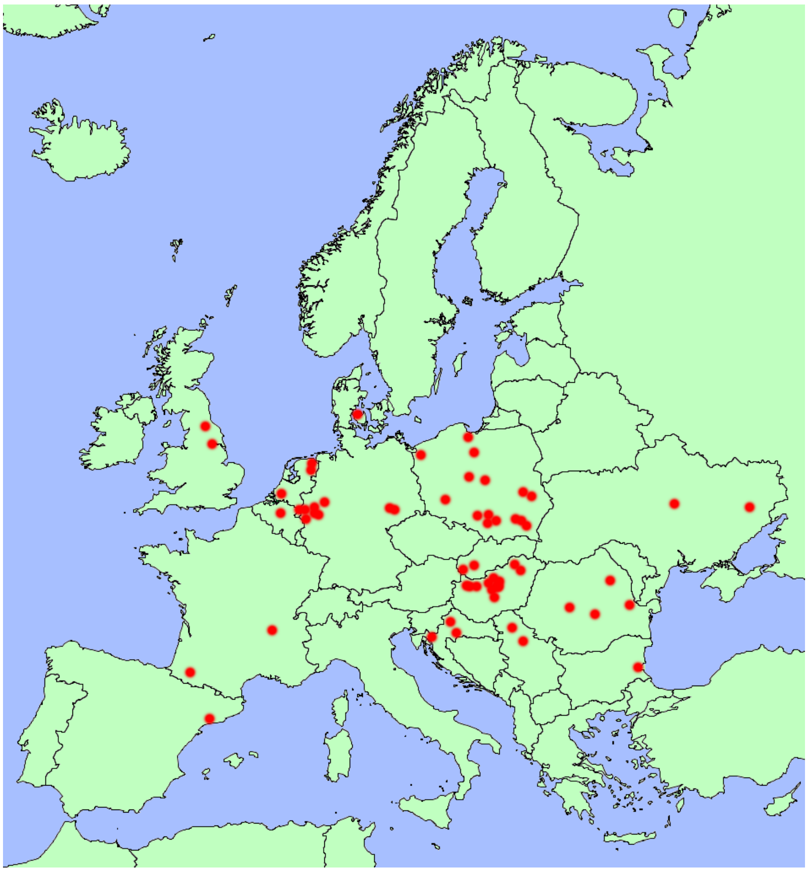


Figure 5: Possible cogeneration sites in Europe for which quantitative information is provided by Gradecka et al. (2015).

5.3 Demand Specification

From their data collection, Gradecka et al. (2015) derived the thermal and electrical power demands of the 59 possible European industrial cogeneration sites. Figure 6 shows the distributions in thermal and electrical energy demand. It is clear that most sites demand less than 100 MWth and less than 50MWe. However, the industrial steam condition requirements vary quite a lot from site to site and from region to region.

Poland

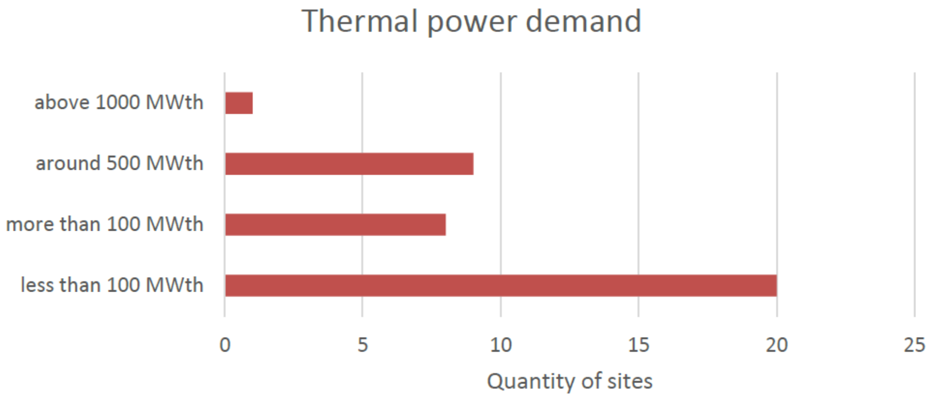
In Poland, the main demand is for medium to high pressure steam (15-140 bar) at a temperature of ~500°C. The study shows that ~60% (35/61) of the existing steam boilers are to be decommissioned or upgraded before 2019. At such short timeframes, replacement by nuclear cogeneration is not possible. For the remaining sites, replacement by nuclear cogeneration might firstly be envisaged for small light water cooled reactors thanks to the existing licensing framework for light water cooled reactors. It will certainly take longer to deploy HTRs as the licensing framework is not existing.

Eastern Europe

In eastern Europe, the main demand is for low to medium pressure steam (2-35 bar) over a large temperature range strongly varying from 100°C to1600°C.

Rest of Europe

In the rest of Europe, the main demand strongly varies from low to high pressure steam (2-300 bar) at a temperature lower than 600°C. In addition, for the rest of Europe it should be noted that many sites are located in non-nuclear perspective countries like Germany and Belgium.



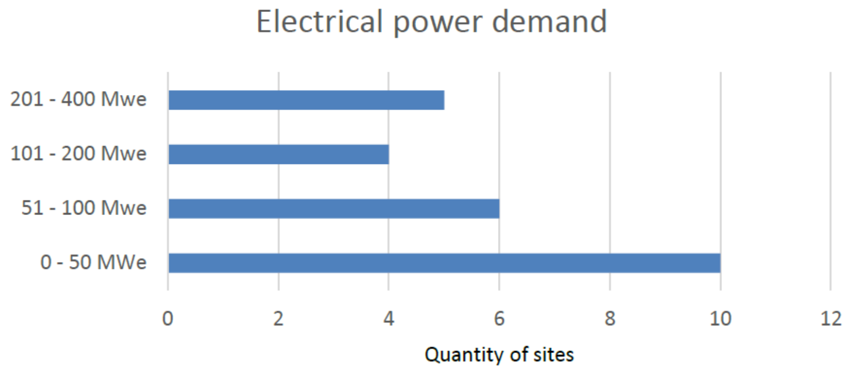


Figure 6: Demand specification for 59 possible European industrial cogeneration sites (Gradecka et al., 2015)

5.4 Deployment Scenarios

A number of scenarios for deployment of nuclear cogeneration is presented by Stahl (2015) in which the CO_2 price is varied. She uses the main assumption that share of nuclear (industrial) process heat remains below 40% and the share of nuclear cogeneration including district heating remains below 20%. All scenarios assessed show deployment of nuclear cogeneration roughly between 2025-2045. Depending on the scenario, the number of deployed HTRs in Europe is in the range of 10 to 20 reactors.

Apart from the economic considerations, an important additional incentive for nuclear energy production and nuclear cogeneration specifically is found in the national or regional security of energy supply. Where such issues in the early zeros were considered to be outdated, the current political situation in Europe urges countries on a national level, and Europe on a regional level, to reconsider the energy production strategy. The current trend is much more directed towards energy independence on a national or at least on a regional level.

6 HTR Demonstrator Specifications

At the moment, there is no European consensus on the design of a cogeneration HTR. As a first step towards consensus and a European design, Plet (2015) has collected functional specification for an HTR demonstrator. Also, Hittner (2015) presents some specifications for a European HTR demonstrator. The main specifications can be summarized as follows:

- The European HTR should possess **inherent safety features**, i.e. no core melt should be possible, even without emergency cooling. This is a necessity to address the public acceptance
- The demonstrator design should prove the **economic viability** of a follow-on commercial HTR. Such a commercial HTR plant should be competitive without government support. In the European context, a minimum power level of about 200 MWth is required. This means that existing small concepts like HTMR, Xe-100, and StarCore (see chapter 4) will not be economically deployable in the European context.
- The technical concept should use **proven technology**. This will shorten the licensing process and ensure early deployment. Therefore, the design should largely be based on existing HTR experience and employ a conventional steam cycle up to 750°C producing process steam up to 600°C.
- The requirements towards the **supply chain** & **skills** should be such that high quality of the manufacturing and construction can be assured.

From these high level consideration, the required power and heat level of the demonstrator can be determined. Firstly, the power and heat level should match the needs of the market. These needs are explained in chapter 5 and summarized below:

- Heat: < 100 MWth
< 750°C (allowing proven technology)
- Electricity: < 50 MWe
- Heat/electricity ratio: depending on application
- Reactor power < 225 MWth (assuming an efficiency of 40% for electricity production)

Further, the specification on inherent safety features implies that the power level should be limited to 300 MWth for a pebble bed design and 600 MWth for a prismatic block design according to Hittner (2015). To the same background of increased safety, it is recommended to design at least two barriers between the primary helium loop and the process steam.

Considerations with respect to the distribution between heat and power are based on heat and electricity price forecasts. From this, Plet (2015) concludes that an increase in prices/cost favors heat above electricity. Furthermore, he indicates that flexibility in the heat/electricity ratio would be welcome allowing to deal with expected intermittent demands in a symbiosis with an increase in the share of renewables in the energy production.

7 Technology Gap Analysis

Within the EU FP7 ARCHER project, Knoche (2014) made a technology gap analysis. This technology gap analysis has been summarized in Roelofs et al. (2014) with table 1. For the technology gap analysis, the experience from the Thorium High Temperature Reactor (THTR) was taken as a basis (THTR, 2014). The THTR was built at a shared site with coal fired power plants and is therefore representative of a system which can be used for co-generating process heat. The outlet temperature of the core was relatively low in order to increase the lifetime of the steam generator. The THTR possessed a pre-stressed concrete reactor vessel which is different to many other HTR designs. Taking the historic THTR gap analysis as a basis, elaborations have been made to generalize the conclusions from this gap analysis to other HTR designs. In this way, a generic HTR technology gap analysis was established. However, it should be noted that a number of identified technology gaps have been considered solved for different designs, like e.g. the gaps on the steam generator. Apart from that, a set of simulation tools required for an HTR modelling package are available. Nevertheless, the rapidly growing computer hardware and knowledge and development of simulation tools allow these topics to be identified as technology gaps. The main findings are reported by component in table 1.

Table 1: Technology gap analysis for an HTR (Roelofs et al., 2014)

Component	**Technology Gap**
Reactor vessel	-
Steam generator & heat exchangers	- Steam generator inspection - Tube sheet design and behavior
Core structure	- Qualification of new graphite - Minimization of bypass flows
Blowers	- Bearings (magnetic vs. oil lubrication) - Orientation (horizontal vs. vertical)
Fuel handling system	- Recycling vs. once through - Performance at elevated pressures, temperatures, and burn-ups
Reactivity control system	- Diverse shutdown systems - Testing and qualification of in-core control rods (if needed)
Core design	- Development of an integral HTR modelling package - Validation
Graphite dust	- Filters & Effect of flushing - Development of a separation concept minimizing contamination - Development of simulation models (formation, activation, transport, deposition, remobilization) - Prevention of dust formation
Air & water ingress	- Development of simulation tools and their validation
Regulatory framework	- Collection and analysis of regulatory requirements and industrial standards
Economical aspects	- Economics of scale with respect to investment costs - Design optimization with respect to economic aspects
Supply chain	- Re-establishment of the (European) supply chain

8 NC2I-R Roadmap

8.1 Technology Roadmap

The information collected in all previous chapters has been integrated in the technical HTR roadmap as presented in figure 7. Firstly, the time schedule provided by the Gemini initiative for the construction and operation of the HTR demonstrator was taken as a basis (Gemini, 2014). Counting backwards from a targeted commissioning date in 2027, the schedule for the HTR demonstrator is constructed. For this, tentative durations have been determined for the developments specified within the roadmap. These durations have been validated with the input of industrial partners within the NC2I-R project. Additionally, the detailed technical roadmaps (INL, 2008 and Venter & Koekemoer, 2008) produced in 2008 within the framework of the US NGNP project have been used to verify the durations and timing of various developments within the NC2I-R technical HTR roadmap.

This exercise clearly shows that conceptual design of a European HTR demonstrator should start not later than 2018 to reach the targeted commissioning date. Given the large experience with HTR reactors and the pre-conceptual designs already available as described in chapter 4, this is well achievable. More urgent however, as figure 7 demonstrates, is to start considering fuel production, at least at pilot scale, and qualification which should start in 2017. This implies that decisions on fuel type and configuration would be required by that time.

Aiming for a design with proven technology for which the technology gaps identified in chapter 7 are not limiting, the development of all other components identified in the technology roadmap should be feasible with a relatively short duration. This is well recognized within the roadmap, where many of the developments are supposed only to take from 2020 to 2022 (3 years).

Some general conclusions can be derived from the detailed HTR technology roadmap:

- Total development costs in order to realize an HTR demonstrator are in the range of 2 to 3 billion Euro. Note that this includes R&D costs which are normally not taken into account for cost estimates of (demonstration) reactors.
- The following technical risks have been identified as of major importance for costs and planning:
    - *Reactor Pressure Vessel*
      Waiting lists for forged vessels are generally long, due to lack of suppliers and an increase of vessel demand.
    - *Fuel*
      Although adequate HTR fuel quality has been achieved reproducibly worldwide, it is still on laboratory scale. Producing HTR fuel on industrial scale requires HTR fuel factories with full qualification.

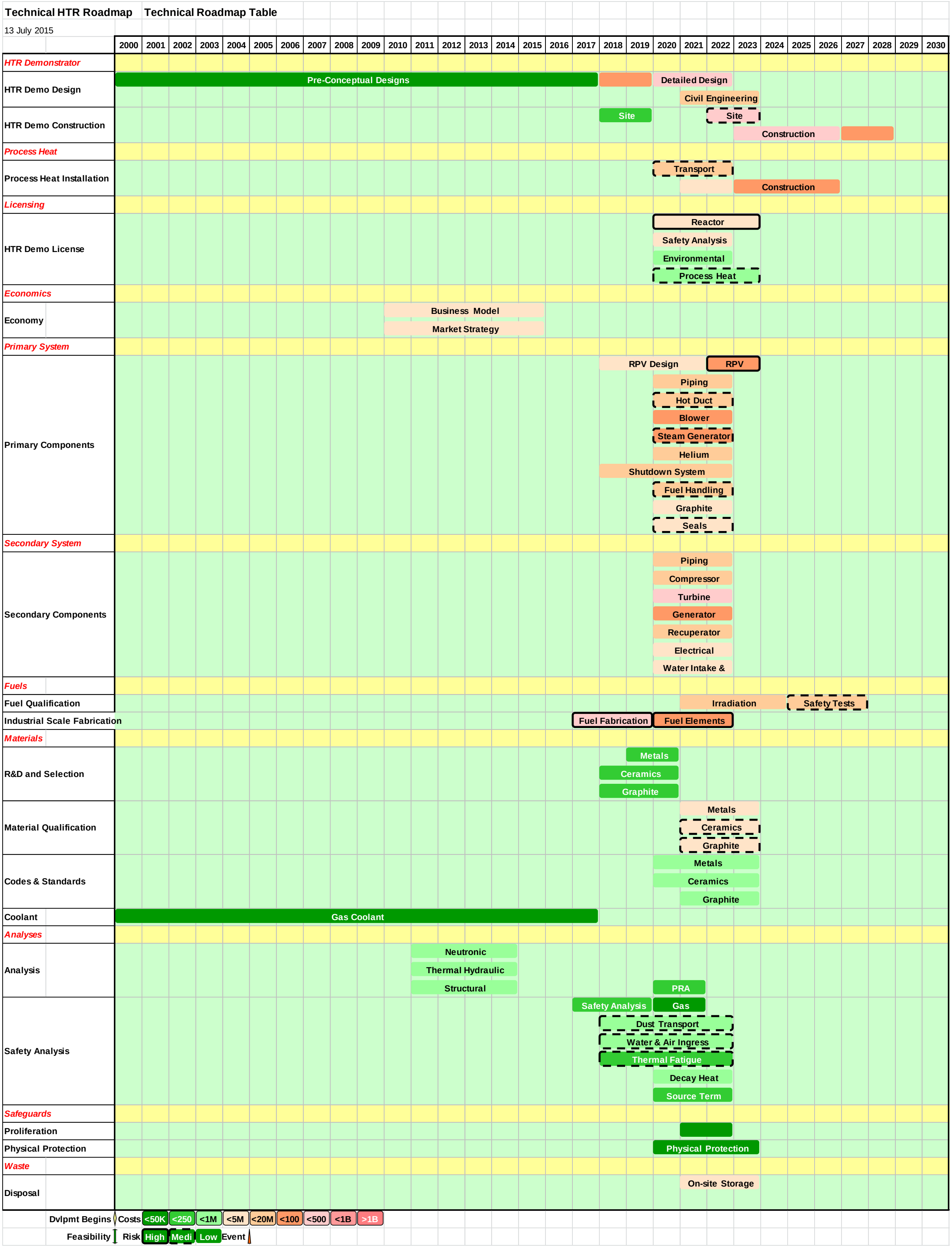


Figure 7: NC2I-R technical HTR roadmap

8.2 Deployment Roadmap

Based on the detailed technical HTR roadmap as presented in figure 7, a higher level roadmap is set up for the deployment of the HTR demonstrator. This roadmap starts from the technical HTR roadmap, but includes information on the international developments, such as the HTR efforts in European framework projects, and foreseen deployment schedules. In Europe, a demonstrator project can potentially be funded in a public private partnership construction in SET-plan framework (European Commission, 2010) as an industrial initiative. The Gemini initiative, started in 2014 as a collaboration between NC2I and the US NGNP, provides important input to this deployment roadmap as elaborated in chapter 3. This is in-line with the latest schedule presented by SNE-TP (2015) in its update of the deployment strategy. In fact, given the current situation, it is expected that further development of nuclear cogeneration in Europe will only take place in collaboration with the US NGNP.

The deployment roadmap as presented in figure 8, provides a high level insight in the European and international developments with respect to the HTR technology, the cogeneration applications, and the realization of a demonstrator and it's successive commercial follow-ons. Apart from that, the main technological challenges which are on the critical path of the realization of the demonstrator are indicated, i.e. the design and manufacturing of large primary system components and above all the fabrication and qualification of fuel.

With respect to the risks identified in the HTR technology roadmap, the following milestones have been included in the deployment roadmap:

- *Reactor Pressure Vessel*

  Waiting lists for forged vessels are generally long, due to lack of suppliers and an increase of vessel demand. To mark this in the roadmap, a milestone has been added where vessel design has to be finished, and the vessel has to be ordered (2021), to be in time for construction, and the target commissioning deadline in 2027.
- *Fuel*

  Although adequate HTR fuel quality has been achieved reproducibly worldwide, it is still on laboratory scale. Producing HTR fuel on industrial scale requires HTR fuel factories with full qualification. Depending on whether existing industrial HTR fuel manufacturing capacity can be used (China, US (partly), South-Africa (partly)), an early decision is required for either establishing fuel manufacturing capability in Europe, or buying HTR fuel from internationally established suppliers. This 'build or buy' decision has been added at end of 2016.

In addition, the following essential decision points have been identified, which determine the start of all subsequent phases of the demonstrator development.

- The system specifications have to be fixed before the final design phase can be finalized (end of 2017).
- Decision on the application, and at what location the demonstrator will be established. For this the milestone ‘site selected’ has been added, coinciding with the system specifications milestone.

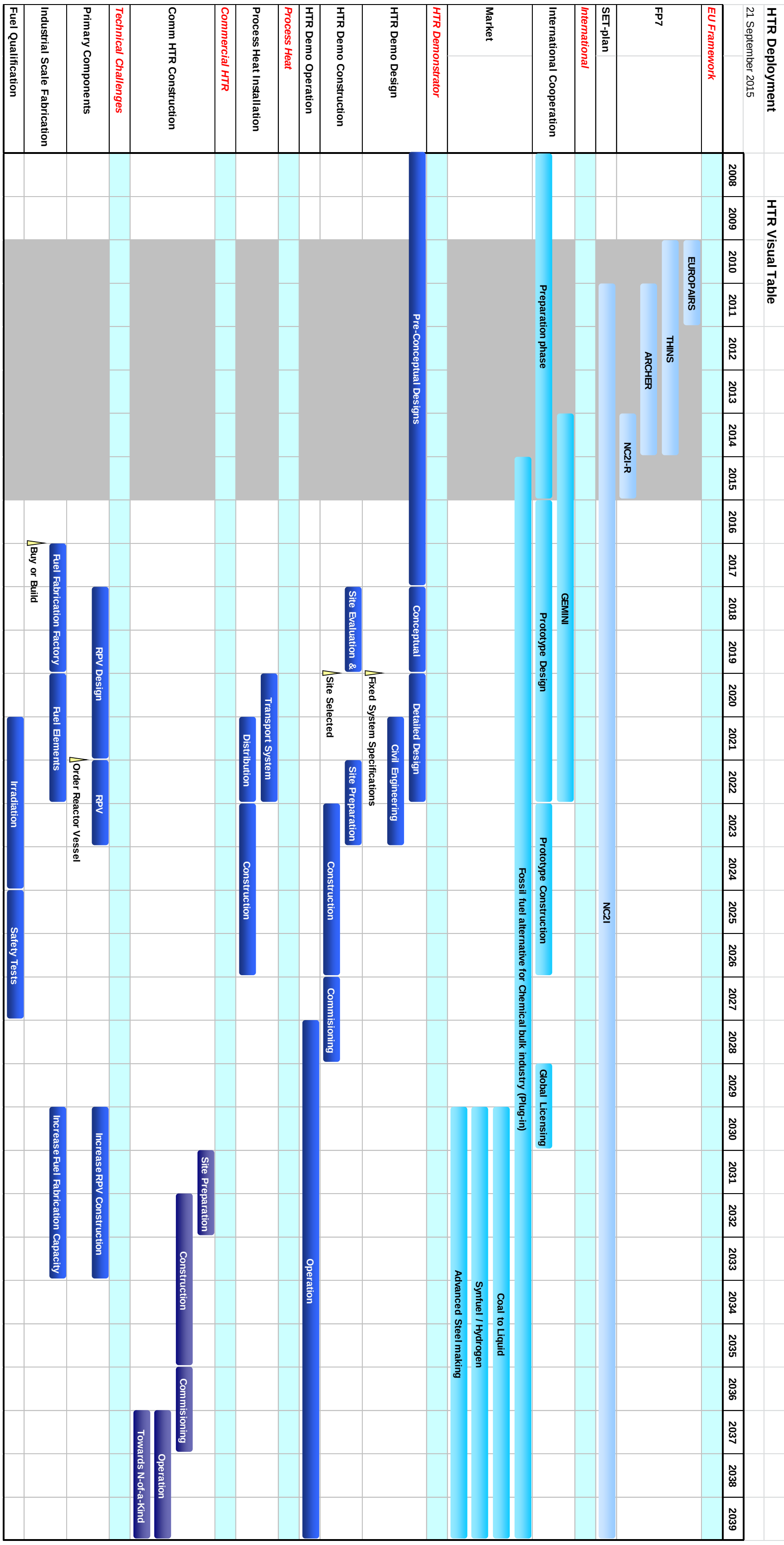


Figure 8: NC2I-R HTR deployment roadmap

8.3 Roadmap

The highest level NC2I-R roadmap is intended for communication purposes, and highlights the most relevant and important aspects of European HTR nuclear cogeneration deployment in the framework of NC2I-R, but avoids details. However, all planning and timing aspects rely fully on the underlying more detailed deployment and technical roadmaps as presented in figures 7 and 8. As such, the timing and duration of developments presented in the NC2I-R Roadmap presented in figure 9 have a solid basis, are checked, and should be considered ambitious but realistic.

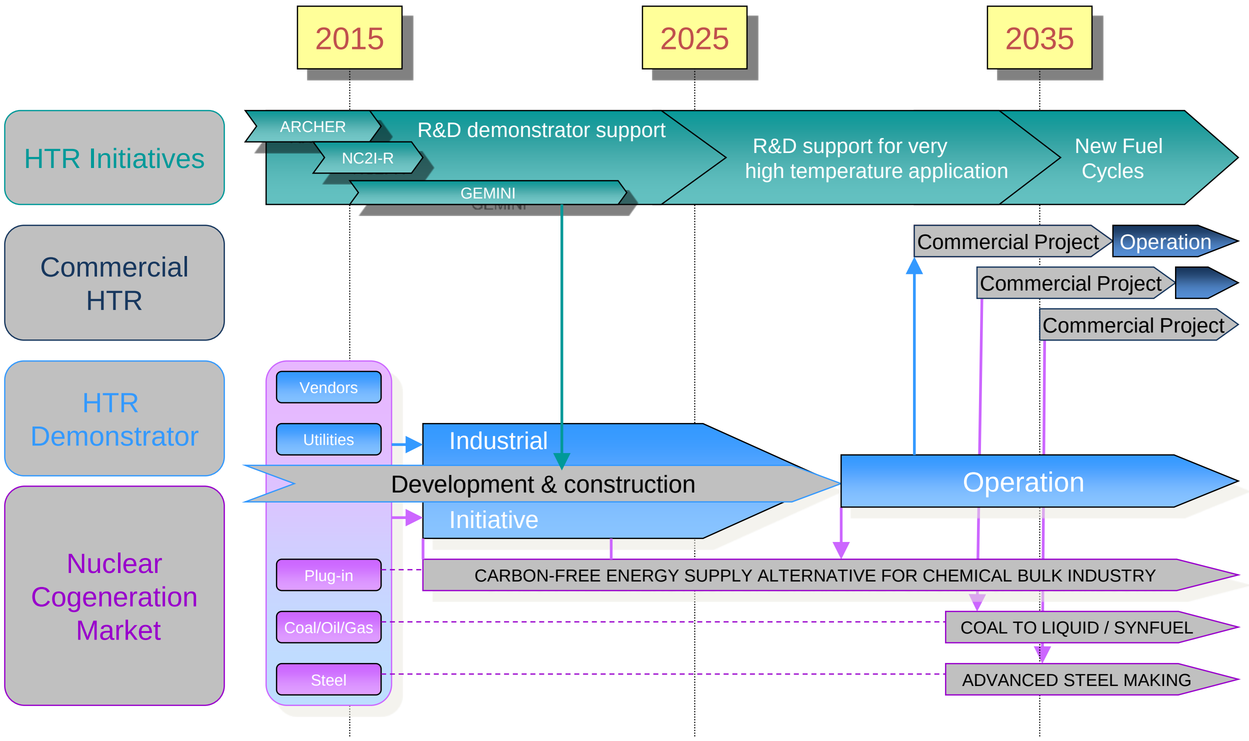


Figure 9: NC2I-R Roadmap

The NC2I-R Roadmap as shown in figure 9 includes 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 (not shown here but in the deployment roadmap) 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.

9 Summary

Construction of a roadmap for the deployment of a system is a tool which helps obtaining an overview on the timing and dependence of the various activities required to establish the end goal, i.e. the deployment of the system. Within the EU FP7 Europairs project, a first HTR cogeneration roadmap was constructed. The aim of the current effort is to update this roadmap with the most recent information and validate the roadmap with industrial and international input.

This report has collected important input for the construction of the NC2I-R roadmap. The underlying roadmap is a detailed technical HTR roadmap. This roadmap is validated based on input of the NC2I-R industrial partners and available HTR roadmaps from the US. Compared to the Europairs roadmap and based on input from the SNE-TP deployment strategy and the Gemini vision paper, the timeline for commissioning an HTR demonstrator has been relaxed. With the latest insights, start of this demonstration reactor is envisaged in 2027.

Derived from this the following critical milestones have been identified:

2017 Build or buy decision for industrial fuel fabrication

2019 Fixing system specifications for the HTR demonstrator

Site selection for the HTR demonstrator

2021 Ordering the reactor pressure vessel for the HTR demonstrator

2027 Start operation of the HTR demonstrator

2031 Start site preparation first commercial HTR

2037 Start operation of the first commercial HTR

Thus, the resulting NC2I-R roadmap will subsequently serve the NC2I platform, SNE-TP, the European Commission, the Gemini EU-US Initiative, and the European and international HTR community at large to structure follow-up activities.

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