MINISTRY OF ENERGY

Possibilities for deployment of high-temperature nuclear reactors in Poland

Report of the Committee for Analysis and Preparation of Conditions for Deployment of High-Temperature Nuclear Reactors

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Warsaw, September 2017

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SUMMARY

The Committee for Analysis and Preparation of Conditions for Deployment of High-Temperature Nuclear Reactors (the HTR Committee, for short) was appointed by the Minister of Energy on July 13, 2016. During several months the HTR Committee collected and **analyzed data on the demand of energy in form of heat with a temperature above 250°C** and investigated a possibility to meet these energy needs with HTR[1] reactors.

Available reactor technologies were reviewed recognizing High Temperature Gas-cooled Reactors (HTGR) as the best option. The advantage of this technology over others results from the unique features of **inherent safety that prevent core melting** as well as technological maturity and technical parameters optimal to the needs of the industry. An estimation of the construction costs of this type of reactor was carried out and the profitability of the investment was preliminarily analyzed in comparison with conventional technologies. It has been shown that while providing reasonably low cost crediting of investment, **the price of steam from HTGR may be comparable to the price of steam from gas boilers.** Today, gas is burdened with a high risk of lack of availability and price increase as well as uncertainty of CO_2 emission costs.

HTGR TECHNOLOGY IS AN ALTERNATIVE, WHICH CAN ENSURE:
Poland becoming gradually less dependent on gas imports from one supplier due to reduction of its needs to the level covered by own extraction, Nordic gas pipeline and gas terminal.
Reduction of CO_2 emissions, which increases the pool available for coal-based energy.
Providing domestic industry with the heat sources of predictable costs, resistant to changes in fuel prices and independent from the price of CO_2 emission allowances.
Launch of production of HTGR reactors with high export potential.

In conclusion, the HTR Committee recommends beginning the preparation of HTGR deployment.

A business model proposed in the report envisages **establishing a special purpose company** own mainly by industrial heat users. The first task of the company **(provisionally called HTR-EPC)** would be to develop a preconception study upgrading the analysis carried out by the HTR Committee and to conduct negotiations with potential foreign partners. Successful conclusion of these steps would give a green light to start designing the reactor. Positive opinion of nuclear regulator should clear the path towards investment decisions and reactor constructions in chosen locations.

[1] In the world literature, the abbreviations of both HTGR and HTR are used to describe high temperature reactors cooled with helium gas. In this report, the abbreviation HTR refers generally to various technologies of high temperature reactors.

The first HTGR's are supposed to be commissioned around 2031. Simultaneously - in fact, right at the start - **the HTR-EPC would begin the preparation and construction of a low-power HGTR experimental reactor**, needed to accelerate design work and licensing of commercial reactors.

THE HEAT DEMAND

The heat demand in Europe is spread at a level of 600-900 GWh / year in temperature ranges below 250°C, 250-550°C and above 1000°C with relatively low demand between 550°C and 1000°C. The lowest range needs can be met by light-water reactors (LWR). However, industrial installations using such temperatures are generally small and scattered, which makes nuclear reactors difficult to use. The district heating sector has significant potential; today however, it uses waste heat from large energy reactors in a few countries only. The source of urban heat could be an SMR reactor of a PWR type, being developed in several countries around the world. However, HTGR reactors have the advantage of possibly being located close to the human settlements because of their inherent security features described below.

The steam of T≈500°C is a standard heat carrier in many large industrial plants, especially chemical ones. There, HTGR deployment could be made easier by exchanging outdated gas of coal boilers, without changes in existing installations that include electricity producing turbines for the needs of the plant. The demand of Polish industry for steam with such parameters is about 6,500 MW in several locations. In practice, the demand for HTGR reactors up to 2050 could be roughly estimated to be 10-20 units in Poland, 100-200 units in the EU and 1000-2000 units in the world.

The highest range, above 1000°C has a bright future due to the production of hydrogen and hydrogen-based fuels. The HTR Committee recommends beginning preliminary research on selected reactor technologies (such as VHTR or Dual Fluid Reactor - DFR) because, as of today, there is no proven nuclear technology in this area.

THE CHOICE OF TECHNOLOGY

According to the HTR Committee, **HTGR reactors are the optimal technology for T≈500°C**. The research programs run by SNETP, the OECD NEA and the British government lead to similar conclusion. Several research and industrial reactors have been built with the use of this technology (including 2 × 250 MW_{th} under construction in China), which confirms its maturity. Still, it is not commercially and commonly used and **its implementation on an industrial scale (serial production of reactors) would be a global breakthrough in the energy industry.**

[2] SNETP „Deployment Strategy", 2015, www.snetp.eu/publications

[3] OECD NEA „Nuclear Innovations 2050", www.oecd-nea.org/ndd/ni2050

[4] "Industrial Applications of Nuclear Energy", IAEA Nuclear Energy Series No. NP-T-4.3, 2017.

[5] "Small Modular Reactors: Techno-Economic Assessment", 2017. https://www.gov.uk/government/publications/small-modular-reactors-techno-economic-assessment

A UNIQUE ADVANTAGE OF HTGR TECHNOLOGY IS ITS INHERENT SAFETY – NO RISK OF CORE MELTDOWN

The TRISO fuel, where the uranium dioxide is in the SiC coating, has been tested to ~1700°C. Even in case of failure of all safety systems and loss of coolant, the core cools down spontaneously because of radiation of heat and convection. This makes possible placing such a reactor in an immediate vicinity of industrial installations or even human settlements.

COSTS AND ECONOMIC ADVANTAGES OF HTGR

The costs of the steam of **540°C and 13.8 MPa** from various sources have been compared. Gas and coal fired boilers as well as 165 MW_{th} HTGR gas were assumed to produce 230 tons of steam per hour. The cost of designing and licensing of HTGR was estimated at PLN 500 million (~120 mln €), while the cost of building one HTGR was estimated at 2.0±0.6 billion PLN net (~480±140 mln €). The analysis was performed using different values of input parameters in order to take into account uncertainties related to the expected price of CO_2 emissions and interest rate. The analysis shows that with the **discount rate of 4%** and the price of **CO_2 emissions 20-50 €/t**, **the estimated levelized cost (LCOE) of steam from HTGR, averaged over the plant lifetime, is 36 PLN/GJ (~7 €/GJ). It turned out to be comparable to the cost of steam from a gas boiler amounting 36-42 PLN/GJ (~7-10 €/GJ).**

Investing PLN 500 million (~120 mln €) for the reactor project (after a positive result of the preconception study) in 2019-2023 would allow making decisions on investments in specific locations after 2023, when the economic conditions will be much better defined.

Making decisions on HTGR technology the following economic factors should be taken into account besides purely financial considerations:

- **reduction of dependency on gas import**
- **reduction CO2 emissions**
- **predictability of operating costs**
- **export potential**

TECHNOLOGY AVAILABILITY

Despite the existence of several research and commercial HTGR reactors - **there is no reactor design ready for multiplication on an industrial scale.** Competences and experience are scattered throughout the word as a result of completion of individual projects. **Existing knowledge is not protected by patents** and many studies are in the public domain**. A large part of the competencies scattered in the EU, USA, Japan and Korea were successfully collected in the Euratom Gemini + project coordinated by the NCBJ.** The key element of HTGR technology is the safe TRISO fuel. There are several production lines in the world where tested fuel may be bought from. Such fuel may be used for the first reactors in Poland before building domestic fuel factory.

BUSINESS MODEL

Currently, none of the big companies designing nuclear reactors (except China) declares their readiness to undertake the implementation of the HTGR project alone. **This creates the possibility of setting up a new company in Poland** - mentioned above HTR-EPC (from **engineering, procurement, construction**) - that would gather scattered competences and intellectual property. **The HTR-EPC should have a majority share of Polish capital** while foreign companies could participate as shareholders or subcontractors. The presence of Polish chemical and energy companies among the participants of the HTGR project would guarantee validity of the preconception study, and in the next stage, adaptation of the reactor design to the specific needs of the recipients.

RECOMMENDED SCHEDULE

- 2018: Agreement between the Ministry of Energy and Ministry of Science and Higher Education on the implementation of the HTGR program + a possible governmental program
- 2018: Establishment of HTR-EPC company + incorporation of foreign partners
- 10 MW_{th} experimental reactor:
    - 2018-20: design (PLN 150 million, ~36 mln €),
    - 2020-25: licensing and construction (PLN 600 million, ~143 mln €)
- 165 MW_{th} commercial reactor:
    - 2018: a preconception study (PLN 10 million, ~2.4 mln €)
    - 2019-23: designing (PLN 500 million, ~120 mln €)
    - 2023-26: preparation of the first HTGR construction (PLN 500 million, ~120 mln €)
    - 2026-31: construction of the first HTGR (PLN 1500 million, ~360 mln €)

INTRODUCTION

The Committee for the Analysis and Preparation of Conditions for the Deployment of High-Temperature Nuclear Reactors was established by the Regulation of the Minister of Energy of July 13, 2016. The Committee composed of the following members:

	Name	Affiliation	Status	Date of appointment / posting
1	Grzegorz Wrochna	NCBJ	Chairman	07.2016
2	Konrad Czerski	University of Szczecin	Member	07.2016
3	Sławomir Jankiewicz	ENEA S.A.	Member	05.2017
4	Sławomir Potempski	NCBJ	Member	07.2016
5	Mirosław Skowron	PeBeKa S.A. The KGHM Group	Member	05.2017
6	Mirosław Syta	Tauron Polska Energia S.A.	Member	03.2017
7	Marek Tarka	Prochem S.A.	Member	07.2016
8	Marcin Wasilewski	PKN ORLEN S.A.	Member	11.2016
9	Krzysztof Wilbik	Energoprojekt-Warsaw S.A.	Member	07.2016
10	Adam Żurek	Grupa Azoty S.A.	Member	10.2016
11	Kamil Adamczyk	DEJ ME	Member	07.2016
12	Andrzej Bacia	DEJ ME	Secretary	01.2017
13	Marcin Dąbrowski	PAA	Observer	08.2016
14	Zuzanna Nowak	NCBJ	Observer	08.2016
15	Piotr Galas	PKO BP	Observer	09.2016
16	Krystian Strabanik	PKO BP	Observer	09.2016
17	Małgorzata Świderska	NCBR	Observer	08.2016 - 04.2017
18	Robert Czarnecki	NCBR	Observer	04.2017

Table 1. Members and observers of the HTR Committee.

In line with the tasks entrusted by the Minister of Energy, **the Committee focused its efforts on analytical work** consisting of gathering available knowledge on **High Temperature Reactors** (HTR), processing this information and drawing conclusions regarding the possibilities of implementing HTGR for the needs of the Polish economy.

This report summarizes the results of the twelve months of the Committee's work from July 2016 to June 2017. **In the Committee's opinion, the results presented in this report provide the basis for the Minister of Energy's directional decision regarding the HTGR implementation process in Poland.** The text of the report is supplemented by internal reports of the committee describing the various elements of the analysis, including a lot of lists of studies (available directly or after obtaining the consent of the authors) regarding HTGR technology and its potential applications.

1. THE NEEDS OF POLISH AND EUROPEAN ECONOMY

1.1. CONSUMPTION OF INDUSTRIAL HEAT IN POLAND AND EUROPE

The data described below present the results of European projects EUROPAIRS and NC2I-R, the Polish HTR-PL project as well as data obtained as part of the committee's work. They do not constitute comprehensive information on industrial heat consumption in Poland or in Europe. Most of all, they concern the possibility of using a nuclear reactor as a heat source in industry.

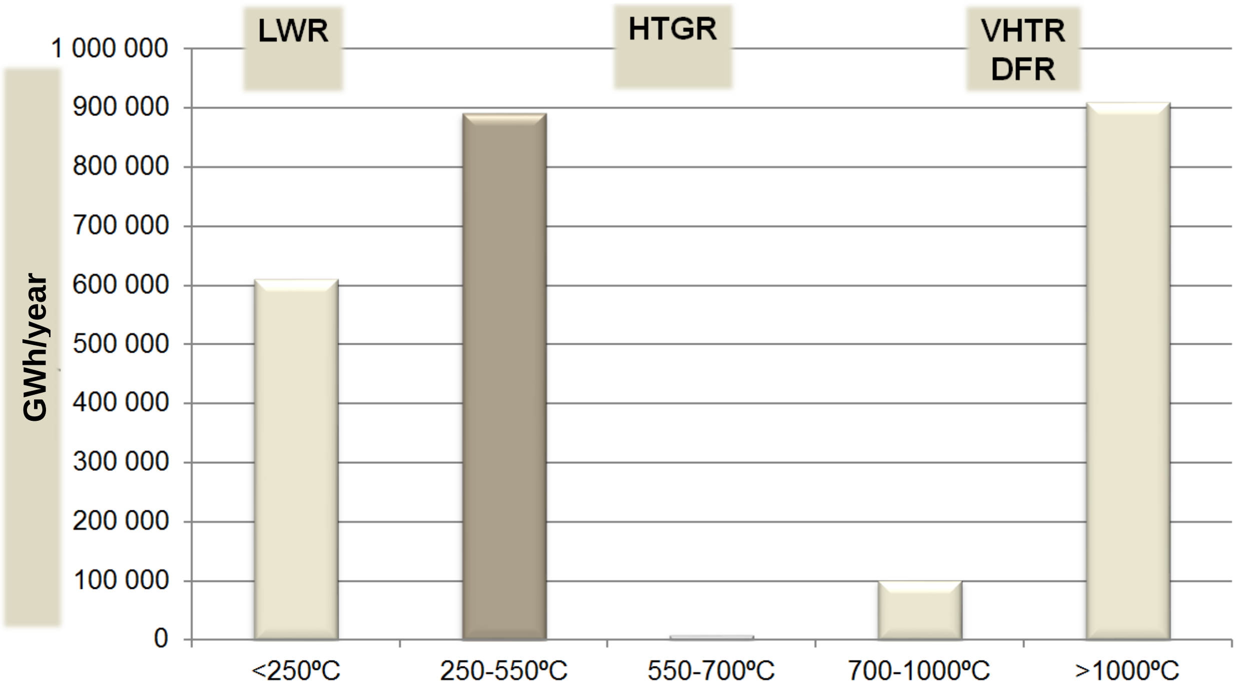

Figure 1. The demand of the European industry for process heat (source - EUROPAIRS). Adequate reactor technologies have been marked.

The heat demand in Europe is in the range of 600-900 GWh / year in temperature ranges: up to 250°C, 250-550°C and above 1000°C, with a small share between 550°C and 1000°C.

The lowest temperature range is used worldwide in the paper industry, heating industry or for desalination of seawater. It can be covered by light-water reactors (LWR). However, industrial installations using such temperatures in Poland are generally small and dispersed, which makes it difficult to use nuclear reactors. The heating sector (heating) has significant potential, which in several countries uses waste heat from large energy reactors. The source of urban heat could be PWR type SMR reactors, which are developed in several countries. However, HTGR-type reactors could be built closer to human settlements because of their inherent safety features.

The highest range, above 1000°C, has a great future due to the production of hydrogen and hydrogen-based fuels, but currently there is no proven nuclear technology in this area. The main challenge is the resistance of materials to simultaneously high radiation and high temperatures. There are no commercial nuclear reactors capable of producing process steam at such high temperatures while maintaining material strength. However, many countries are researching in this direction, considering different reactor technologies that can meet industrial requirements.

In the middle range, steam with a temperature close to 500°C is a standard heat carrier in many large industrial plants, mainly chemicals. The use of nuclear reactors would be made easier by replacing outdated gas or coal boilers with the existing installations, including turbine sets producing electricity for the needs of the plants.

In total, 132 plants or industrial groups were located in Europe that could use nuclear technology in the middle, still achievable, temperature range of 250-550°C. 92 of them were located in Western Europe, 40 in Eastern and Central Europe, including 15 in Poland.

Table 2 presents data on 13 largest Polish industrial heat recipients. The total power of steam boilers installed there is almost 6,500 MW. The energy companies and KGHM Polska Miedź S.A. are also potential users of nuclear cogeneration.

	Plants with the highest installed capacity	Boilers	MW_{th}
1.	PKN Orlen	8	2140
2.	Zakłady Azotowe Puławy S.A.	5	855
3.	Anwil S.A. / ORLEN Group	3	580
4.	ZCH Police S.A.	3	356
5.	Kwidzyn Sp. z o.o. International Paper	6	531
6.	Grupa LOTOS	4	518
7.	Zakłady Azotowe w Tarnowie-Mościcach S.A.	4	630
8.	Zakłady Azotowe Kędzierzyn S.A.	5	395
9.	PCC Rokita	3	160
10.	Rafineria Trzebinia S.A.	4	88
11.	Lotos Czechowice S.A.- LOTOS GROUP	3	89
12.	Lotos Jasło S.A. - LOTOS GROUP	3	74
13.	Rafineria Nafty Jedlicze S.A. - Orlen Group	6	64
	TOTAL	57	6480

Table 2. The largest Polish heat users in the 250-550°C range (data for 2015).

1.2. HEAT RECIPIENTS ON THE EXAMPLE OF GRUPA AZOTY S.A.

Grupa Azoty S.A. consists of dozens of financially linked business entities. Four industrial complexes are dominant:

- Zakłady Azotowe w Tarnowie-Mościcach S.A. (products: saltpetre, caprolactam, polyamide, ammonium sulphate, etc.).
- Zakłady Azotowe “Puławy” S.A. (products: urea, saltpetre, melamine, polyamide, hydrogen peroxide, ammonium sulphate, etc.)
- Zakłady Azotowe Kędzierzyn S.A. (products: urea, saltpeter, oxo alcohols, plasticizers, etc.)
- Zakłady Chemiczne Police S.A. (products: urea, NPK fertilizers, titanium white, etc.)

In all these locations, the chemical complexes are accompanied by energy. It satisfies the entire thermal needs of the plants and, to a large extent, the demand for electricity. It works in cogeneration, producing both technological steam with different pressures, hot water for technological and heating purposes as well as electricity. Energy in the form of heat is also sold to external customers, mainly as central heating. The sale of electricity is marginal.

The basic energy and chemical raw material consumed directly in the technological processes is natural gas (over 2 billion m^3 per year). However as far as energy in individual plants is concerned, the main fuel is hard coal with a consumption of 1.3 million tons per year. The specificity of energy in the Group is the need to adapt to the changing loads of both - seasonal and resulting from the changing load on the part of technology, in short periods of time - often counted in minutes. This forces the necessity to use several units in each location, so that it is possible to work in a wide range of possible technological spectrum of loads. **The dominating units, typically, are steam boilers with thermal powers below 200 MW_{th}, producing steam with temperatures of 510-540°C.**

2. SELECTION OF REACTOR TECHNOLOGY AND PARAMETERS

2.1. COMPARISON OF DIFFERENT TECHNOLOGIES

Nuclear reactors are increasingly used not only in the production of electricity, but also in the production of heat and have the potential for further development in this respect. In the field of electricity production, the global market is dominated by large (~ 1000 MW_e) light water reactors (LWR). The heat that is a by-product of reactions in LWR's is used for heating cities, desalination of sea water and chemical production. However, as Figure 1 shows, low-temperature LWR cogeneration can only respond to part of the industry's demand. For industries such as chemical, metallurgical, etc., higher temperatures are necessary, which indicates the need of employing other reactor technologies.

The widest international initiative supporting the development of new reactor technologies is GIF - Generation IV International Forum (www.gen-4.org) gathering EU countries and 13 non-EU countries. As part of its work, GIF has chosen six most promising technologies for further research:

	REACTOR TECHNOLOGY SELECTED BY GIF
SFR	***Sodium-cooled Fast Reactor*** sodium-cooled fast reactor
LFR	***Lead-cooled Fast Reactor*** lead-cooled fast reactor
GFR	***Gas-cooled Fast Reactor*** gas cooled fast reactor
MSR	***Molten Salt Reactor*** in MSFR (Fast) and MSThR (Thermal) variants molten salt reactor, fast and thermal
SCWR	***Supercritical Water-cooled Reactor*** supercritical water-cooled reactor
VHTG / HTGR	***Very High Temperature Reactor*** cooled with gas at a temperature above 1000°C is an extension of **HTGR - High Temperature Gas-cooled Reactor** (500-1000°C).

One of the variants of the concept of MSR is the so-called DFR (Dual Fluid Reactor) reactor. This concept is described in the dedicated internal report of the Committee - "Characteristics of the DFR reactor and research plans".

These reactors are classified as so-called fourth generation. It should be noted that this name may be somewhat misleading, as the task of the fourth generation is not to replace the third one, but to supplement it in new areas of application. In particular, fast reactors allow the reuse of fuel burned in third-generation reactors after its appropriate processing. Their use will allow using uranium and reducing waste better.

In Europe, the development of nuclear reactors is supported by the SNETP - Sustainable Nuclear Energy Technology Platform (www.snetp.eu). It brings together dozens of industrial partners, research organizations and other entities involved in nuclear energy. It is the official advisory body of the European Commission as part of the SET-Plan (Strategic Energy Technology Plan). SNETP's work is organized in three pillars:

- **NUGENIA** – generation 2, 3 and 3+ reactors
- **ESNII** – fast reactors SFR, LFR and GFR
- **NC2I** (Nuclear Cogeneration Industrial Initiative) – use of reactors for combined heat and electricity production and other applications.

For its own projects, NC2I selected HTGR technology (High Temperature Gas-cooled Reactor) as the most promising one. On the one hand, the inherent safety features of this reactor (described below) make it possible to place it directly close to industrial installations. On the other hand, the technology's maturity - seen in a dozen research and commercial reactors built so far - allows us to expect large-scale deployment already at the beginning of the 2030s. This was reflected in the SNETP Deployment Strategy [6] published a year ago, which provides for the launch of the first of the series (FOAK - the first of a kind) HTGR around 2030.

Experts appointed by the OECD Nuclear Energy Agency to develop a "road map" titled "Nuclear Innovations 2050"[7] also came to a conclusion that HTGR technology is the most auspicious one. In the diagram below, HTGR is presented as one of the SMR (Small Modular Reactors or Small & Medium Size Reactors) types expected to be implemented around 2030.

At the end of 2017, **the International Atomic Energy Agency IAEA** also published the "Industrial Applications of Nuclear Energy" document[8], where it devotes a lot of space to HTGR reactors, in particular to their use in the production of industrial heat.

[6] SNETP „Deployment Strategy", 2015, www.snetp.eu/publications

[7] OECD NEA „Nuclear Innovations 2050", www.oecd-nea.org/ndd/ni2050

[8] "Industrial Applications of Nuclear Energy", IAEA Nuclear Energy Series No. NP-T-4.3, 2017.

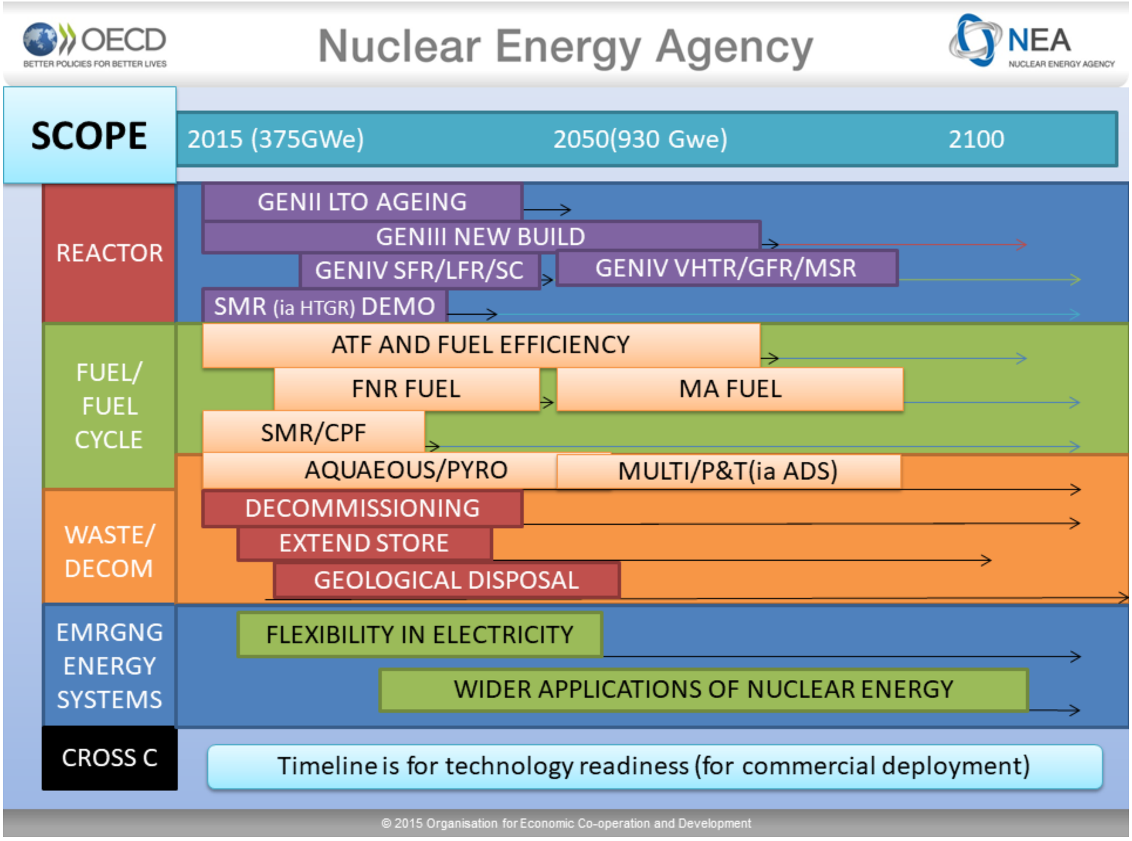

Figure 2. HTGR on the road map of the OECD Nuclear Energy Agency - Nuclear Innovation 2050
The designations of SFR, LFR, VHTR, GFR, and MSR reactor technologies are given on page 12.

The UK government has also initiated a review of the various SMR technologies that could be used in this country. At the end of 2015, the "Techno-Economic Assessment" (TEA) of available technologies was launched, and in 2016 the British government announced a competition for the SMR (UK SMR competition) reactor project, allocating GBP 250 million for the development of selected technologies. The official results of TEA[9] were published only after completion of the work of our Committee, but several centers involved in the evaluation had previously published their own studies. Two of them, presented at the UK SMR Summit conference in October 2016, are presented below.

In both studies, **light-water reactors** (LWR)**, in particular, low-pressure** (PWR) **reactors are perceived as SMR's closest to implementation. However, right behind them are HTGRs, which gain an advantage in industrial applications.**

[9] "Small Modular Reactors: Techno-Economic Assessment", 2017.
www.gov.uk/government/publications/small-modular-reactors-techno-economic-assessment

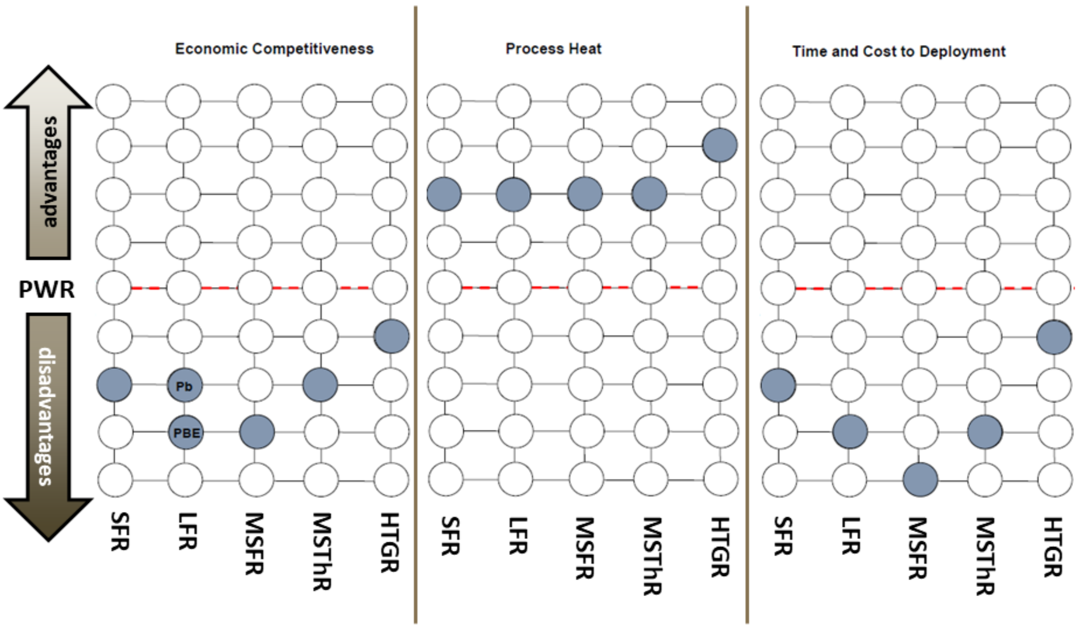

Figure 3. Comparison of available nuclear technologies (according to Gregg Butler, Manchester University).The individual features are compared with the reference PWR reactor. (The abbreviations are described on page 12)

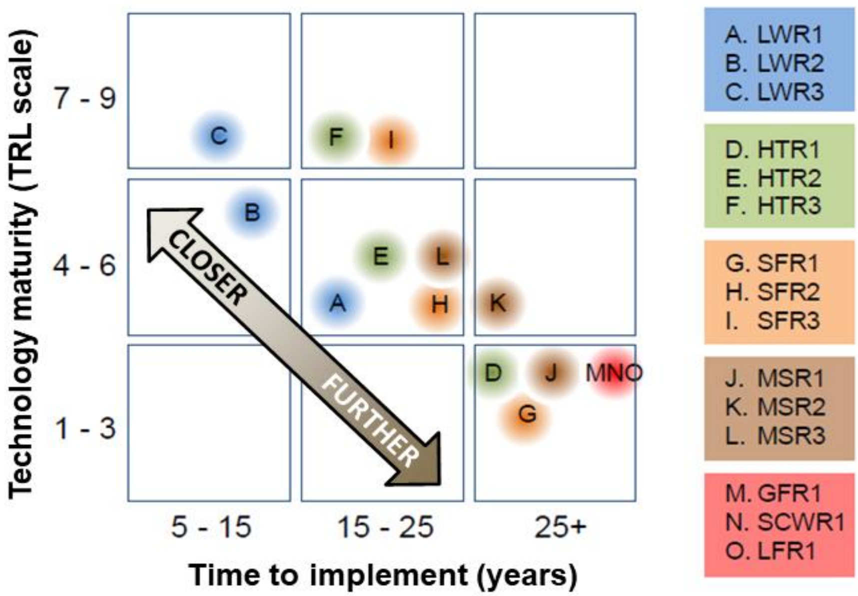

Figure 4. Comparison of available nuclear technologies (Andrew H. Sherry, National Nuclear Laboratory). Examples of projects proposed for Great Britain are illustrated.

2.2. SELECTION OF A REACTOR FOR POLISH INDUSTRY

The above-mentioned superiority of HTGR technology, especially in the 250-550°C range, is mainly due to the following features:

- **inherent safety (inability to melt the core)**
- **technology maturity (several HTGRs already built)**
- possibility of obtaining high temperatures (tested to 950°C and possible over 1000°C)
- ease of handling spent fuel

These features are presented and justified in chapters 2.4, 0 and 4.

The first application of HTGR in the Polish industry may be used for the production of steam at a temperature of 550°C. Due to the advancement of technology, such a reactor could be connected (in time) to existing chemical installations instead of outdated (coal or gas) boilers. Remarkably, there is no need to modify the installation itself. What's more, **HTGR is an inherently safe technology,** which makes it possible to place such a reactor in the immediate vicinity of other installations at the industrial plant, which limits the loss of heat during its transmission. At the same time, some part of the reactor's power could be used to produce electricity for the plant's needs, similarly to the existing boilers.

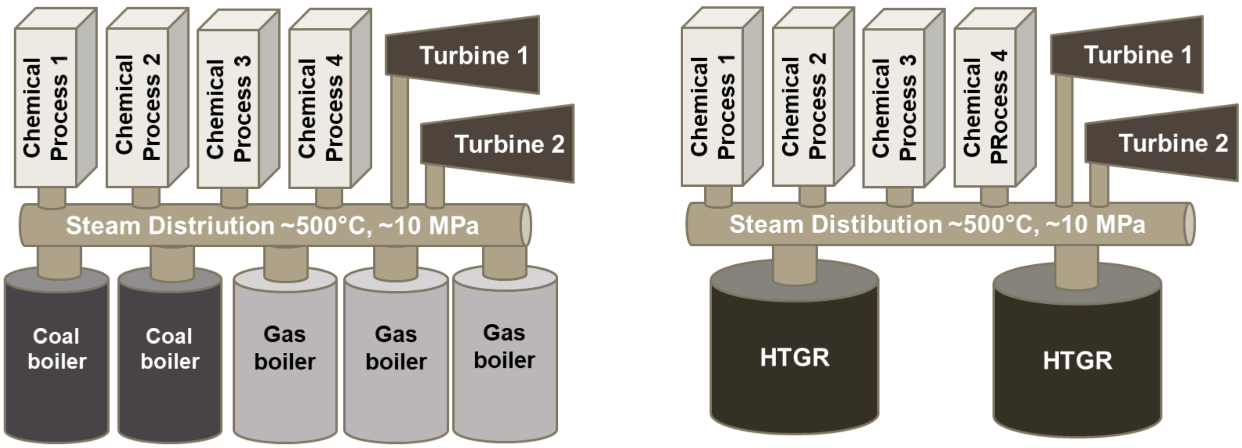

Figure 5. Replacement of coal or gas boilers with HTGR reactor.

For further analysis, the main parameters of the HTGR reactor were chosen so that it could replace one of the standard boilers used in the industry: OG-230 gas fired, OP-230 pulverized coal fired or OFz-230 fluidized bed coal fired. The parameters of such a reactor are collected in Table 3.

PARAMETER	VALUE
Nuclear thermal power	165 MW_{th}
The core temperature at the outlet	750°C
Inlet temperature core	250°C – 450°C
Maximum steam temperature	570°C
Steam pressure	17 MPa
Steam performance	230 t/h

Table 3. The main parameters of the HTGR reactor.

Another application of HTGR reactors may be **replacement of long-serving power units (with a capacity of around 200 MW_e) in the future**. There are 52 such units in Poland, most of which are already outdated. The renovation program that is currently being prepared will allow extending their usage for another 15-20 years. It is hoped that the earlier application of HTGR in the chemical industry will allow optimizing the production of these reactors so much that in the case of high gas prices and CO_2 costs, they will become competitive.

2.3. HTGR IN THE WORLD

The most advanced country in the implementation of HTGR technology is China. Next to Shidaowan, in the Chinese province of Shandong, a power plant with twin HTR-PM reactors - 250 MW_{th} each - is being built. Mentioned twin HTR-PM reactors will supply one 210 MW_e steam turbine. Construction began at the end of 2012 and the launch of the plant is scheduled for the end of 2018.

The preliminary feasibility study at the beginning of 2015 was followed by the construction of two HTGR reactors - each with a capacity of 600 MW_e - in the city of Ruijin, in the Chinese province of Jiangxi. It is expected that the construction of reactors in Ruijin will begin next year and their connection to the grid will take place in 2021.

China Nuclear Engineering Corporation (CNEC) has signed a contract with the National Atomic Energy Agency in Indonesia (Batan) to jointly develop an HTGR reactor in **Indonesia**. Before the introduction of large HTGR reactors Batan is considering, the construction of an experimental reactor with a capacity of 3-10 MW_e, and a thermal power of 10-30 MW_{th}.

In addition to Indonesia, CNEC has partnered **with Saudi Arabia** and **South Africa** to promote its HTGR technology. In South Africa, work was carried out on a high-temperature reactor called PBMR (Pebble Bed Modular Reactor). In 2010, they were discontinued despite the high level of advancement.

In the **US**, HTGR technology is being developed, among others, by:

- New Generation Nuclear Plant (NGNP) based on the US AREVA concept called ANTARES (A New Technology Advanced Reactor Energy System),
- *Steam Cycle High-Temperature Gas-Cooled Reactor* (SC-HTGR) with a capacity of 625 MW_{th}
- X-energy – Xe-100 reactor with a capacity of 125 MW_{th} and approx. 50 MW_e, which received in January 2015 $ 40 million support from DOE (*Department of Energy*).

In **Japan**, for a dozen or so years, until the Fukushima disaster, a HTTR (High-Temperature Test Reactor) test reactor was in operation with a capacity of 30 MW_{th} (it is currently turned off). Japan and **South Korea** are considering the development of technology towards higher temperatures that allow the production of hydrogen and hydrogen-based fuels.

The UK is considering HTGR as one of the technologies of small and medium sized reactors (so-called SMR), which it would like to invest in. One of them may be U-Battery HTGR with a capacity of 10 MW_{th} or 4 MW_e.

2.4. CHARACTERISTICS OF HTGR

HTGR is a high-temperature gas-cooled reactor, where the moderator is graphite, and the coolant is gas - usually helium. The fuel is TRISO - small balls with fissile material (in addition to uranium, there may be admixture by the thorium) with a silicon carbide or zirconium carbide shield.

TRISO FUEL CHARACTERIZES HIGH RESISTANCE TO CORE MELTDOWN

It was tested that raising the temperature up to 1700°C does not release radioactive substances from the TRISO fuel. These fuel features constitute the inherent safety of HTGR. Because in HTGR with a capacity less than 600 MW_{th}, such temperature cannot be reached - there is no risk of melting the core.

This makes it possible to place the reactor in the immediate vicinity of industrial installations or human settlements. Even in the event of failure of all systems and loss of coolant, the core cools spontaneously because of the radiation of heat and convection.

This was confirmed by calculations and simulations, as well as an experiment carried out on the Japanese HTTR reactor. During operation with a 30% of the nominal power, the cooling system and control rods were turned off. The reactor cooled down spontaneously, as predicted. Tests are planned at full reactor power.

There are two basic types of HTGR reactors:

- Reactor **with a ball bed**, "pebble bed" – small balls with fuel are dispersed in a graphite matrix, from which larger spheres are formed - these are placed on top of the stack forming the core, they are picked up at the bottom and directed to the top of the stack or treated as waste depending on the degree of a burn-out. Helium is being pumped through this bed. The main advantages of HTGR with a ball bed are the ability to work without interruptions for fuel reloading and simplicity of construction. The disadvantage is the possibility of graphite dust when the balls move.
- Reactor **with prismatic core** – fuel particles are dispersed in a graphite matrix in the form of cylinders, which are placed in openings in large hexagonal graphite blocks, thus forming a core. The blocks contain vertical channels through which helium flows. The main advantage of this type of reactor is easier predictability of the immobile fuel operation parameters. The disadvantage is the need to shut down the reactor to replace the fuel.

Another advantage of TRISO fuel is safety of storage after firing. The SiC coating (ZrC) protects against the release of radioactive substances even in harsh environmental conditions.

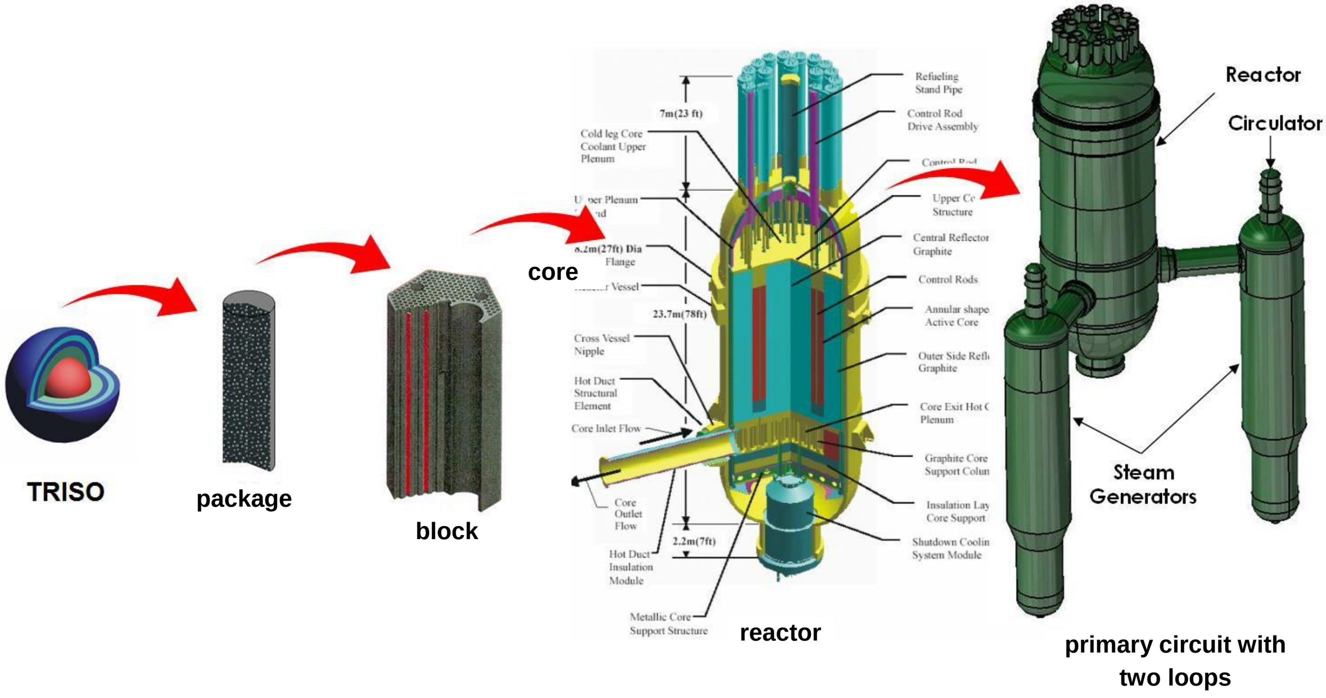

Figure 6. HTGR prismatic reactor model.

2.5. HTGR FUEL CYCLE

The TRISO fuel used in HTGR is relatively comfortable after burn-out because of its unique features:

- **Storage of burn-out fuel from HTGR reactors has already been implemented in several countries, where research and commercial reactors of this type have been operating. There were no serious, unexpected technological problems.**
- The PyC and SiC coating is a very durable and corrosion-resistant barrier that retains radioactive substances, which reduces the need for additional barriers.
- Low energy density means that passive air cooling is enough to drain energy.
- High burn-up results in the efficient use of uranium and the plutonium which is generated in the reactor.
- The isotopic composition of the spent burn-out fuel is a small proliferative risk.

These features make it possible to successfully use the methods developed for storing medium-active radioactive waste for storing burn-out HTGR fuel.

For example, the decay heat of the THTR 750 MW_{th} reactor, which worked in 1983-1988, was less than 20 kW and was removed by radiation and natural convection. All spent fuel from the AVR 46 MW_{th} reactor, which worked in 1967-1988, was releasing heat below 15 kW. After 1-2 years, the spent fuel left the reactor building and went to the intermediate storage, where it was cooled by convection. Similarly, in the Japanese HTTR research reactor, the spent fuel is stored in the reactor building.

The biggest challenge so far associated with the HTGR fuel cycle was the utilization of spent fuel from the American commercial reactor at Fort St. Vrain with a capacity of 842 MW_{th}, operated in 1977-1992. All of the fuel was first transported successively to the Idaho National Laboratory and then placed in a warehouse near Platteville, 65 km from Denver. 130 m^3 of fuel was placed in a concrete building with dimensions of 44 × 22 × 25 m. The fuel is cooled by natural air circulation.

It is planned to transport the fuel to the destination long-term storage, when it will be launched in the USA.

Attempts to develop a method for crushing TRISO particles and recovering uranium or thorium were undertaken by the Oak Ridge National Laboratory in the USA, Forschungszentrum Jülich GmbH in Germany, CEA in France and JAEA in Japan. Jaw and hammer crushers, ball mills, etc. were tested. The results obtained were not very satisfactory due to the high mechanical resistance of SiC coatings. This confirmed that TRISO fuel is very safe from the point of view of preventing the proliferation of nuclear materials.

So far, the most effective method of TRISO fuel processing has been developed by the Japanese JAEA. However, with today's relatively low uranium prices, it is unprofitable to recover it from TRISO fuel. **Both technical and economic arguments clearly speak in favor of choosing the storage option of the spent TRISO fuel without modification.**

It is anticipated that ultimately, the spent HTGR fuel will be treated as intermediate waste and stored in geological repositories.

3. ECONOMIC PROFITABILITY OF HTGR

3.1. CONSTRUCTION AND OPERATION COSTS OF THE HTGR 165 MW_{th} REACTOR

The cost estimation for the use of the HTGR reactor for the process heat generation was made on the basis of data provided by:

- NGNP – „New Generation Nuclear Plant" Industrial Alliance: www.ngnpalliance.org
- "HTR600" - undisclosed source
- NC2I-R: www.nc2i.eu
- X-energy: www.x-energy.com

The calculation details are given in the NCBJ report[10]. The following are the key assumptions and results:

A. It is assumed to be **another reactor in the series (NOAK – *Next Of a Kind*)**.

B. **Steam and heat output parameters:**

Production capacity: 230 tons of stream per hour, steam temperature 540°C, steam pressure 13.8 MPa. This translates into reactor power of 165 MW_{th}. The parameters are approximate as they were used with the ready-to-go conceptual projects of HTGR. While implementing the final project, it is possible to technically adjust the parameters by selecting the appropriate loading nuclear fuel (influenced by reactor power) as well as the design of the steam generator and adjusting the working pressure (influence on parameters and steam stream).

C. It is assumed that the **cogeneration takes place through the collector** rather than directly in the reactor system. The cost calculation does not include turbine and steam distribution system, regeneration exchangers, pumps, etc. but includes the cost of the so-called "Nuclear Island" only. Nuclear Island is the reactor and its auxiliary systems and steam generator (helium-water). Generally, potential recipients may not only already have steam distribution systems but also turbines for electricity production. We accept that water (condensation) goes to the generator under the appropriate pressure from a fuel-powered pipeline. The water refill system shall be taken into account.

D. Assumed **helium temperature** at the outlet of reactor (ROT) **= 750°C**

All the estimations were made on the basis of advanced conceptual design by summing up the cost of components (a few hundred per a reactor) and their installation. Methodology that was used was developed by the ECONOMIC modelling working Group of the Generation IV International Forum11. Since the available projects had different powers, it was necessary to rescale to the target HTGR 165 MW_{th}. The scale was made in contact with / together with the project authors and the level of different cost categories. Only X-energy Company has provided a project optimized for 165 MW_{th}.

[10] *Technologia i oszacowanie kosztów źródła pary technologicznej z wysokotemperaturowym reaktorem chłodzonym gazem* (HTGR), NCBJ 2017.

[11] Cost estimating guidelines for generation 4 Nuclear Energy Systems, GIF/EMWG/2007/004.

The calculation details are given in the NCBJ report cited above, and the final result in table 4.

Items	HTR600	NC2I-R	NGNP	X-energy
Technology	Block	Block	Block	Ball
Original design				
Prices per year	2016	2014	2015	2016
Power	600 MW	2x250 MW	350 MW	165 MW
Cost	1357 M€	1010 M€	611 M$	388 M$
Designs scaled to 165 MW				
Items	HTR600	NCBJ	NCBJ	X-energy
Cost	2566 M PLN	1995 M PLN	1519 M PLN	1358 M PLN

Table 4. Comparison of costs (overnight, excl. VAT) construction of HTGR. Preparatory costs (500 million PLN) were taken into account. Design costs (included in the economic analysis) were not included. Assumed 1 $ = 3,5 PLN, 1 € = 4,2 PLN.

Unfortunately, it is hard to get reliable data on the cost of China-built reactors HTR-PM. Only comparative information is available, indicating that the unit cost of HTR-PM is 15% higher than the typical LWR reactor while the cost of the nuclear part is 55% of the total. The cost of the LWR power plant in China, according to the OECD, is from 1.8 to 2.6 million $/$MW_e$, i.e. PLN 22-31 million / MW_{th}. This gives about PLN 2.0-2.8 billion for HTGR 165 MW_{th} which doesn't contradict the data in table 4, especially since HTR-PM are prototype reactors.

The total cost of construction (overnight construction cost) includes the preparatory costs of 500 million PLN, which consist of the cost of preparing the site, licensing, obtaining other consents, etc. It also includes PLN 50 million as 1/10 cost of the reactor design of PLN 500 million, assuming that the cost of design is distributed among the first 10 reactors. The design cost does not include the design of the electrical part (since it already exists with the customer), the fuel factory design and the licensing cost (it's included in the construction costs).

Costs that were obtained were diverse – from 1.4 to 2.6 billion – which could indicate a high uncertainty of assessment. However, it must be noted that the higher is the original reactor power is the higher the costs are. This is understandable, because each of the projects was optimized for a different nominal power. Reducing the power of the reactor crosses various technological barriers and allows nonlinear cost reduction. E.g. above 200 MW_{th}, the reactor vessel must be made in parts that are combined on the construction site. However smaller reactor vessel, which would be 4-4.5 m in diameter, could be made in its entirety by the rolling method and transported to the site. In this scenario, a large part of the tank's instrumentation could be installed in the factory, shortening the installation time on construction site and thus reducing the costs.

Before finalizing the conceptual design it is hard to assume whether or not a reactor with a power of 165 MW_{th} satisfies this condition. If not, a set of 2 × 83 MW_{th} should be considered.

On the basis of above data it is possible to conclude that the cost of PLN 1.4 billion estimated for the reactor optimized at 165 MW_{th} should be the closest to reality. Although it is a pebble bed reactor and therefore of a different design than others, there is no expectation of a cost difference between a pebble bed reactor and a prismatic block one that is greater than 10%. A medium value of 2 billion PLN was, however, adopted, considering the dispersion of 0.6 billion PLN **a measure of uncertainty.**

3.2. SIMPLIFIED CALCULATION OF THE COST OF INDUSTRIAL HEAT AND INVESTMENT PROFITABILITY

The Committee compared the cost of producing steam of 540°C and 13.8 MPa with gas-fired, coal-fired and HTGR boilers with a power of 165 MW and a capacity of 230 t/h.

In addition, the following assumptions were made:

- Include 10% of the cost of design and general licensing of 500 million PLN which will mostly be distributed between the first 10 reactors.
- Assume 15 days per a year for fuel reloading and for inspections. 80% of the energy effectively used over the rest of the time due to the variable steam demand of the plant.
- One HTGR at a given location. Two or more HTGR per site would give better results, because of having many common elements.
- Lifetime of HTGR is 60 years, and coal and gas boilers 30 years, which require their exchange in the middle of the analyzed period.
- Price of fossil fuels and steam price at the current level.
- Lack of support from public funds

The following cost values were obtained:

	OCC [million PLN]	OPEX [million PLN]	
Price of CO_2 emission allowances [€/Mg]		20	50
Pulverized coal boiler OP-230	275	118	174
Fluidized bed coal boiler OFz-230	370	119	174
Gas boiler OG-230	166	184	215
HTGR 165 MW_{th}	1903	99	

Table 5. Investment costs. OCC (overnight construction cost) - total cost of construction, excl. VAT. OPEX – Annual cost of operation

To compare economic viability, three variables were selected:

- **Balanced unit cost (LCOE) of steam production in PLN/GJ**
- **Financial net current value (F-NPV) in PLN million**
- **Economic Current net value (E-NPV) in PLN million**

	LCOE [PLN/GJ]				F-NPV [million PLN]				E-NPV [million PLN]			
Discount rate	8%		4%		8%		4%		8%		4%	
Price of CO_2 emission allowances [€/Mg]	20	50	20	50	20	50	20	50	20	50	30	50
Pulverized coal boiler OP-230	27	37	25	35	412	158	1 371	619	163	-91	633	-119
Fluidized bed coal OFz-230	29	39	26	36	368	120	1 292	555	56	-193	364	-373
Gas Boiler OG-230	37	43	36	42	159	20	561	144	144	4	515	98
HTGR 165 MW_{th}	55		36		-268		538		-268		538	
HTGR 165 MW_{th} Construction 8 years	64		38		-494		387		-494		387	
HTGR 165 MW_{th} outlay + 50%	84		48		-966		-276		-966		-276	

Table 6. Economic parameters of coal, gas and HTGR boilers.

The biggest uncertainties for coal and gas technologies are the CO_2 and fuel prices, respectively. For nuclear technology, the highest risk is the investment costs, technology risk, duration of construction and cost of money over time. These uncertainties cause that the investment decisions would be based more on risk analysis than purely numerical economic comparison. However, as the discount rate will be known at the time of starting the investment, HTGR gives the best stability of the operating costs forecast. It speaks in favor of this technology, when the steam price and F-NPV of various technologies are comparable. An E-NPV, that includes external costs, provides an additional preference for HTGR.

For the purposes of this report, two discount rate values were adopted: 8% and 4%. The first one is the minimum value that is currently used for large investments by industry in Poland. The second one is the value possible to obtained on the Polish financial market today. Two values for the CO_2 emission allowances were also adopted: €20 and €50/ton. The value of €50 is the price anticipated by the European Commission. The expected lower limit of the CO_2 emission allowance price is €20. The adoption of extreme advantageous and unfavorable variants determines the "playing field" - an area of indicators within which the HTGR project will be implemented with high probability.

The analysis shows that **at the discount rate 4% of the steam cost (LCOE) from HTGR is comparable to the cost of steam from a gas boiler** and slightly higher than from a coal boiler. At a discount rate of 8%, the financial profitability (F-NPV ≥ 0) of the investment can be achieved with the amount of PLN 650 million invested. Since the grant can be difficult to accept by both - he public opinion and the European Commission, the preferred option is to make possible a discount rate of 4% by minimizing the risk with such solutions as: provision of heat and electricity (model Mancala, as referred to in Chapter 7.1), or government loan guarantees, etc.

Mobilizing PLN 500 million for the reactor project (after the positive outcome of the preconception study) in the years 2017-2022 would allow to make investment decisions in specific locations after 2022, when economic conditions would be known much better.

Today, making decision on launching projects on HTGR technology, one should take into account not only numerical economic indicators but also other important economic factors. HTGR Technology can offer:

- Reduction of dependency of Poland on gas import from one external supplier by reducing the demand to the level available through own mining, the Nordic Pipeline and LNG terminal;
- Reduction of CO_2 emissions, increasing the pool of allowances available for coal
- To provide the national industry with a foreseeable cost of heat, which is resistant to changes in fuel prices and prices for CO_2 emission allowances;
- Launch of production of HTGR reactors with high export potential.

4. MATURITY AND AVAILABILITY OF HTGR TECHNOLOGY

4.1. EXPERIENCE IN THE CONSTRUCTION AND OPERATION OF HTGR

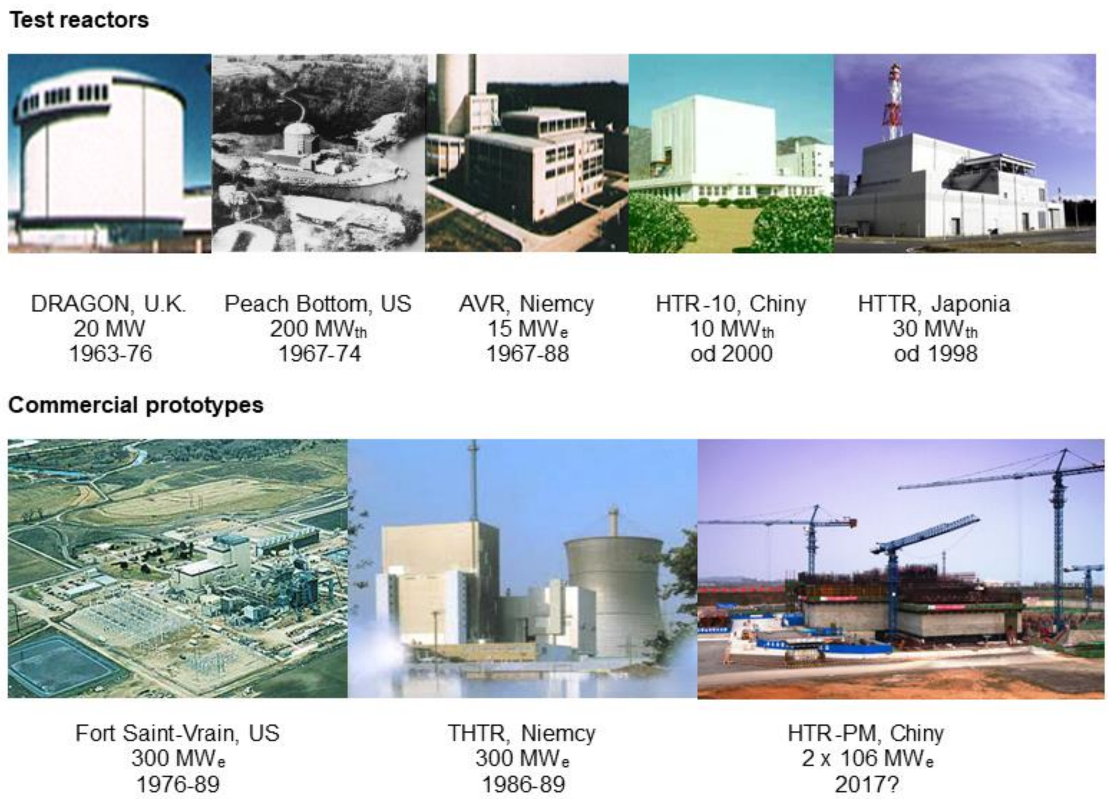

Figure 7. Realized projects of research and commercial HTGR.

HTGR technology was developed in the 1960s and has been systematically improved. The above chart shows the research and commercial reactors that were built in different parts of the world.

The commercial reactor at Fort Saint-Vrain was in operation for 13 years. Unfortunately, the THTR reactor in Germany has been closed after 2 years. Quite elementary structural errors of the THTR reactor did not cause the release of radioactive substances, but frequent reactor downtime undermined its economic viability.

The stagnation of the nuclear industry caused by the negative atmosphere surrounding nuclear power in 90s – hindered the development of HTGR technology. **The nuclear industry was unable to risk financing of the project**. On the other hand, **potential users were afraid to take the risk of investing in a reactor project before checking the prototype**. This vicious circle was broken in China and after the successful tests of research reactor HTR-10 construction of two reactors HTR-PM with a power of 250 MW_{th} begun. They are going to supply a turbine set with a power of 210 MW_e. Currently the construction is coming to an end and the reactors will be in operation probably in 2018.

4.2. AVAILABILITY OF TRISO FUEL

The key and most technologically advanced element of the HTGR reactor is TRISO fuel. It was invented more than 25 years ago and all of the related patents have expired.

Existing production lines are listed below.

- BWXT in the **USA** – Compact fuel, extensively tested in terms of irradiation; the ball fuel is currently tested under the X-energy contract funded by the DOE. The efficiency of the BWXT production line should suffice for the experimental reactor, but not for commercial use.
- NFI in **Japan** – compact fuel for an existing in HTTR reactor.
- Esko in **South Africa**, Pelindaba – the pebble fuel factory for the PBMR reactor, whose construction was discontinued; Factory restart is being considered.
- **Russia** – gained rights from German company NUKEM, but the pebble fuel production line was sold to China.
- **China** – the pebble fuel production line of NUKEM for the HTR-10 reactor; Start new line for reactors HTR-PM; Fuel tests on completion. Today, it is the only TRISO-enabled production line with sufficient capacity for industrial reactors.
- CEA in **France** – production on a laboratory scale, fuel tested mechanically, but without irradiation.

It should be added that there are no essential obstacles for production of TRISO fuel in Poland. In particular, there are no license restrictions on the purchase of the production line.

4.3. INTELLECTUAL PROPERTY OF HTGR TECHNOLOGY

HTGR technology is no longer protected by patents; however there is a lot of knowledge protected by intellectual property rights in many places around the world. There are several ready-made projects for licensing. Only the HTR-PM Chinese reactor passed the full license procedure.

The HTR-GmbH Gesellschaft für Hochtemperaturreaktoren in Mannheim is a European company owned by AREVA-G (50%) and Westinghouse (50%). The company has a rich archive of projects with different powers and extensive documentation which is useful for licensing. One of the projects was sold (not exclusive) to ESKOM in South Africa.

Though many studies have been created **in Europe** such as graphite, structural materials, various components, analysis, licensing, construction, and even decommissioning of HTGR reactors they are scattered between small businesses, such as "hot gas duct" at Becker Technologies. Some of them are still recoverable, but it may not be in the future. Some others probably has already been lost, like e.g. SULZER Steam Generator Project.

Partial information concerning these aspects has been collected in the NC2I-R reports project:

- **R&D and Industrial infrastructures**, Deliverable D 2.21 for the FP7 NC2I-R Project, 9 Sep. 2015. M. A. Fütterer (JRC), C. Auriault (LGI), O. Baudrand (IRSN), G. Brinkmann (Areva), D. Hittner (Areva), S. Knol (NRG), Th. Mull (Areva), K. He (CVR), D. Vanvor (BriVaTech), K. Verfondern (FZJ),
- **Report on Gap Analysis.** Deliverable D 2.31 for the FP7 NC2I-R Project, 11 November 2015. S. Knol (NRG), F. Roelofs (NRG), M. A. Fütterer (JRC-IET), P-M. Plet (EON), D. Hittner (AREVA)

The United States has gathered the most knowledge and documentation on HTGR technology. The company **Ultrasafe Nuclear&Technology Insights** owns several **General Atomic** projects (among others **GT-MHR**) which also have experience with the reactor in **Ft. St. Vrain**.

The NGNP Industrial Alliance Consortium has completed a wide range of preparatory work for licensing in partnership with the US NRC. It also carried out several advanced technical and economic studies. Since these works were carried out by the US DoE from public funds (altogether around 600 million), the results are generally available at www.ngnpalliance.org.

AREVA NP Inc., an American branch of AREVA designed the **Antares** reactor with a power of 625 MW_{th} and **SC-HTGR** reactor of 350 MW_{th} was made under the NGNP Industrial Alliance Consortium.

The recent work on a 100-200 MW_{th} pebble bed reactor was undertaken by **X-energy**. It won the last contest of DOE and received funding of 40 million USD.

In Canada, Starcore Nuclear began work on a block reactor with a power of 36-180 MW_{th}.

South Africa started the **PBMR** (Pebble Bed Modular Reactor) program which is taking advantage of the German experience and the support of American experts. However, the project was suspended in 2010. Recently, the energy company ESKOM has expressed an interest in the possibility of restarting the project.

China. It is expected that if the first two reactors of HTR-PM are successfully launched, the country will be offering such reactors for export.

4.4. INTERNATIONAL COOPERATION

As described in Chapter 2.3, HTGR are designed and built in many countries and there are no major technological difficulties with their implementation. Moreover, HTGR technology is no longer patent-protected and there are several ready-to-upgrade projects that can be purchased with an affordable price. However, the problem is that there is no company – expect China and to some extend Japan - which has a team of experts able to design and build HTGR. **Expert knowledge is scattered among different companies and research centers in the world**.

Therefore, one of the major challenges of the HTGR project is the knowledge management and consolidation of the intellectual capital necessary for the construction of a reactor.

The fact that there is no company ready to take full responsibility for the HTGR design as well as the dispersion of knowledge and experts is – at the same time - a chance for Poland. Poland is already actively involved in various projects and partnership agreements aimed at mobilizing know-how in order to implement HTGR technology:

NC2I	One of the pillars of the SNETP platform is the Nuclear Cogeneration Industrial Initiative (NC2I), which aims to promote HTGR and other technologies for applications other than electricity production. Areva, E-ON, Fortum, NRG, and from Poland - AGH, NCBJ and Prochem participate in NC2I activities. Several projects were undertaken to review available technologies, to analyze needs, economic conditions, etc. under the NC2I. The Polish project NCBR HTRPL, closely related to NC2I, has made similar analyses specifically for Poland.
GEMINI	NC2I together with the American Next Generation Nuclear Plant (NGNP) started the GEMINI initiative. The goal is a joint project of the HTR with possible variants of 600 MW_{th} for US and 300 MW_{th} for Europe. Sharing R&D costs gives to both parties mutual access to the IP. There were several workshops of GEMINI, alternately in Washington DC and Brussels. NGNP also establishes cooperation with Korea and Japan.
Visegrad Group (Czech Republic, Hungary, Slovakia, Poland)	The V4 nuclear institutes, including NCBJ, formed the V4G4 (Visegad-4 for Generation-4 reactor) association. The goal is to jointly enhance the design and construction of the generation IV reactors. The main project is the demonstrator ALLEGRO – a fast reactor cooled with helium gas. As ALLEGRO has the same coolant as the HTGR one can think of a synergy between the two projects.
GEMINI+	In response to the European Commission's Horizon 2020 competition, a consortium based on NC2I and NGNP prepared a "GEMINI +" project, which was selected for funding by the EC. It was the only project among others concerning the Small Modular reactors (SMR) that won the financing. GEMINI + deals with the development of design assumptions, location selection and licensing of HTGR reactors. Already achieved at the preparatory stage, the project also focused on connecting all European and global experts in the HTR technology – a total of 27 partners from 9 EU countries take part in the consortium (including from Poland - Energoprojekt, Prochem, Tauron and NCBJ), the USA, Japan and Korea. The consortium received a decision to grant funding in February 2017.

As can be seen from research results, there is the potential to design and manufacture almost any HTR component in Poland and in other countries of V4 and of the EU. Experts in this topic are well recognized and, as the above-mentioned projects show, **the international community is ready to support the implementation of HTGR technology in Poland**.

5. RESEARCH NEEDED FOR HTGR

HTGR reactors already exist, so there are no major technological barriers and also there is no need to research the technology. However, none of the manufacturers offer a "mass" production, so the reactor design will undoubtedly encounter technical problems that require testing. But these studies will be limited to choosing the best technological solution for each specific problem.

In addition to the design work, the second reason for conducting research is licensing procedure. Responding to the questions of nuclear regulator will probably require specific research activities to be carried out.

In general, the basic directions of research should address the following issues:

- Deterministic safety analysis for HTGR reactors including thermos-hydraulic and neutronic calculations, including:
  - Development of integrated models for thermo-hydraulic and neutronic analyses,
  - Construction of high fidelity computational models for the HTGR reactor,
  - Validation of numerical design tools for HTGR covering a number of issues of neutronics and thermo-hydraulics (e.g. power distributions, neutron fluxes, temperatures)
  - verification of developed codes by participating in benchmarks;
- Probabilistic safety analysis for the HTGR reactor, taking into account its operation as a part of the chemical plant process system;
- Integrated risk analysis of the entire chemical and nuclear installation, including the interaction between chemical and nuclear parts;
- Material tests on mechanical, thermal and corrosive properties under specified radiation conditions to determine safety limits of the reactor;
- Studies for the determination of the basic characteristics of the HTGR reactor, such as reactivity (chain reaction intensity), core temperature distributions, changes in pressure gradient;
- Studies involving the development and testing of HTGR reactor instrumentation;
- Development of new concepts of fuel and core.

5.1. MATERIAL LABORATORY NOMATEN

In order to perform the research activities mentioned above, the National Centre for Nuclear Research is going to the launch the Laboratory for Material Research NOMATEN.

NCBJ, together with the French CEA institute and the Finnish VTT laboratory, submitted an application to the European Commission to co-finance the project from the structural funds as part of the TEAMING competition. NOMATEN has won the first stage of the competition and received 400 000 € to prepare a detailed project along with a business plan. NCBJ also explores the potential for regional structural funds to apply for them together with industrial partners.

The laboratory would also be a base for research on future generation reactors, ensuring temperatures of the order of 1000°C, such as VHTR and DFR (see the internal report of the committee "Characteristics of the DFR reactor and research plans").

5.2. EXPERIMENTAL REACTOR HTGR 10 MW_{TH}

The HTGR project, due to its complexity, may encounter delays in implementation, especially since the **current regulations and licensing procedures are adapted to water reactors**. It is therefore necessary to amend the rules and develop appropriate procedures for HTGR, which is discussed in detail in Chapter 6.

In this situation, the best way to mitigate risk in implementing the HTGR project is to build a European low power experimental reactor. This would reinforce safety analyses of large HTGR by direct measurements and simulations validated on a small reactor. Work on such a reactor would also be an excellent field for the preparation of personnel and supply chain for large reactors. As a preliminary step, before the construction of the experimental reactor, one could consider building a critical assembly with TRISO fuel and an experimental test-bed for thermal-flow tests.

The main purpose of the construction of the reactor, in addition to conducting research implicated by project needs and the licensing process, is to build competencies and know-how. In the future, the experimental reactor could be used to develop innovative technologies for new concepts of fuel and core (e.g. mixed cycles, new fuel forms).

The location of the reactor at NCBJ in Swierk, next to the reactor Maria, would have a number of advantages:

- Location already suitable for nuclear facilities,
- Lower costs because of existing infrastructure (security and energy),
- Harnessing the NCBJ manpower for design, licensing and construction,
- The target use of HTGR to supply the center with electricity and heat.

Multiannual research program of the reactor would be;

- Study of ageing of materials exposed to high temperatures and high velocity helium flow,
- Experimental support for the development of HTGR reactor calculation and simulation software,
- Tests for new technologies, in particular new types of fuel.

The British U-Battery project by URENCO in collaboration with Wood (former Amec Foster Wheeler) **and Atkins can be used as demonstrator**. It is a HTGR with a power of 10 MW_{th} using TRISO Fuel in a prismatic block system. The reactor is equipped with a turbine that produces 4 MW_e. The cost of building the reactor is estimated at PLN 500 million. Construction should be financed from the Structural funds of the next EU programming period. The project is advanced enough that it would be possible to proceed to its licensing already in 2019 and to put it into service in the year 2025.

Even faster, though probably a bit more expensive, would be to copy the Japanese HTTR experimental reactor, possibly developing a smaller (10 MW_{th} instead of 30 MW_{th}) and a modernized version.

At the same time, NCBJ conducts preliminary discussions with competing companies designing similar reactors. However, the contained confidentiality agreements do not allow the disclosure of company names and the details of the talks at this stage.

In parallel with the construction of the experimental reactor, a large HTGR project should be started, which would allow to start the licensing in 2022. Involving the National Atomic Energy Agency (PAA) to the work on small HTGR, gives an opportunity to accelerate the licensing of large HTGR by up to 2 years.

5.3. FINANCING THE HTGR EXPERIMENTAL REACTOR

Without choosing the specific design of experimental reactor, the financing issues may be illustrated by the example of U-battery. U-battery design costs are estimated at approx. PLN 150 million. PLN 90 million have already been invested for the U-Battery consortium. The remaining amount could be co-financed in a 1:2 proportion by the bilateral program of the NCBR and the British BEIS. The amount financed by NCBR funds would be used to design by NCBJ and cooperating entities - certain reactor components or to perform appropriate simulations and analyses. The resulting intellectual property would constitute a contribution to the U-battery company, which was converted to 10-15% of the shares.

The cost of building an experimental HTGR in Świerk is estimated at approx. 600 million PLN. This investment could be **funded by the Structural funds of the next EU financing period** i.e. 2021-2027. The funding conditions of next 3 years should be negotiated with the European Commission.

If you choose a supplier other than U-battery, the cost of design and construction as well as the possibility of financing them would be similar, perhaps somewhat higher in the case of HTTR. The choice of a specific instrument for possible co-financing by NCBR or other agencies will depend on the final implementation model of the project. For example, the most appropriate instruments available today are:

- ✓ for the design stage:
    - mentioned above NCBR bilateral programs with foreign agencies
    - Operational program innovative development 1.1.1 "fast track"
- ✓ for construction stage:
    - Operational program innovative development of 4.2 "research infrastructures".

6. LEGAL REGULATIONS

6.1. CURRENT LEGAL STATUS

Licensing-related activities such as the construction, start-up and operation of a potential HTGR-type reactor is governed by **the law of 29 November 2000 – Atomic Law (Journal of Laws of 2017, items 576 and 935) and the law of 29 June 2011 on the preparation and implementation of nuclear power plants and associated investments (Journal of Laws of 2017, item 552)**, together with the relevant Regulations of the Council of Ministers, including:

- Regulation of the Council of Ministers of 11 February 2013 on the requirements for the start-up and operation of nuclear Installations (Journal of Laws of 2013, item 281);
- Regulation of the Council of Ministers of 31 August 2012 on nuclear safety and radiological protection requirements to be taken into account by the design of the nuclear installation (Journal of Laws of 2012, item 1048);
- Regulation of the Council of Ministers of 31 August 2012 on the scope and method of carrying out security analyses prior to the application for a permit to build a nuclear installation, and the scope of the preliminary reported nuclear safety facility (Journal of Laws of 2012, time 1043);
- Regulation of the Council of Ministers of 10 August 2012 on the specific scope of the assessment of the site for the location of a nuclear installation, excluding the possibility of a site being considered as meeting the location requirements for nuclear installation and on the requirements for a nuclear object location report (Journal of Laws of 2012, item 1025);
- Regulation of the Council of Ministers of 30 June 2015 on the documents required for the application and authorization of activities related to the exposure to ionizing radiation, or when reporting the performance of this activities (Journal of Laws of 2015, item 1355).

The abovementioned provisions were designed mainly for light water reactors, aimed at the production of electricity and for current technologies in the field of nuclear energy. There is no provision for the possibility that the final product of a nuclear installation may not be electricity but heat which can be used for industry. **Therefore, many requirements need to be changed, taking into account the characteristics of HTGR, and many provisions require legal interpretation to decide whether this provision also applies to a type reactor HTGR.**

In the future, it is necessary to include security issues related to the interaction of an industrial plant and a HTGR-type reactor in a law which is a source of industrial heat. Therefore, other rules in particular for the provisions of environmental law may also require rewording or reinterpretation.

6.2. ATOMIC LAW ANALYSIS FOR HTGR REACTORS

After the analysis of Polish laws and regulations regarding their adaptation to the HTGR project (that is presented in the document "Licensing of HTGR reactors"[12] developed as a product of the HTR-PL[13] project), it can be stated that one of the necessary changes **is redefinition of a nuclear object.** Currently, the nuclear law lists only two types of nuclear objects that use nuclear fuel for energy production: nuclear power stations and research reactors without indicating the difference between them. So, if one wish to build a small reactor with low power (e.g. proposed under the project of the U-battery - reactor with a capacity of 10 MW_{th}) with a turbine for power generating, it is not possible to clearly determine with existing regulations whether this will be a research reactor or a nuclear power plant. Also, a HTGR-type reactor with more power can no longer be classified as a nuclear power plant because the name "nuclear power plant" means that the final product of the facility is electrical energy but not industrial heat. One of the examples proving that, at the time of the creation of the Polish legal requirements, it was not envisaged that a nuclear installation can produce as a final product industrial heat is the article 38d paragraph 1. 2 of the Nuclear Law. The article indicates that there is a need to pay by the nuclear power plant the tax for decommissioning fund only for each megawatt-hour of electric energy produced.

The second necessary change to adapt the Polish legal requirements to the HTGR while maintaining the highest safety level required, would have to be the change of regulations listed above. Regulations were mostly based on the IAEA safety standards and the reference levels of the European Association for Nuclear Installations (WENRA) for existing and new reactors. These provisions were designed for conventional reactors and did not take into account small modular reactors and HTGR-type reactors. It would be possible to design a HTGR meeting these requirements, but to apply them would oversize the reactor and consequently significantly increase the cost of the project and construction without affecting its level of safety. An example of such requirements is article 67 of the Regulation of the Council of Ministers n on nuclear safety and radiological protection requirements to be taken into account for the design of the nuclear installation. It dictates a nuclear power plant – regardless of the impact on nuclear safety - the installation of two safety housings (internal and external) and one casing to research reactor. At the same time the Regulation does not specify which construction object can be called the safety case and what specific requirements must be met by this housing. Since the HTGR-type reactor project is designed to provide the possibility of excluding serious core damage on any hypothetical failure, it should be considered redefining the traditional approach including defense in depth for this technology.

[12] „Licensing of HTGR reactors", updated version: NCBJ Report B-10/2017.

[13] Consortium project under the leadership of AGH, funded by the NCBR.

These two problems could be solved by a change in the Nuclear law of the definition of a nuclear object by:

1) Additionally to Nuclear power plant and research reactor defining an object that would the characteristics of a HTGR-type reactor and, consequently, supplementing the specific requirements of the regulations on nuclear safety requirements for this object,

or

2) Changing the name of the nuclear power plant to the new name of the facility, which would scope nuclear power plants, as well as objects producing industrial heat, and consequently changing the specific requirements for this facility contained in the Regulations, in order to unify the rules, while complying with the highest safety standards, enable these requirements to be met by either a conventional reactor or a HTGR reactor without limiting them.

After resolving the issue of the definition of a nuclear installation relating to HTGR-type reactor, it could be concluded that the provisions concerning the fulfilment of the localization requirements and the documents necessary for the application for a permission for construction, commissioning, operation or decommissioning of nuclear installations does not require major changes. The majority of the documents required by these provisions do not indicate exactly what the content of the document is and what it is intended to contain, and thus does not target the specific type of reactor technology.

6.3. LICENSING MODEL AND SCOPE OF ATOMIC LAW

In addition to the issues described above, the problem is the scope of atomic law and the licensing model. Three basic issues are described below.

THE SAFETY CRITERIA CONTAINED IN THE LEGAL ACTS

Currently, the criteria for the release of nuclear reactors for use are enshrined in Nuclear Law and Council of Ministers regulations. This solution has two serious flaws. The inclusion of detailed safety criteria in the laws and regulations of the Council of Ministers has a negative effect on their technological neutrality and makes it necessary to amend them frequently as technology evolves. Meanwhile, technological neutrality of atomic law is a principle adopted in almost all countries. Decision concerning safety criteria should be the domain of the president of the PAA. Otherwise, there is a risk of not substantive tightening or loosening the safety criteria in order to achieve political objectives.

PROPOSAL TO INTRODUCE A REACTOR TYPE INTO THE CERTIFICATION LAW

The current atomic law requires the full licensing procedure for each nuclear object, even if an object of the same type has already been licensed. This approach, tested for large reactors of the order of 1000 MW_e, is not appropriate for small modular reactors (SMR), produced in series. This class also includes the HTGR reactors considered in this report due to their relatively low power and the expected large number of them.

It would be advisable to introduce Nuclear Law solutions based on the British Generic Design Assessment, which is a type of confirmation by nuclear regulator that the design of a given the reactor type satisfies the general requirements of safety and can therefore be implemented.

PRESCRIPTIVE AND EVIDENCE BASED LICENSING

Licensing models in different countries can be divided into two types of: prescriptive and evidence based licensing.

The prescriptive licensing, used e.g. by the US NRC, requires the licensee to meet a predetermined list of criteria. This list facilitates the licensing process for standard light water reactors. However, it is a significant barrier to other technologies, as this list cannot be technologically neutral.

Alternative method used e.g. by the UK ONR, is the **evidence based licensing**. It gives the licensee the freedom to choose methods to prove the reactor's safety. This method is more demanding for nuclear regulator, but is inherently open to new technologies. **The prospect of the implementation of HTGR reactors in Poland strongly indicates the need to introduce evidence licensing in Polish nuclear law.**

6.4. COOPERATION WITH REGULATORS OF OTHER COUNTRIES

It is advisable to cooperate with the US NRC, due to its experience primarily in the qualification of TRISO fuel. A serial production of a HTGR-type reactor also indicates the need for a general license for a given reactor type. This model is valid among others in the UK and Canada. The British ONR also has a large experience with commercially used gas-cooled reactors (CO_2) with a graphite moderator. **Developing regulations for HTGR, Poland would be at the European forefront of modernizing nuclear law.**

7. BUSINESS MODEL OF IMPLEMENTING HTGR

7.1. ENGINEERING, PROCUREMENT AND CONSTRUCTION (EPC)

REACTOR OWNER AND OPERATOR

Due to the specificity of the nuclear installation and the scale of the investment, the only possible - in practice - investment implementation model is the scenario where **the owner and operator of the reactor is a special purpose company (SPV)**; let's give them a working name HTR-OP. A chemical plant would buy energy (steam) from HTR-OP produced by HTGR. The issue of the HTR-OP ownership structure remains open. In the Mankala model (effectively implemented in Finland), the company does not generate any profit, and its shareholders are the main customers who buy energy at production costs. The HTR-OP should entrust subcontractors with nuclear experience for, at least, the first few years.

STRUCTURE OF ENGINEERING, PROCURMENT AND CONSTRUCTION (EPC)

In the case of high power reactors, the model of integrated **EPC (Engineering, Procurement and Construction)** dominated so far, where all three elements were covered by one supplier or two-part model, where EP and C were covered by two suppliers. At present, however, there is no large company on the market that would be able to cover even the reactor's engineering project alone. On the one hand, this is an additional big challenge, but on the other hand it gives a chance to better **embed the project in Poland and poses most of the intellectual property generated in the project.**

In order to implement HTGR, we should therefore establish a special-purpose company, (a working-name HTR-EPC). It would be responsible for both design and construction of reactors, coordinating the work of the subcontractors' chain. In the process of building specific reactors, **it would act as a substitute investor**. This is illustrated in the diagram on Graphic 9. **The HTR-EPC company would become the owner of the conceptual and engineering design of HTGR and would profit from its implementation in various domestic and foreign locations.**

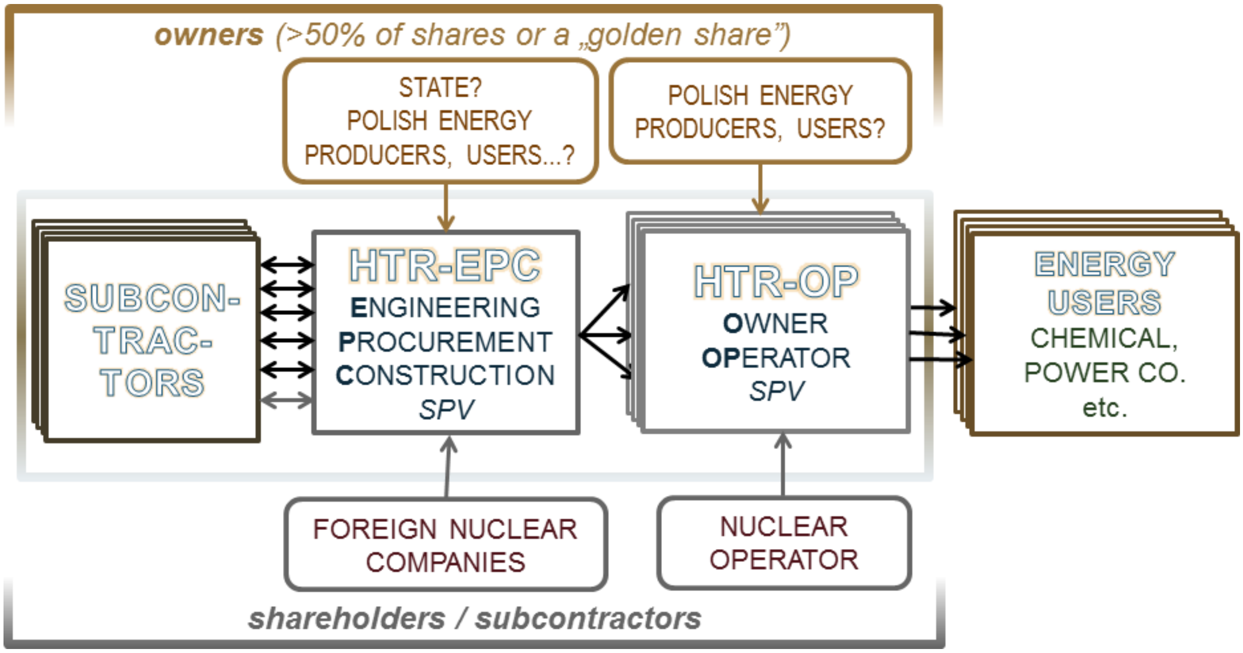

Figure 8. Business model of implementing HTGR.

OWNER STRUCTURE HTR-EPC

The issue of the HTR-EPC ownership structure remains open. The owner (understood as a majority shareholder or having a "golden share" that provides an advantage in voting) could be directly the State Treasury. The advantage of such a solution would be the coordination of activities for the entire Polish economy. The disadvantage - the need to recapitalize the company from the budget by the amount of PLN 500 million in the first few years of its operation. An indirect solution is also possible - the owner could be not the State Treasury directly, but **a state entity**, such as NCBJ. This solution works, for example, in France, where the research institute CEA is a significant shareholder of AREVA NP. And in that case, it would be necessary to top up with budget funds, as NCBJ does not have adequate capital.

The most optimal solution would be to create a special-purpose company HTR-EPC by 4-6 Polish investors. The presence of Polish chemical and energy companies among the participants of the HTGR project would guarantee the substantive correctness of the preconceptual study, and in the next stage, adaptation of the reactor design to the specific needs of the recipients. Details of such a model are described in the following subsections.

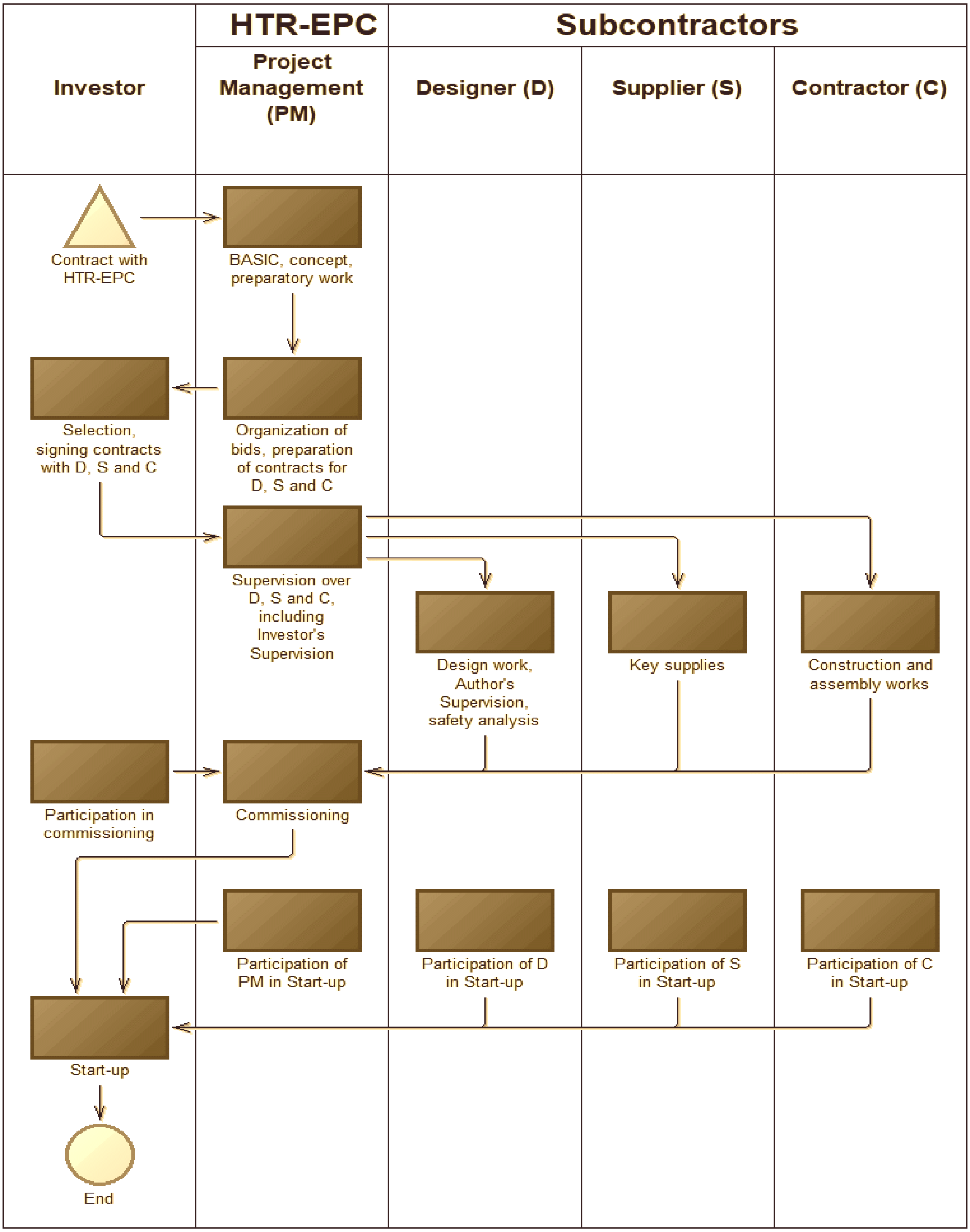

Figure 9. The replacement investor model in the HTGR construction process.

7.2. IMPLEMENTATION OF THE PROGRAM AND RISK MANAGEMENT

Due to the innovative nature of the venture, **a clear division of the program implementation into individual stages completed with milestones is necessary. Successful implementation of mentioned milestones would be a prerequisite for launching the next stage.**

The proposed division into stages, including the costs of their implementation, is presented below.

Stage	Time	Works / milestones	Committee	Cost [PLN million]
1	**2018**	**Preconception study**	**10-20 people**	**10**
1a		• Mobilization • Due diligence of foreign partners • Contacts with foreign partners • Preconception studies, cost estimate • In-depth economic analysis		
2	**2019-23**	**Commercial reactor project**		**500**
2a	2019-20	• Conceptual design • Security options report	40-70 people	50
2b	2020-21	• Preliminary design • Preliminary safety analysis report	50-80 people + subcontr.	150
2c	2022-23	• Final design • Final safety analysis report	60-90 people + subcontr.	300
3	**2023-31**	**Construction of the first HTGR**		**2000**
3a	2023-26	• Site preparation, obtaining consents		500
3b	2026-31	• Construction and commissioning of the reactor		1500

Table 7. The division of program implementation into stages.

The proposed division into stages minimizes the risk of investment as the project financing is increased each time after the successful completion of the previous stage. This is illustrated by the graph of the half-yearly costs of individual stages below.

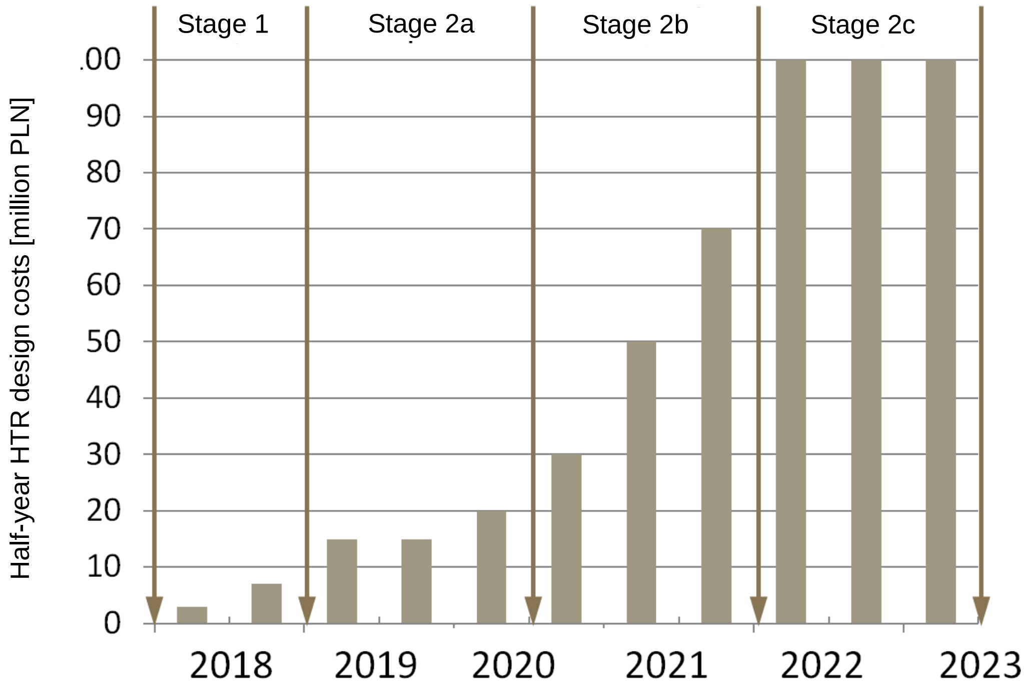

Figure 10. Semi-annual HTGR design costs in stages.
The arrows indicate the decision to start financing the next stages.

7.3. PROPOSED BUSINESS MODEL - SUMMARY

The recommended business model is illustrated in Table 8. It assumes **the creation of a special-purpose company HTR-EPC by 4-6 Polish investors.** The role of investors may be played by the companies which are interested in using HTGR reactors in the future, i.e., chemical, energy companies, etc. The shareholders' agreement should assume a gradual recapitalization of HTR-EPC as the work progresses. Funds for the implementation of stages 1 and 2 should come from research and development budgets of potential investors. The launch of stage 2 would be conditioned by a positive result of the preconceptual study.

In stages 1 and 2, due to the highly innovative nature of the undertaking, **funding from the NCBR is desirable**. The most effective way to create such funding would be the **agreement of the Ministry of Energy with the Ministry of Science and Higher Education** on the implementation of the HTGR program. This justifies the strategic nature of the program, proven by including it in the Strategy of responsible development.

	Stage 1 Preconcep-tual study	**Stage 2 Reactor design**	**Stage 3 Reactor construction**	**Stage 4 Reactor operation**
Implemen-tation	2018	2019-23	2023-26: licensing 2026-31: reactor construction	2031-90
Investor structure	HTR-EPC (*engineering, procurement, construction*)		HTR-EPC / HTR-OP (owner & operator)	HTR-OP
Ownership structure	About 5 investors, mainly Polish producers and energy consumers		About 5 investors / special purpose companies of Polish producers and energy consumers	Special purpose companies of Polish producers & energy consumers
Expenses	10 million PLN	500 million PLN	2000±500 million PLN Most of the expenses 2026-31	Covered from revenues
Commercial product	-	Reactor design (IP as a license)	HTGR reactor	Technological steam
Return on investment	-	Sale of ≥10 licenses. The market till 2050: PL=10-20, EU=100-200. world=1000-2000	NPV> 0 after 20-30 years of use	

Table 8. The scheme of implementing HTGR reactors in Poland

The shareholder agreement should also provide for the possibility of resale <50% of shares to foreign entities that would make a significant substantive contribution to the design of the reactor.

7.4. INVOLVEMENT OF FOREIGN POTENTIAL

Due to the very limited pool of experts in the country, **it is necessary to take advantage of the potential of foreign companies.** They could be minority shareholders or subcontractors of HTR-EPC. American companies associated in the NGNP Industrial Alliance (including Southern Company, Atkins, Areva NP Inc., Ultrasafe Nuclear, Excel Services, SGL) and X-energy, as well as a number of Japanese entities, have expressed great interest in participating in such a venture, with JAEA in the lead. Initially, they also expressed interest in European companies such as Wood (formerly Amec Foster Wheeler), Areva NP, Mott Mc Donald and a few smaller ones.

Talks at government level with Japan, Great Britain and the US showed a convergence of view on new nuclear technologies. An advantage of this approach would be the division of costs between partners and the acceleration of work. The disadvantage - the division of intellectual property. This disadvantage could, however, be offset by a significant increase in export potential.

The use of the structure, staff, knowledge and IP of foreign companies would have the following advantages:

- significantly reducing technological risks,
- bringing forward the project implementation by 2-3 years,
- business stabilization of the project - increasing resilience to political risk,
- reducing the cost of the project for Polish investors,
- easier access to global markets.

It would also have disadvantages, which, however, can be mitigated:

- a significant part of IP in foreign hands - mitigation through the ownership structure (> 50% in Polish hands);
- part of the supply chain outside of Poland - but redundancy in the supply chain is desirable
- the need to share profits - it can be compensated by the expansion of the market.

In the Committee's opinion, the advantages presented outweigh the disadvantages; therefore **the committee recommends significant involvement of foreign potential in all three forms: employment, subcontracting and shares. The desired range of foreign shares is around 25-45%.**

7.5. FINANCING THE CONSTRUCTION OF THE REACTOR

The cost of investing in the construction of each reactor should be borne by its future owner, the HTR-OP company. As estimated in Chapter 3.1, for HTGR with a capacity of 165 MW_{th} it would amount to approx. PLN 2 billion net (including purchase of licenses and preparation costs). Such a large investment should be financed by a loan with a moderate share of own resources.

OWN FUNDS

The expected share of own funds is min. 20% of planned expenditures. Own contribution funds can come from the following sources:

- the founding capital of the Company,
- subordinated loans granted by shareholders,
- issue of shares and introduction of the Company to the stock exchange allowing to maintain control over the Company,
- subsidy.

EXTERNAL SOURCES OF FINANCING

The following sources can be used:

- syndicated loan from Polish commercial banks,
- loan from international banks: EIB, EBRD, World Bank, etc.
- issue of bonds addressed to: investment funds, corporate companies, natural persons.

Due to the long period of return on investment, the cost of money is a significant part of the project's costs. Therefore, it is necessary to use available instruments reducing this cost, e.g. by reducing the risk level with government guarantees, using preferential loans, etc.

7.6. SYNERGY OF HTGR 10 MW_{TH} AND 165 MW_{TH} PROJECTS

To maximize the experience from building a 10 MW_{th} experimental reactor to prepare a commercial HTGR implementation, it should be run by HTR-EPC. The parallel finalization of the 10 MW_{th} project and the start of HTGR 165 MW_{th} design by HTR-EPC will have a number of advantages:

- quick familiarization with HTGR technology,
- the possibility of transferring technological solutions from the 10 MW_{th} project to the 165 MW_{th} project,
- testing and development of HTGR calculation, simulation and safety analysis tools,
- optimization of cooperation with nuclear supervision at an early stage,
- early creation and testing of the subcontracting chain.

8. SCHEDULE OF DECISIONS AND ACTIONS

8.1. NUCLEAR ROADMAP FOR POLAND

Sustainable development of nuclear energy, just like any other branch of the economy, requires a proper hierarchy of investment, implementation and research programs. Schematic is presented in the table below. The level of readiness for implementation is given in the international TRL (Technology Readiness Level).

Type of program	Investment	Implementation	Searching
Output TRL	8-9	5-7	1-4
New intellectual property	0-20%	20-80%	80-100%
Time to implement	≈10 years	10-15 years	20-30 years

Table 9. Hierarchy of investment, implementation and research programs.

Parallel running of these three types of projects ensures constant improvement of the technological level, preparation of personnel in research projects and their transfer to projects that will be implemented in future. It also enables development of investment projects with a large own intellectual contribution. In the case of the Polish nuclear program such synergy is ensured by simultaneous research into the future VHTR and DFR technologies, implementation of HTGR for industrial applications and investment in large LWR energy reactors.

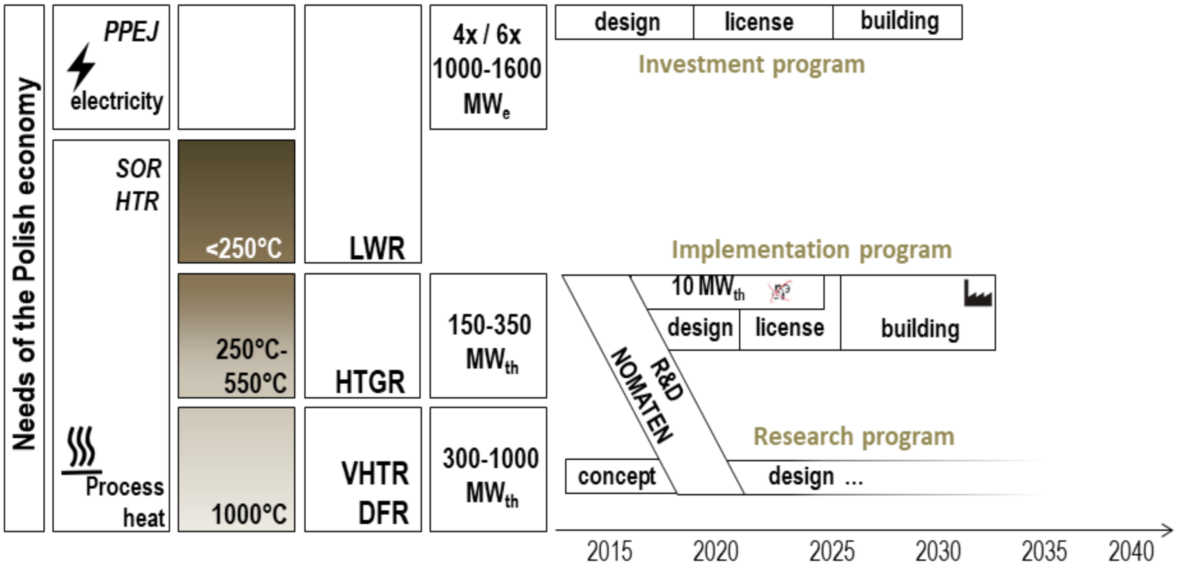

Figure 11. Nuclear road map for Poland

8.2. EXPERIMENTAL REACTOR HTGR 10 MW_{TH}

So far, the following actions have been taken:

- NCBJ has made a preliminary technology review.
- NCBJ signed cooperation agreements on the U-Battery reactor with URENCO representing the British consortium and on cooperation with JAEA, owner of the HTTR experimental reactor.
- A business model for cooperation was initially developed.
- Possible sources of project financing have been identified (described in chapter 5.3).
- NCBJ pre-selected the detailed location of the reactor in the Świerk center.
- At the government level, talks were held between the Ministry of Energy and DECC / BEIS. The parties expressed their will to cooperate in the development of HTGR technology, in particular the U-Battery reactor

A detailed schedule of works on experimental HTGR is presented in the following diagram (Table 10).

Stage	Process / milestone	2018		2019		2020		2021		2022		2023		2024		2025	
		I	II	I	II	I	II	I	II	I	II	I	II	I	II	I	II
1	**Preconception study**	■															
2	**Reactor design**		■	■	■	■											
2a	Concetual design		■														
	Security options report		◆														
2b	Preliminary design			■													
	Preliminary safety nalisysis report			◆													
2c	Final design				■	■											
	Final safety analysis report					◆											
3	**Reactor construction**						■	■	■	■	■	■	■	■	■	■	■
3a	Site preparation, obtaining consents						■	■	■								
	Building permission								◆								
3b	Reactor construction									■	■	■	■	■	■	■	■
	Launch of the reactor																◆

Table 10. Schedule of experimental HTGR 10 MW_{th} work in Świerk.

In case of a positive decision regarding the development of high-temperature technology in Poland, **the committee proposes to take the following actions in the near future**:

- Launching funding for NCBJ development activities by NCBR in the field of HTGR technology.
- Choosing a strategic technology partner.
- Beginning HTGR experimental design.
- Negotiations with the European Commission on the use of Structural Funds for the period 2021-2028 to finance the experimental construction of HTGR in Świerk.

8.3. THE FIRST INDUSTRIAL HTGR REACTOR

An indicative work schedule related to the design, licensing and construction of the first industrial HTGR is shown in the diagram below. The first reactor could be commissioned 13 years after the investment was launched, i.e. around 2031.

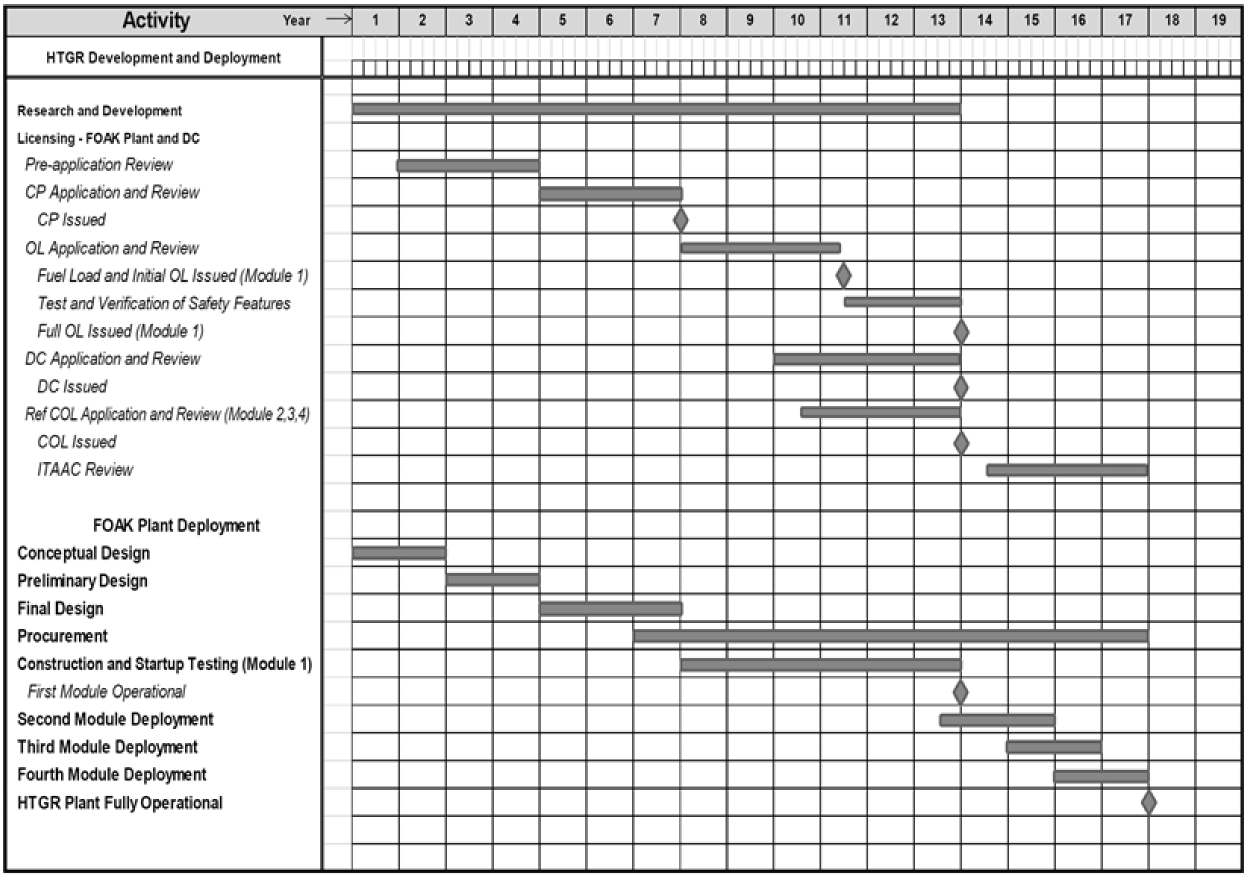

Table 11. Schedule for the implementation of the first industrial HTGR (Source: NC2I)

Studies on the possibility of implementing HTGR in Poland have been carried out for several years now. In particular, the HTRPL program financed by the NCBR was implemented. In addition, Polish entities have participated in several European initiatives described in the chapter on international cooperation.

Using the results of this work and additional analyzes carried out by the parent members' organization, **the HTR committee achieved the following results:**

- The demand for industrial heat in Poland and Europe was assessed.
- Installations where the heat carrier is water vapor with a temperature of 250-550°C as the most suitable area for the application of nuclear technologies

- It has been confirmed that the technology of high-temperature gas-cooled reactors (HTGR) is the most mature and therefore the fastest to be implemented in this area.
- The entities that have knowledge and equipment useful for implementing HTGR were identified, with the majority of them established cooperation (Gemini + project, bilateral agreements).
- On the basis of data from existing installations in Poland, optimal reactor parameters have been determined.
- In cooperation with foreign entities, the costs of construction and operation of HTGR were estimated.
- An economic model has been built to study the economic viability of HTGR.
- On the basis of the model, the profitability of HTGR with coal and gas boilers with similar parameters was compared. Sensitivity of the results to project assumptions and external factors was tested.
- Variants of the HTGR business model were discussed and the optimal one was recommended.
- The main incompatibilities of current atomic law with HTGR technology have been identified.

In the committee's opinion, the results collected and presented in this report may form the basis for the Ministry of Energy to decide on the initiation of the HTGR implementation process in Poland.

Assuming such a decision, the next steps should include:

- Establishment of the HTR-EPC company and commencement of its activities described in chapter 7.
- Signing an agreement between the Ministry of Energy and the Ministry of Science and Higher Education about the implementation of the HTGR program.
- Preparation of the government program.
- Launch of funding for HTGR 165 MW_{th} reactor design by NCBR.
- PAA's collaboration with US, UK and Canadian regulatory authorities in the field of HTGR licensing.
- Preparation for the necessary modification of atomic law and implementing regulations.

8.4. NEW APPLICATIONS OF INNOVATIVE NUCLEAR REACTORS

In the longer term, you can consider:

- Possibilities of implementing HTGR for other applications, such as:
    - replacement of generating units with the capacity of 200 MW_e and smaller, where it is not possible or economically justified to use large LWR reactors,
    - municipal combined heat and power plants and integration into low emission decommissioning programs.
- Extension of HTGR work above 1000°C and work on alternative technologies such as DFR (see internal report of the "Characteristics of the DFR reactor and research plans").
- Possibilities of using other types of nuclear reactors for the production of combined electricity and heat as well as for non-electrical applications.

9. BENEFITS FROM IMPLEMENTATION HTGR IN POLAND

The choice of HTGR technology and implementation of high temperature cogeneration in Poland will bring many economic benefits:

Reducing the dependence of the economy on fuel imports
HTGR is the only alternative to fossil fuels as far as heat production is concerned. The Polish industry (due to its energy intensity) is sensitive to possible interruptions in supplies and the level of raw material prices. Heat production in HTGR reactors would reduce the dependence of the Polish economy on gas imports and would make the level of system heat prices more predictable.
Increasing the resilience of the industry to new environmental regulations
In particular in the field of CO_2 or carbon footprint of products. The production of system-wide heat based on coal causes that the systematic tightening of environmental requirements by the EU and the possible increase in prices of CO_2 emission allowances in the future will put Polish entities in a worse position than competitors from other countries. Partial exchange of gas and carbon heat sources on HTGR will contribute to maintain competitiveness by Polish entities. Moving away from coal energy generation to HTGR in the case of the 13 largest chemical installations will reduce CO_2 emissions per year by almost 19 million tons.
Impulse for economic growth
Based on the development of products with higher added value. Implementation of a large, ambitious project of a scientific and infrastructure nature will launch a series of interactions throughout the economy and will become one of the revolving wheels of reindustrialization.
Value added for the design of large nuclear power plants
The development of HTGR will involve the development of nuclear potential both on the part of institutes and industry. It will allow raising staffing levels and creating opportunities for sub-suppliers of components for nuclear energy, which will pay off when building large nuclear units.
Increasing Polish potential in the area of energy technology export
The HTGR reactor due to the very high safety standards, relatively small size and the multiplicity of potential applications will naturally become an export commodity.

10. GLOSSARY OF TERMS AND ABBREVIATIONS

ANTARES	-	A New Technology Advanced Reactor Energy System – HTGR concept by US Areva
BEIS	-	Department for Business, Energy & Industrial Strategy, - British equivalent of the former Ministry of Economy
CEA	-	Le Commissariat à l'énergie atomique et aux énergies alternatives – French Commissariat for Atomic Energy and Alternative Energy Sources
CNEC	-	China Nuclear Engineering Corporation
DECC	-	Department of Energy & Climate Change - British equivalent of the Ministry of Energy, from 2016 replaced by BEIS
DEJ ME	-	Department of Nuclear Energy of the Ministry of Energy
DFR	-	Dual Fluid Reactor – two-fluid reactor
DOE	-	Department of Energy – Department of Energy in the USA
EBI	-	European Investment Bank
EBOR	-	European Bank for Reconstruction and Development
EPC	-	Engineering, Procurement, Construction
EUROPAIRS	-	End user requirement for process heat applications with innovative reactors for sustainable energy supply – project financed by Euratom
FOAK	-	First Of A Kind
GEMINI	-	Transatlantic cooperation platform between NC2I and NGNP Industrial Alliance
GEMINI+	-	The Euratom project proposed by Gemini, whose aim is to prepare the construction of an HTGR experimental reactor
GFR	-	Gas-cooled Fast Reactor
GIF	-	Generation IV International Forum (www.gen-4.org)
GPW	-	Polish stock Exchange
HTGR	**-**	**High Temperature Gas-cooled Reactor**
HTR	**-**	**High Temperature Reactor**
HTR-PL	-	Development of high-temperature reactors for industrial applications - a project financed by Polish research funding agency NCBR
HTTR	-	High-Temperature Test Reactor
IAEA	-	International Atomic Energy Agency
LCOE	-	Levelized Cost of Energy
LFR	-	Lead-cooled Fast Reactor

GLOSSARY OF TERMS AND ABBREVIATIONS

LWR - Light Water Reactor

MSR - Molten Salt Reactor

NC2I - Nuclear Cogeneration Industrial Initiative - Industrial Initiative of Cogeneration Nuclear, one of the three pillars of SNETP

NC2I-R - Nuclear Cogeneration Industrial Initiative – Research - the Euratom project, which aimed to study HTR

NCBJ - National Center for Nuclear Research

NCBR - National Centre for Research and Development

NEA - Nuclear Energy Agency

NGNP - Next Generation Nuclear Plant Industrial Alliance – cooperation platform of the nuclear industry in the USA working on a high-temperature reactor

NOAK - Next Of A Kind

NPV - Net Present Value – the net present value, E-NPV – economic, F-NPV - financial

OCC - Overnight Construction Cost – total construction cost, without the cost of the loan ("one

OECD - Organization for Economic Co-operation and Development

PAA - National Atomic Energy Agency (Państwowa Agencja Atomistyki)

PBMR - Pebble Bed Modular Reactor

PWR - Pressurized Water Reactor

SC-HTGR - Steam Cycle High-Temperature Gas-Cooled Reactor

SCWR - Supercritical Water-cooled Reactor

SET-Plan - Strategic Energy Technology Plan - a strategic plan in the field of energy technology of the European Commission

SFR - Sodium-cooled Fast Reactor

SMR - Small Modular Reactor or Small & Medium Size Reactor

SNETP - Sustainable Nuclear Energy Technology Platform – the European Technology Platform for Sustainable Nuclear Power

TRISO - Tristructural-isotropic - isotropic three-layer nuclear fuel

TRL - Technology Readiness Level

V4 - Visegrad Group - Czech Republic, Poland, Slovakia, Hungary

V4G4 - Visegad-4 for Generation-4 Reactors - association of nuclear institutes of the V4

VHTR - Very High Temperature Reactor – very high temperature reactor, extension of HTGR technology