Fast Reactors and Nuclear Cogeneration: A Market and Economic Analysis

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Abstract. Fast reactors are typically considered for their potential to make optimal use of natural resources or for their potential to minimize the amount and level of nuclear waste. The additional opportunity of fast reactors designed for cogeneration applications (i.e., production of electricity and process heat), which can bring an enormous reduction in CO2-emissions, is made possible by the elevated temperatures characterizing the primary circuit of such reactors, compared to traditional light water reactors. This article will provide a state-of-the-art overview on the cogeneration market with emphasis on opportunities for lead, gas, and sodium fast reactors, summarize recommendations for these fast reactor systems and their interfaces with a cogeneration application, and discuss the results of a top down cost estimate for a lead fast reactor system with a typical cogeneration application. The economic analysis clearly shows that coupling a small or medium sized fast reactor to a cogeneration application seems attractive.

Key Words: Fast Reactors, Cogeneration, Market Analysis, Economic Analysis.

1. Introduction

Fast reactors are typically considered for their potential to make optimal use of natural resources or for their potential to minimise the amount and level of nuclear waste. The additional opportunity of fast reactors designed for cogeneration applications (i.e., production of electricity and process heat) is made possible by the elevated temperatures characterizing the primary circuit of such reactors, compared to traditional light water reactors. Nuclear Power Plants are already used worldwide for low temperature applications; in Russia, the BN350 fast reactor has been used for electricity production and desalination purposes for more than 20 years.

This article provides a state-of-the-art overview on the cogeneration market with emphasis on opportunities for fast reactors, the recommendations for fast reactor systems and their interfaces with a cogeneration application, and the top down cost estimate for a fast reactor system with a typical cogeneration application.

2. Identification of Cogeneration Markets for Fast Reactors

2.1.Nuclear Cogeneration Market

Nuclear cogeneration is simultaneous generation of electricity and useful heat by a Nuclear Power Plant (NPP) as presented in figure 1. Currently, about 30% of the world's primary energy is used for electricity generation and approximately 2/3 of this energy is thrown away as waste heat [1]. Operating in a Combined Heat and Power mode (CHP) can increase the overall efficiency of a conventional light water cooled nuclear power plant from 34% (typically more than 40% for a fast reactor) up to more than 55% [2]. Indeed, less electricity is produced but the production of heat offsets this loss.

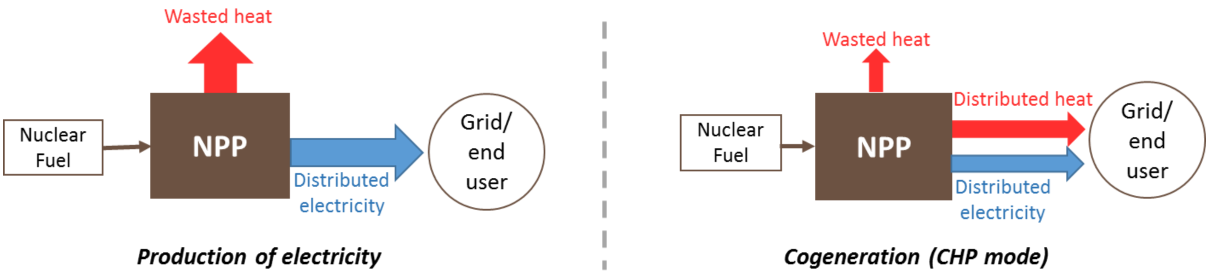

FIG 1: Schematic principle of nuclear cogeneration

Nuclear cogeneration is not an innovative concept, some of the first civilian reactors were used in that purpose. In Europe, The Calder Hall plant in the United Kingdom provided electricity to the grid and heat to a fuel reprocessing plant starting in 1956. The Agesta plant in Sweden provided hot water for district heating of a suburb of Stockholm from 1963. However, nuclear power remains today primarily a source for electricity generation. Less than 1% of the nuclear heat is being used for non-electric applications [3]. Practically, the temperature for these applications does not exceed 200°C.

However, research is conducted concerning higher temperatures, typically around 750°C. These temperatures are required for industrial applications such as the production of hydrogen, or processes in the oil and refining industry. Generation II and III reactors cannot reach such temperatures, so other types of reactors are required. The High-Temperature Reactor (HTR) can reach temperatures over 700°C. No nuclear cogeneration using HTR exists today, but it was successfully proven in Germany [4], the United Kingdom and the United States. HTR test reactors are currently operated in Japan and China. China is also building an HTR demonstration plant to be commissioned in the next years.

Nuclear cogeneration requires co-siting of a nuclear power plant and a process heat application, as the distance over which the heat (typically in the form of steam) can be transported is limited. For district heating, distances of 80 km have been considered [5]. A few kilometers is typical for industrial applications [3], which appears broadly compatible with the size of large industrial facilities provided the nuclear plant is sited adjacent to the facility.

The lifetime of the process heat application may be required to be reasonably compatible with the nuclear plant for the project to be worthwhile. Modern nuclear plants typically have target lifetimes of 60 years, with a ~10-20 year lead time prior to operation. Discounting effects will mean that the large majority of the net present value of any reduction in energy generation cost can be realized within the first 20-30 years of reactor operation.

2.2.Application of Cogeneration to Fast Reactors

Belonging to Generation IV reactors, fast reactors operate in a closed fuel cycle using fast neutrons. Thanks to this specification, fast reactors would be able to provide energy for thousands of years as well as easing concerns about waste [6]. Four main fast reactors options and innovative designs are considered today ([7], [8]):

- Sodium-cooled Fast Reactor (SFR)
- Lead-cooled Fast Reactor (LFR)
- Gas-cooled Fast Reactor (GFR)
- Molten Salt Fast Reactor (MSFR)

In this study, only the SFRs, LFRs and GFRs are taken into account.

Research and development projects related to fast reactors are currently conducted all over the world. Table 1 presents the status, the thermal and electric power and the outlet temperature of different designs, relevant for nuclear cogeneration.

Table 1: CHARACTERISTICS OF SEVERAL FAST REACTOR DESIGNS ([6], [8])

Fast Reactor	Design	Country	Status	Thermal Power (MWth)	Electric Power (MWe)	System Temperature (°C)
SFR	ASTRID	EU	Basic Design	1500	600	500-550
	4S	Japan	Detailed Design	30	10	510
	PRISM	USA	Detailed Design	840	311	484
LFR	ALFRED	EU	Conceptual Design	300	125	400-480
	ELFR	EU	Pre-Conceptual Design	1500	630	400-480
	BREST-OD-300	Russia	Detailed Design	700	300	540
	SVBR-100	Russia	Detailed Design	280	101	490
GFR	ALLEGRO	EU	Pre-conceptual Design	75	-	800
	EM^2	USA	Conceptual Design	500	240	850

To identify the potential applications for nuclear cogeneration for fast reactors, the outlet temperature of the different concepts is the key indicator that allows the segmentation of the heat industrial market. The heat industrial market can be divided into three main types of applications:

- Low-temperature applications: typically below 200°C
- Mid-temperature applications: typically between 450°C and 500°C
- High-temperature applications: typically above 800°C

Table 2 shows the different application ranges by temperature required and the potential fast reactors which can be used for cogeneration. Cogeneration between industrial applications and fast reactors is highly dependent of the outlet temperature of a reactor. For the ESNII concepts, ASTRID, ALFRED and ALLEGRO, this temperature can be easily estimated. However, for commercial fast reactors at their industrial size that are expected to follow, being commissioned in 20 to 30 years, the outlet temperature is still not well known and will depend on progress made in research work.

Table 2: OUTLET TEMPERATURES AND POTENTIAL APPLICATIONS OF DIFFERENT EUROPEAN FAST REACTOR CONCEPTS

Type of applications	**Temperature required**	**Examples of applications**	**Type of reactor**
Low-temperature applications	< 200°C	- District heating - Desalination	- All demonstrators
		- Paper industry	- GFR demonstrator (ALLEGRO)*
Mid-temperature applications	450°C – 500°C	- Oil refinery - Chemical industry - Soda ash - Coal-to-liquid - Oil sands	- SFR demonstrator (ASTRID) - LFR demonstrator (ALFRED)
High-temperature applications	> 750°C	- Aluminium industry - Oxygen production - Hydrogen production - Coal-to-liquid	- SFR (<800°C), LFR, and GFR long-term view

*Water and not superheated steam

Concerning SFR, to reach higher outlet temperatures, materials must be developed to be compatible with the primary coolant environment (chemistry and temperature). SFRs will also have to face safety margins against primary coolant boiling (880°C). A maximum temperature of approximately 800°C (primary side) is considered the upper limit (physical limit) for normal operating conditions.

Regarding the LFR technology, the temperature for ALFRED is limited by corrosion effects which increase with temperature and which are difficult to manage above 500-550°C (primary side). In a long-term option, if proper materials are developed, the primary temperature could be increased and would be limited theoretically by a boiling temperature of 1750°C. However, it will be difficult to develop materials which can be compatible with a temperature above 800-850°C (technological limit).

Finally, GFR is not affected by concerns about boiling of primary coolant nor by corrosion enhanced by the coolant environment. Today, the main limitation of the GFR is the selection of structural materials able to withstand high fast neutron fluence and high temperature. This is one of the reasons why ALLEGRO is currently based on available materials and fuel with an outlet core temperature of 530°C (primary side). In the long term option, the aim is to reach HTR conditions (700-850°C core outlet), achievable only when proper materials will be developed.

3. Recommendations for system specifications and requirements

The general architecture of a cogeneration system basically depends on the thermal cycle selected for the NPP of interest. In general, when the Balance of Plant (BoP) is based on a Rankine cycle (i.e., making use of steam turbine(s) only), the typical architecture will not differ excessively from the one depicted in figure 2. However, aiming at higher temperatures and flexible electricity-to-heat ratios, the (live) steam will most probably be extracted upstream of the high pressure turbine. High degrees of steam superheat are typically not desirable and de-super heating stations (steam attemperation) are used to control steam temperatures, in combination with other NPP internal needs. Additional flexibility is achievable combining non-condensing (or back pressure) and condensing steam turbines, and through multiple controlled pressure steam extraction points feeding more than one process header [9]. Similar considerations are in common with cogeneration applications based on fossil-fired boilers, where turbines selection (either back pressure or condensing, with or without controlled extractions) are basically dictated by the process steam parameters, and ad-hoc designed [10].

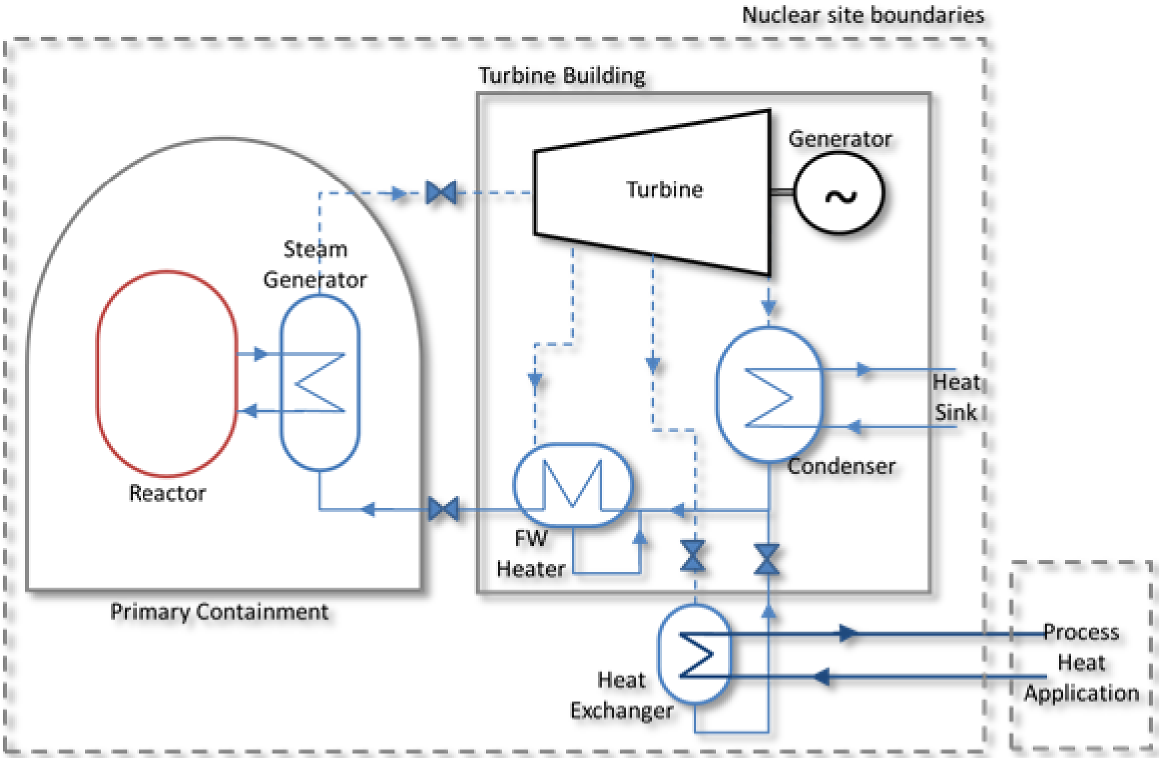

FIG 2: Typical architecture for a low temperature nuclear co-generation application (components, like pumps and other valves, are not included for graphical convenience).

When the BoP is based on a Brayton cycle (potentially direct in the case of Helium-cooled gas reactors, or indirect as an option for other fast reactor concepts), the advantages of the combination of gas and steam cycles can be exploited to further increase the overall efficiency. The general architecture could be defined to optimize for a controlled extraction of high, medium and low temperature process heat. Such configurations are considered potential coupling architectures in the long-term [11].

In principle, based on the above general architecture, a good flexibility on electricity-to-heat ratio is allowed and process heat can be extracted to meet the demand, as far as within the design limitations. Higher flexibility is usually related to higher costs due to more demanding technical specifications on systems and components. Moreover, when a significant fraction of the reactor power is diverted to heat production, the electricity production will have an impact on the grid, which shall be carefully analyzed. Technically, co-generation has good synergies with the Small Modular Reactor (SMR) concept, thanks to the added flexibility deriving from multiple units of smaller size [12]. Improved safety features of advanced reactor concepts (also in the SMR range) could more easily meet regulatory requirements and be perceived as more acceptable for siting closer to population and industrial centers, this reducing heat losses along the transmission lines. The general architecture depends strongly on the selected cogeneration application. However, no detailed architecture has been developed yet. A gas secondary cycle would offer the possibility to combine a Brayton and Rankine cycle in multiple design option, thus offering the flexibility to select the most effective depending on the targeted market. The following system independent recommendations for system specifications and requirements have been identified:

- The reliability of the heat source, which is key to most process heat end-users, can be improved by construction of multiple units, by diversification of heat source (combining with fossil fired or renewable heat source), and by installing reserve capacity.
- The cogeneration system will at least need two independent barriers to the nuclear heat source. Apart from that, care should be taken to increase the pressure from the primary system to the cogeneration application. And finally the risks associated with the processes of the conventional industrial plant shall not impact the nuclear heat source and vice-versa.
- The chemical compatibility of the coolant and the process heat system may require intermediate systems.
- The safety features of the nuclear reactor should match the safety requirements of the cogeneration application and vice-versa.

4. Top-down cost estimate

In order to evaluate the economic potential of a fast reactor with cogeneration, as a starting point, the cost estimate for an nth-of-a-kind ALFRED based Small to Medium sized Fast Reactor (SMFR) has been used [13]. This cost estimate shows that, taking into account all underlying assumptions (a.o. no interest during construction is taken into account), the nominal costs including contingencies for such a reactor are about 750 M€.

The next step in the approach is to select a heat application. In order to facilitate rapid deployment and limit the economic impact, a plug-in application is assumed. This means that a nuclear heat source, in this case an ALFRED based SMFR, will be coupled with an interface to an existing heat application process. The selected heat application is based on a heat application assessed for a High Temperature Reactor with cogeneration [14]. The application is fictive but realistic and is representative for a large chemical complex which uses steam as the energy carrier between the different units. Steam has been identified as the obvious heat transfer medium if a nuclear heat source is introduced in conventional industries. This would require a minimum of modifications in existing, well established industrial plants. The selected heat application requests steam at a temperature of 220°C and a pressure of 16 bar at a flow rate of 200 t/hr. The selected, relatively low, temperature should be very well feasible to obtain with an ALFRED based SMFR operating typically with a core outlet temperature of 480°C [15]. The resulting heat demand sums up to 153 MWth. The ALFRED based SMFR is designed to produce 300 MWth at an efficiency of 41.5% when only electricity is produced [15]. Taking into account the selected process heat application, this means that 147 MWth remains to produce electricity which corresponds to 61 MWe. As it is assumed that the application is already existing, the additional systems needed to couple the nuclear heat source to the process heat application are limited. It is assumed that the extra costs are mainly associated with heat exchangers to transfer the heat from the nuclear heat source to the process heat application. As a first estimate, it is assumed that the interface costs are in the order of 20 M€. However, as these costs contain a high range of uncertainty, a sensitivity study has been performed with respect to these costs.

The economic potential of a possible cogeneration application can only be assessed if next to the energy generation costs, also the revenues are taken into account of selling the energy. A nominal electricity price of 70 €2014/MWh is assumed for the current study and for the sensitivity study a range from 50 to 120 €2014/MWh is assumed. An overview of heat prices for varying carbon prices is provided in [16]. Based on these data, it is assumed that the heat price will be in the range of 30 to 80 €2014/MWh. For the current study, the mean value of the heat price range is taken as the nominal value, i.e. 55 €2014/MWh.

The cost estimate is performed using the G4Econs (Generation 4 Excel Calculation of Nuclear Systems) tool. G4Econs is an Excel based nuclear fuel cycle simulation tool [17] developed by the Economic Modelling Working Group (EMWG) of the Generation IV International Forum (GIF). Apart from the description [17], elaborate cost estimating guidelines have been developed [18]. The tool allows the user to calculate levelised unit electricity costs by taking into account design characteristics, fuel characteristics, the associated fuel cycle and its costs, the O&M costs broken down in a code of accounts, the capital costs broken down in a code of accounts, financing costs, and contingencies. For the ALFRED based SMFR this is described in details in [13]. However, within G4Econs also the costs of a nuclear heat source coupled to a heat application are evaluated. The revenues are calculated separately based on the amounts of produced electricity and heat and the respective electricity and heat prices.

Using the information on costs (expenses) and revenues, the net profit ratio or return-on-sales is determined. As the future electricity price and heat price are highly uncertain, this is done for a fixed electricity price, varying the heat price, and for a fixed heat price, varying the electricity price. Finally, with this information, an economic comparison can be made of an ALFRED based SMFR used for electricity production only with an ALFRED based SMFR coupled to a process heat application. Figure 3 shows the profitability of electricity only production versus cogeneration in a graph using 3 dimensions. This graph allows the user to vary the heat and the electricity price simultaneously and shows the areas in which cogeneration becomes more attractive and the areas in which electricity production only is more attractive.

This 3-dimensional representation shows that in general at lower heat prices, electricity only becomes more attractive while higher electricity prices shift the transition point. When interpreting this figure one should realize that the trends are more important than the actual numbers.

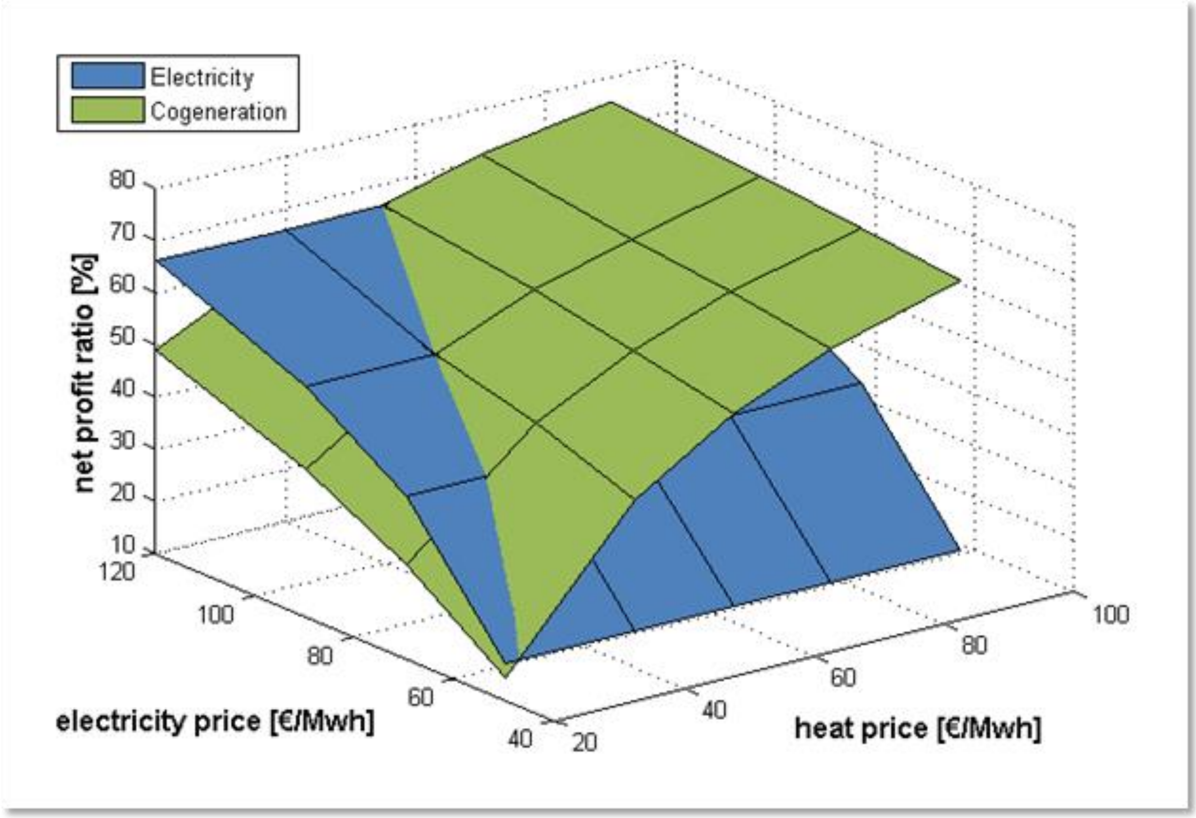

FIG 3: Profitability of electricity production only versus cogeneration

Finally, the dependence of the net profit ratio on the capital investment required for the process heat application interface is considered. In the nominal case, the assumption was made that this investment would be limited to about 20 M€. It was realized however, that this employs a large uncertainty and the actual numbers might be much higher. Therefore, the investment costs for the process heat application interface were varied over a range from 10 to 2000 M€. This assessment shows that cogeneration becomes less attractive with higher investment costs (which is no surprise). On the other hand, it has also shown that, under the current assumptions, there is a huge margin on capital investment for the process heat application interface. The net profit ratio only becomes less than zero at a huge and probably unrealistically high capital investment which is close to the upper limit of the assessed range.

5. Conclusions

The main conclusions with respect to the state-of-the-art overview on the cogeneration market with emphasis on opportunities for fast reactors, the recommendations for fast reactor systems and their interfaces with a cogeneration application, and the top down cost estimate for a fast reactor system with a typical cogeneration application are summarized below.

Identification of Cogeneration Markets for Fast Reactors

With respect to low temperature applications (<200°C), fast reactors will have to compete in an existing (mostly non-nuclear) market and above that will face competition from the well-integrated existing light water reactors. Typical application can be district heating or desalination. The latter is e.g. considered for ALLEGRO GFR demonstrator, but is in principle applicable to all systems.

With respect to medium temperature applications (~450-500°C), this is the focus of the current R&D. The required conditions are compatible with the ASTRID SFR and ALFRED LFR demonstrators.

With respect to high temperature applications (>750°C), this should clearly be considered as a long term perspective. In principle such temperatures should be feasible for all fast reactor systems but mostly for LFR/GFR. SFR will have an upper limit of about 800°C.

Recommendations for system specifications and requirements

It has been shown that the general architecture depends strongly on the selected cogeneration application. However, no detailed architecture has been developed in the frame of this article. A gas secondary cycle would offer the possibility to combine a Bryton and Rankine cycle in multiple design option, thus offering the flexibility to select the most effective depending on the targeted market. Furthermore, cogeneration has a good synergy with small to medium sized reactors, thanks to flexibility from operating multiple units of small size and improved safety features which may be realized in small power reactors. The following system independent recommendations for system specifications and requirements have been identified:

- The reliability of the heat source, which is key to most process heat end-users, can be improved by construction of multiple units, by diversification of heat source (combining with fossil fired or renewable heat source), and by installing reserve capacity.
- The cogeneration system will at least need two independent barriers to the nuclear heat source. Apart from that, care should be taken to increase the pressure from the primary system to the cogeneration application. And finally the risks associated with the processes of the conventional industrial plant shall not impact the nuclear heat source and vice-versa.
- The chemical compatibility of the coolant and the process heat system may require intermediate systems.
- The safety features of the nuclear reactor should match the safety requirements of the cogeneration application and vice-versa.

Top-down cost estimate

Given the current assumptions for the top down cost estimate of the reactor, it is recommended only to consider cogeneration at heat prices higher than a certain threshold. In general, when electricity prices increase compared to heat prices, it is economically more attractive to generate electricity only with the nuclear heat source. Finally, even if a large uncertainty in the capital investment for the process heat application interface is considered, a small or medium sized fast reactor coupled to a cogeneration application seems attractive.

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