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Preliminary study of economic viability of HTR cogeneration for industrial purposes

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Summary

This preliminary economic study sketches the main cost items and lists the key uncertainties for the cost estimation of an HTR demonstrator. It gives some illustrative figures and makes recommendations on further necessary investigations.

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Preliminary study of economic viability of nuclear cogeneration with high temperature reactors for industrial purposes

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Table of content

About the authors

LGI Consulting is a consultancy company dedicated to strategic studies, innovation consulting and project management. The firm was created in 2005 by partners who capitalised their know-how and complementary expertise. Based in France, the company has a European scope of action, particularly for setting up networks or entities for technological research and innovation, or managing large-scale or complex innovative projects. Key competences include project management, strategic and innovation-related studies, organisation consultancy, information technology management, and communication. Spoken languages comprise English, French, German, Spanish, Italian, Greek, Swedish, Czech, and Romanian. The company's main field of activity is the energy sector, where LGI has developed sectorial expertise.

This report was prepared by Alexandre Bredimas, who has a background in system engineering (French Ecole Centrale de Lyon) completed by an MPhil in Technology Policy at the University of Cambridge. He has several years of experience working in the nuclear field, at the UK Parliamentary Office for Science and Technology, at German utility E.ON Kernkraft and at French nuclear vendor Areva. He has also been a reviewer for the Elsevier's Journal of Energy Policy and is a lecturer at Ecole Centrale de Lyon in Energy policy and Ecology. In recent years he has dealt with issues related to nuclear education & training, and more generally with nuclear policy at European level, by being actively involved in the Sustainable Nuclear Energy Technology Platform.

The report was reviewed and approved by Vincent Chauvet, co-founder and managing director of LGI Consulting. He has a background in engineering (French AgroParisTech and ENGREF) and years of experience in innovation and project management in the energy sector – nuclear in particular. He is presently coordinating the secretariat of the Sustainable Nuclear Energy Technology Platform (SNETP). Among other tasks, his activity as a consultant addressed organisational projects involving opportunity studies, risk management, organisational structures assessment, costing and business cases, communication strategy, and so on.

Foreword

This report aims at introducing the economics of nuclear cogeneration for industry and comparing, on the basis of this preliminary analysis, its economic viability to supply industrial heat-consuming processes against the current reference heat production technology (gas cogeneration plant and gas boiler).

Part 1 introduces to the costing methods for cogeneration plant and points out the important uncertainties surrounding such economic evaluation.

Part 2 reports indicative production costs calculated on the basis of confidential data obtained from nuclear industry, and carries out an illustrative sensitivity analysis against the price of gas.

Part 3 identifies hot topics and makes recommendations on the key aspects that should be researched in the future to get a comprehensive view of the economics of nuclear cogeneration by HTRs.

Disclaimer

For the purpose of this study, LGI has been processing confidential data provided by nuclear industry. Details of the cost elaboration are kept confidential.

The present report must be seen as a guidance document with average figures, and does not commit either LGI or its client to any future commercial action. The assumptions and results are to be considered as illustrative and not as final figures.

1. Introduction to cost estimation

This part presents briefly the different cogeneration schemes (section 1.1), the main phases and types of costs of a cogeneration project (section 1.2). Section 1.3 lists the material project costs and their uncertainties while section 1.4 list all the other costs, in particular the immaterial costs aspects.

1.1. Cogeneration schemes

The cogeneration scheme is of prime importance for the costing. The fuel is used for producing high pressure steam. This high pressure steam can be sent directly to the end-user or can be used to generate electricity. Since energy has been drawn out for generating electricity, the steam output after the electricity generation system has a medium to low pressure and can be also used by the end-user. At all time, the end-user must be supplied with the precise energy mix and quality of steam at different temperatures and pressures and electricity he needs.

Four simple options can exist as depicted by the graph below (Kumana, Al-Gwaiz 2004):

- Mode 1a and 1b: the system targets an exact thermal match with the HP/LP steam needs of the process end-user. This incurs either a power deficit or surplus. The balance of power is then imported or exported.
- Mode 2a and 2b: the system targets an exact power match with the end-user need but this leads to either a steam deficit or steam surplus. In the latter case, steam is ejected in a condenser and the energy is lost. In the former case, LP steam deficit must be made up with the HP feed.

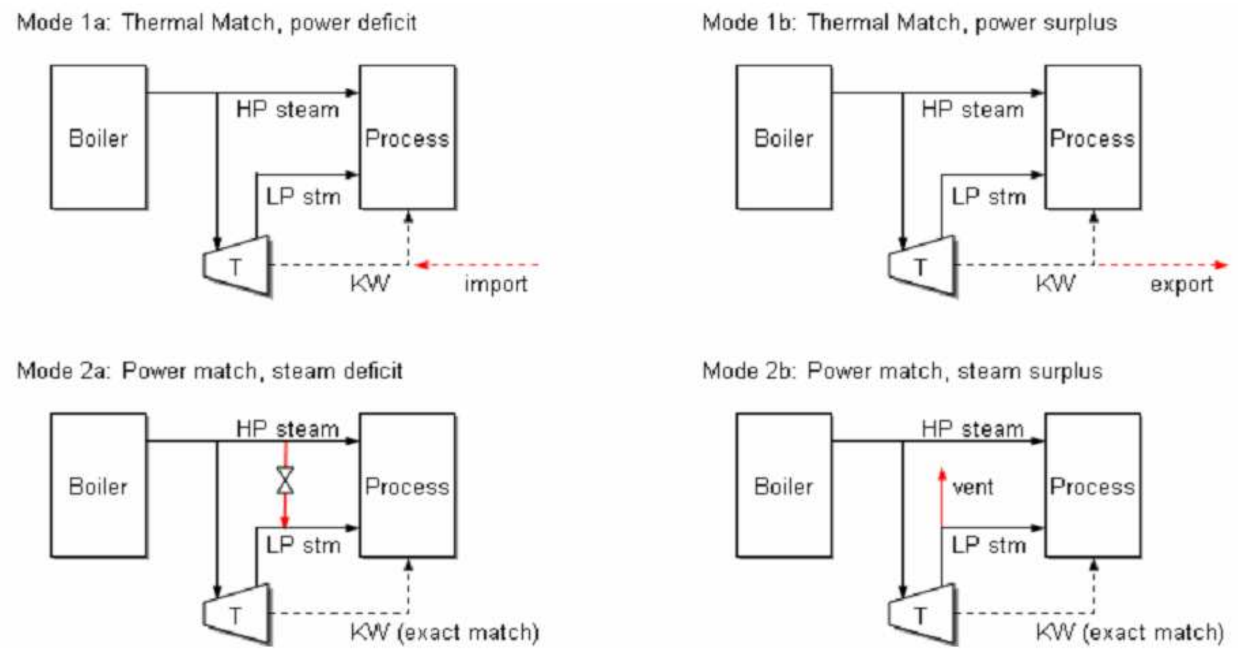

Figure 1 Generic cogeneration modes (Kumana, Al-Gwaiz, 2004)

Owing to high transport and storage losses, heat has to be consumed locally while electricity can be fed in and drawn from the electrical network in a flexible manner.

The thermal match is therefore the priority for industrial cogeneration. In particular, the high pressure steam flow must be sized in order to fit the end-user HP and LP steam needs. Depending on the energy needs of the end-user, the sizing and cogeneration arrangement may yet provide both an exact thermal and electrical match.

In any case, the chosen strategy will impact the size and cogeneration arrangement of the plant to be built, and following its cost. The requirements for steam specification for industrial purposes have a major impact on the overall performance of the cogeneration plant (production rates of steam and electricity) and then on its viability.

1.2. Cost structure of a cogeneration plant

A cogeneration plant, like any industrial project, demonstrates a general cost structure over time as depicted in the figure below. This figure sketches schematically the yearly cash movements from the point of view of the plant operator during the whole plant lifetime up to dismantling.

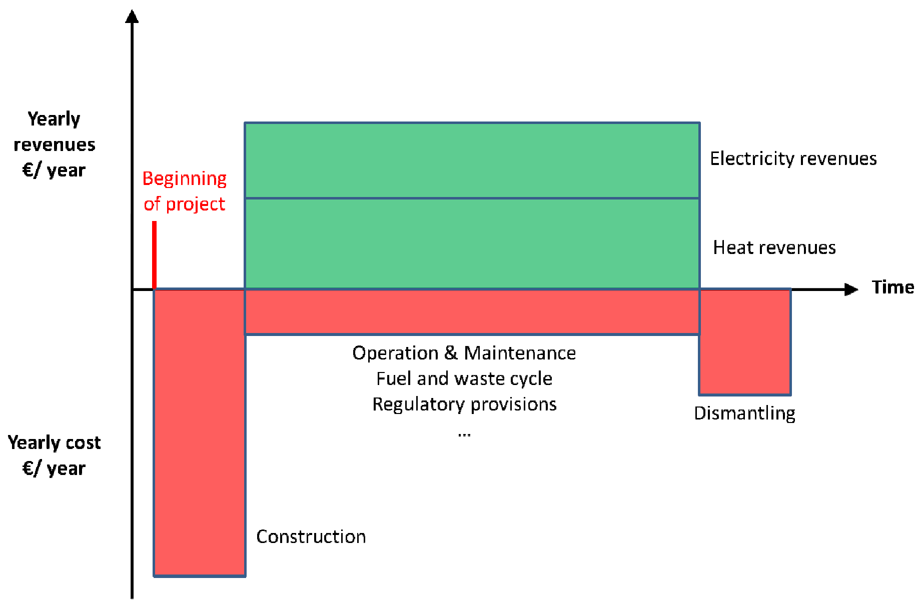

Figure 2 Generic cost structure of a cogeneration plant project

- Construction costs are upfront, generally high investment costs during the restricted duration of the plant construction. They depend on the installed capacity and are expressed usually in €/kW
- After commissioning, the plant operation and maintenance incurs yearly costs, which can either be fixed (depending on the installed capacity, in €/kW) or variable (depending on the past production volume, in €/MWh).
- During operation, the fuel must be bought and diverse provisions must be made following the national regulations in force. Back-end cycle costs must be added in the case of nuclear energy (waste retreatment and disposal). These costs are typically variable, i.e. correlated to the heat and electricity production.

- At the end of the operation period, the power plant has to be decommissioned and dismantled, leading again to some costs to be distributed over the dismantling period. They depend on the installed power and are usually a fixed part of the construction cost.

Revenues come from the sale of heat to the heat end-user (usually through long-term supply contracts). Electricity can be sold to the end-user, usually through long-term contracts and the excess electricity can be fed in the grid (usually sold at market price or at a fixed feed-in tariff in certain countries supporting cogeneration). Net heat production costs can be calculated by deducting the revenues from electricity sold to the market (depending on the electricity/heat generation ratio of the plant).

Each project is compared with respect to its production cost in € / production unit, €/MWh finally delivered to the end-user in the form of heat and/or electricity for cogeneration projects.

Valuing heat produced by a cogeneration plant has been a long-lasting and difficult debate. The usual methodology is to consider one product at its market price (typically electricity) and to value accordingly the other but this may lead to inconsistent results (Kumana, Al-Gwaiz, 2004).

Many assumptions intervene in cost estimation, making it a complex task and giving a result with an uncertainty margin.

1.3. Cost estimation parameters: the main technical drivers

The costs driver required for the determination of overnight construction costs and productions of nuclear power plants are detailed and described in this section. Taken into account the maturity of such R&D projects, cost assessment is bounded by important range of uncertainty. The roots of this uncompleted knowledge are detailed below

<u>Construction</u>

Construction costs derive mainly from the type of design, the necessary preliminary work and the construction and commissioning effort itself:

- RD&D activities in case of a demonstrator to advance and prove certain aspects of it
    - Salaries and effort of scientific staff involved, research facilities used to validate component materials or subsystems, etc.
    - Uncertainty relates to the fundamental risk of research and development, an activity in which the return is unsure
- Pre-construction costs
    - Licensing costs, site permits, plant studies, safety reports
    - Uncertainty relates to the licensing and regulatory risks but the cost ranges are small.
- Engineering phase: to make a detailed design specifically adapted to the specific project (end-user requirements, site characteristics and environment conditions...)
    - Salaries and effort of engineers and their overheads
    - Uncertainty relates to some blocking points which may be identified for a specific new build project (availability of water, siting issues, customer specific requirements, etc.) which demand specific adaptations to the detailed design

- Component fabrication and procurement in order to manufacture all subsystems and their component to be installed in the plant (following the detailed design)
  - Salaries and effort of manufacturing staff and their overheads, raw material prices, manufacturing costs, delivery costs, energy costs, subcontracting costs, etc.
  - Uncertainty in product cost relates to the volatility of each cost, in particular the prices of raw materials and energy costs, and to a lesser extent manufacturing costs.
- Construction and commissioning
  - Construction and commissioning are the phases during which the civil works are carried out, the components and subsystems are mounted and tested and the whole plant is thoroughly tested. It is a major cost for nuclear energy due to the complexity of the installed systems and this is where the major uncertainty lies.
  - Salaries and effort of the construction staff on site and overheads, subcontracting costs,, site and climate characteristics, availability of infrastructures and construction equipments, pre-operation tests, etc.
  - Uncertainty here relates mainly to the project planning and the construction time, and the siting which impacts the local staff cost and the construction environment.

The so-called owner's costs include the costs for the site, the cooling infrastructures, the administration and associated buildings, the site works, the switchyards, the project management and the licences.

<u>Operation, fuel and maintenance</u>

- Operation and maintenance costs are rather well known for nuclear energy. Most of them are fixed (independent from the energy produced in the year)
  - Operation costs includes the staff costs and raw materials buying and processing (e.g. boron, water demineralisation); these costs are mostly fixed
  - Uncertainty is generally low because the number and profile of staff necessary to operate a plant is known in advance, as well as the inputs and outputs of the reactor in operation.
  - Maintenance costs appear during the short periodic maintenance breaks of nuclear plants in parallel of refuelling activities and include the cost of replacing equipments and the temporary staff hired during the break. These costs are also mostly fixed since they follow a maintenance programme defined in advance.
  - Uncertainty relates to the duration of the maintenance break, depending on the events which occurred during operation in the past period. Usually, the more important the event, the longer the maintenance and reparation time.
- Fuel costs depend on the cost of mining, transporting ores, converting uranium ores, enriching, fabrication and back-end operations on nuclear fuels and assemblies. They represent the principal variable costs of nuclear energy and are rather negligible in comparison to the O&M costs.
  - Fuel costs depend on the cost of each phase but are in the case of nuclear energy very low in comparison to operation and maintenance costs because a nuclear plant consumes a few tons to a few tens of tons of fuel per year only, depending on the

reactor type and size. The costs of back-end fuel cycle depend on the waste management policy implemented nationally.
  - Uncertainty is rather low and relates to the uranium ore prices and each industrial phase. Uncertainty may increase following the back-end cycle, but the impact on the energy production cost remains marginal.

Dismantling

- Dismantling is a specific activity where different options can be chosen: either short dismantling time with high costs for manipulating highly radioactive materials or long dismantling time letting highly radioactive materials decay to a lower activity
- Uncertainty relates to the dismantling planning, the radioactive inventory of the materials in the plant, the staff costs (including its necessary equipment).

Comparison with a gas cogeneration plant

Uncertainty in gas cogeneration plant projects is rather similar except that:

- The gas technologies in operation today are rather well known and the construction itself does not represent any major uncertainty, except that cogeneration plants are complex systems. Yet, environmental policies may at some point impose to equip gas plants with carbon capture and storage equipment, which represent a costly and still unknown investment, since the technology is being demonstrated and requires CO2 transport networks and logistics. Construction costs account for around 5% to 10% of the final energy production cost.
- The operation and maintenance costs have also a high variable part (contrary to nuclear which is mostly fixed); this variable part derives from the ageing of materials and components during the plant operation and implies cost uncertainty. CO2 emissions costs are also adding a significant uncertainty. O&M costs account for 5% to 10% of the final energy production cost.
- Fuel costs are high, potentially fickle and unpredictable and represent 80% to 90% of the total production costs; uncertainty is then directly related to gas prices and is particularly high.
- Another aspect is that gas plants consume several millions and up to several billions of cubic meters of gas each year while the storage capacity of gas is low. The security of supply is therefore a critical issue and requires implementing costly mitigation strategies (e.g. commissioning liquefied natural gas storage facilities).
- The dismantling (as well as construction) planning is rather well known since there are no major issue like radioactive materials.

The uncertainty of nuclear and gas cogeneration technologies do not appear at the same project phase. Nuclear has a high upfront uncertainty during construction but is rather secure afterwards whereas gas has the highest uncertainty during operation.

1.4. Risk of a cogeneration project

Whatever the cogeneration technology, the plant must be built at a specific site, under specific environmental conditions and heat must be transported on a given distance with a certain quality to the end-user.

All these arrangements incur further costs, and consequently additional uncertainty. National and international regulations on safety and security for gas and/or nuclear energy may impose constraints on the distance between the cogeneration plant and the end-user facility as well as technical requirements on the heat transport pipelines and coupling scheme.

Furthermore, the mix of steam supplies at different pressures may be made at the cogeneration plant by the cogeneration scheme or by the end-user itself, which may use high-pressure steam directly and produce low-pressure steam through its industrial processes. This has to be agreed upon between both the operator and the end-user and this will impact the cogeneration scheme.

The end-user is submitted to several risks which all impact indirectly the cogeneration project.

The figure below provides a non-exhaustive list of risks intrinsic to both the cogeneration plant and the end-user, the coupling and near environment and the overall context.

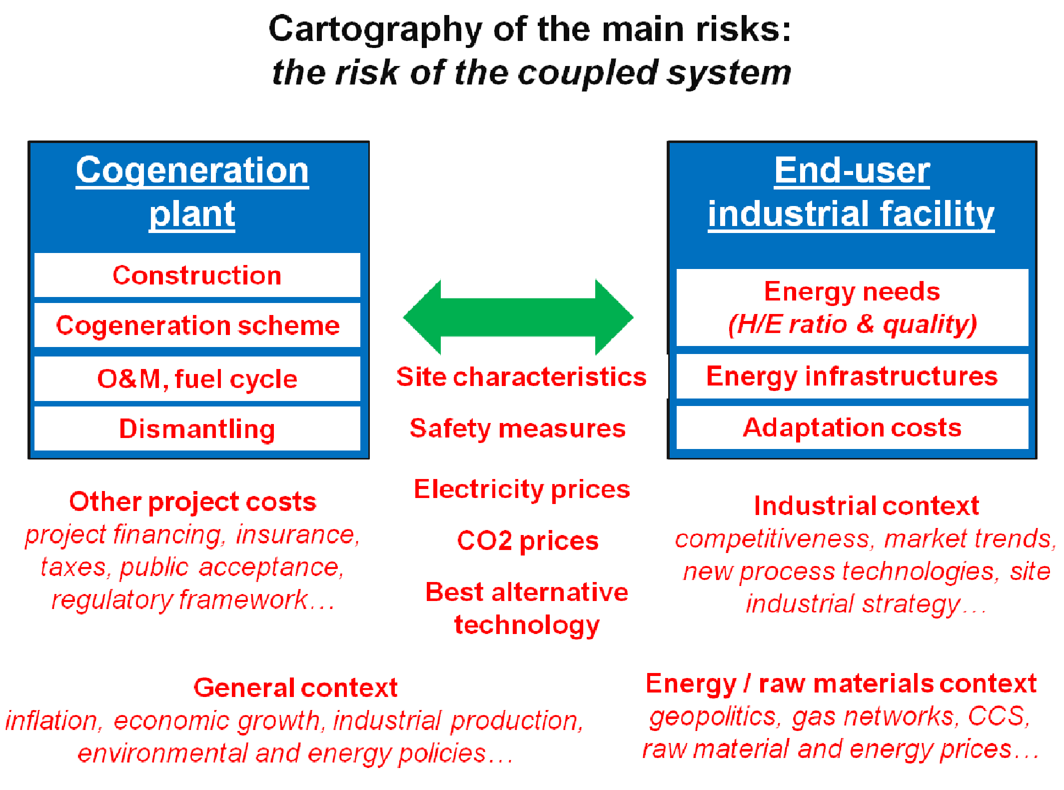

Figure 3 Key uncertainty factors for the evaluation of the economic viability of nuclear cogeneration

The overall risk results from the multiplication of every individual risks and their interrelations.

Listing all risks and estimating all costs and their uncertainty range precisely is therefore a major issue which has to be addressed in a future report, possibly based on realistic case studies.

1.5. Other aspects impacting in the cost estimation: financing and marketing issues

Project financing

A project is generally financed either by debt or by equity. In each case, a return on investment is required by the financial partner in the form of interests or dividends.

The weighted average cost of capital depends on:

- The project characteristics (construction duration and key steps principally)
- The financing structure (type of investors, portfolio of debt, equity, own effort...)
- The loan structure and duration
- The risk of the project and the end-user's sector

The financing costs may be lowered if the buyer or the buyers of the plant (in case of a joint ownership from several industrial and/or financial stakeholders) have pre-existing self-investment capacities and if one or several public authorities (national governments, regional authorities, European or international institutions, public financial organisations...) provide some public support to the project, in the form of pre-financing, direct public investment (debt or equity), loan guarantees, tax incentives, etc.

Insurance and provisions

As any energy project, a cogeneration plant operator needs to subscribe to insurance contracts. International treaties concerning possible accidents of nuclear civil plants demand also to finance a provision fund which may reimburse the damages and victims of a potential nuclear accident.

Cost escalation factors

Cost escalation factors can impact the construction costs, in particular inflation, prices of raw materials, energy prices, industrial manufacturing indexes, taxes, trade tariffs, transport costs, social costs, etc. These assumptions can significantly impact the final cost estimate.

Similarly, the production costs for the end-user, even through long-term contracts, are usually indexed on external economic factors such as the spot price of the fuel, inflation rate, interest rates, etc.

Cost escalation factors and long-term contracts raise more generally the question of how far heat and electricity producers can transfer the volatility of their production costs to the end-user. The risk is usually shared contractually on a common basis between the CHP producer and its end-users.

Expected revenues

Revenues from potential by-products are also a key aspect, but they are also subjected to some uncertainty (produced volumes and/or market price). For cogeneration, heat is generally sold in the form of steam through long-term contracts with relatively stable but indexed prices to local end-users. Electricity may be sold partly to the end-user through long-term contracts and partly to the grid at the electricity gross market price, which itself depends on the electricity production mix and the demand and offer balance. This revenue may therefore fluctuate over time and impact the financial evaluation of the project and the net production cost of heat to end-users. Revenues from electricity depend on the electricity/heat ratio of the cogeneration plant.

Expected economies of scale

Another source of uncertainty in cost estimation comes from the economies of scale that can be expected from

1/ the thermal capacity to be installed: the higher the thermal capacity, the lower the construction costs per kW a priori but major thresholds limit the size of the power plant due to the manufacturing capacity and the cost of additional safety systems.

2/ the construction of several nuclear cogeneration plants, i.e. the cost decrease of a NOAK (nth of a kind) as compared to the cost of a FOAK (first of a kind); such economies of scale derive mainly from the accumulated experience for construction and licensing, which can be difficultly estimated.

3/ in-series production of standardised modular plants may incur also savings but this is difficult to assess, like for NOAK economies of scale; experts estimate that the economies of size overweight the economies of replication.

Impact of time as a key parameter

The factor “time” or “duration” is a key parameter for economic evaluations. Firstly, the construction duration will significantly impact the total construction costs, including the financing costs based on the estimated intrinsic construction risk. Secondly, the high upfront investment for a cogeneration plant will be paid back after a certain time only so the depreciation period has to be carefully determined according to the expected operational lifetime of the plant. Should the plant stop operating before the depreciation period ends, the project would face net losses.

Other aspects impacting the total cost of production

Finally, the uncertainty aspects reported above relate only to the cost of production of the cogeneration plant. They do not include:

- The heat and electricity transport infrastructures to the end-users
- The adaptation measures in the end-user’s facility and processes to accommodate a cogeneration plant, in particular a nuclear one
- Site specific issues, like site characteristics, industrial surroundings, safety measures, exclusion zones between the cogeneration plant and the end-user facility...
- The end-user’s heat quality requirements: end-users would consume nuclear heat in the form of steam at a given temperature, pressure and purity but the mix of steam qualities is unique in each end-user facility so the nuclear steam production and operation system is unique. The cogeneration mix of heat and electricity is therefore also unique.
- The electricity arrangement mechanisms in order to valorise any unused heat for generating electricity. The arrangement must be a technical and economic optimum depending on the characteristics of the end-user’s heat consumption.

These costs are important to estimate, especially as regards nuclear cogeneration. They should be also based on real case studies.

Viability analysis

Finally, it must be noted that the viability of nuclear cogeneration is established in comparison with the best alternative technology, namely gas cogeneration plants or industrial gas boilers; coal cogeneration may also be a competitive technology in countries where coal is cheap or widely used (e.g. Poland). Depending on the economic factors of these technologies, nuclear may be found competitive or not. Yet, the economic evaluation of these gas technologies is also subject to large uncertainties, amongst others: gas price, gas security of supply, gas infrastructure, environmental and CO2 policies, carbon capture and sequestration progress and economics, public regulations (e.g. on long-term gas supply contracts), cogeneration technologies economics and end-user site characteristics (e.g. production of calorific off-gases that can be burnt in a boiler or process furnace).

The complete viability analysis of nuclear HTR cogeneration requires therefore an extensive technical and economic investigation.

1.6. Information sources on high temperature nuclear reactor cost evaluation

High temperature reactors have already been and are still being tested in several experimental facilities: Dragon (UK, 1963-1976), AVR (Germany 1967-1988), Peach Bottom 1 (USA, 1967-1974), HTR-10 (China, 2008-), and HTTR (Japan, 1998-).

Demonstrators of HTRs include Fort St. Vrain (USA, 1976-1989, prismatic design) and the THTR-300 (Germany, 1983-1989, pebble bed design).

Yet, no robust economic data have been gathered on the operational phase. The Fort St. Vrain has been a proof-of-concept rather than a first-of-a-kind, i.e. some systems and technologies were still in a test status during operation (see for instance Moses and Lanning, 1985).

The German THTR-300 was rather a HTR first-of-a-kind but it was operated only for a short period. It was commissioned in 1983, first generated electricity in 1985 and was decommissioned in 1989, following a political decision after the Chernobyl accident.

The previous references, although quite old, provide interesting figures for the feedback of proof of concept model but economic evaluation for industrial purposes require proof of performance for industrial power plant.

Some attempts have been made to evaluate the production costs, especially for local projects (see for instance Van Heek 1996, Kupitz, 2000); the Generation IV International Forum WG on Economics Modelling has in particular issued guidelines (GIF 2007) and a software to support the economic evaluation of Generation IV nuclear systems, including HTRs (so-called G4-ECONS Software Package). This work is probably the most up-to-date and representative one, since GIF gathers all nations envisaging GEN IV systems. The NGNP initiative has also produced interesting papers and economic pre-assessment of HTR technology.

Nuclear vendors are yet the best source of information and they may have the most precise estimate of construction costs. All costs related to plant operation may yet be less precise.

2. Cost comparison for HTR and gas technologies

This section presents illustrative results based on confidential data obtained from the nuclear industry. The objective is to present rough estimates of nuclear heat production costs. As mentioned in the previous section, such projects face numerous uncertainties so it is impossible to reproduce in a short study all the possible cases. The methodology is therefore very simple and its results are to be considered only as illustrative and in no case as final and precise.

2.1. Overview of the methodology

The general methodology for this study is to:

1. Sum up all costs (in €), including the construction, the fuel, the O&M and the financing costs.
    a. The construction and O&M costs are calculated based on the economic evaluation of real costs during construction and the expected O&M costs during operation.
    b. The fuel costs are calculated for every phase (mining, conversion, enrichment, fabrication of nuclear fuel and fuel assemblies and back-end cycle costs).
    c. Dismantling costs are calculated as a provision generated at a risk-free rate during the plant operation in order to reach 15% of the overnight construction costs at the decommissioning date.
    d. The generic financing costs (debt and equity) are calculated with an annuity factor based on the lifetime of the cogeneration plant at a representative financing rate
2. Deduct the expected revenues from electricity sales to the grid (in €)
3. Divide this total net cost by the expected heat production during the whole lifetime of the plant (in MWh), depending on the expected load factor.

Time is taken into account by discounting all costs following the year at which they are expected.

2.2. Scope and general assumptions

Two high temperature nuclear reactor designs are compared with a gas cogeneration plant and a gas boiler. The main assumptions for the present study are reported in the table below:

Table 1 Assumptions of thermal power, availability, lifetime of the pebble bed and prismatic reactor designs and CCGT and gas boilers

Technology	Thermal power	Availability	Lifetime	Remarks
Pebble bed HTR	250 MWth	95+%	40 years	Pebble bed reactors use nuclear fuels in the form of spheric pebbles moving down through the reactor pressure vessel; since fuel pebbles can be removed and replaced during operation, the load factors of this type of reactors can be very high (95%).
Prismatic HTR	625 MWth	91%	40 years	Prismatic reactors look like current pressurised water reactors with fuel being organised in rigid assemblies in the reactor pressure vessel; this reactor design enables to reach safely higher thermal power capacities than pebble bed reactors.
CCGT	750 MWth	91%	30 years	
Gas boilers		91%	30 years	

The electricity and heat production ratios of CCGT are assumed to be 50% heat and 35% electricity, that is to say an overall efficiency of 85%

The electricity and heat production ratio of both HTR plants is assumed to be 70% for heat and 15% for electricity, with an overall efficiency of 85% as well.

The difference in heat and electricity production ratios comes from the different schemes of nuclear and gas cogeneration. CCGT use a combined cycle (one for electricity, one for heat production) whereas nuclear would operate only one thermal cycle for both heat and electricity cogeneration. Nuclear reactors may achieve similar ratios than CCGT but this would require different steam temperature and specific trade-offs.

The steam is sent via the steam network to the end-user facility while electricity is sold to the grid (in order to compensate for the net heat production cost) at a supposed market price of 55 €/MWh.

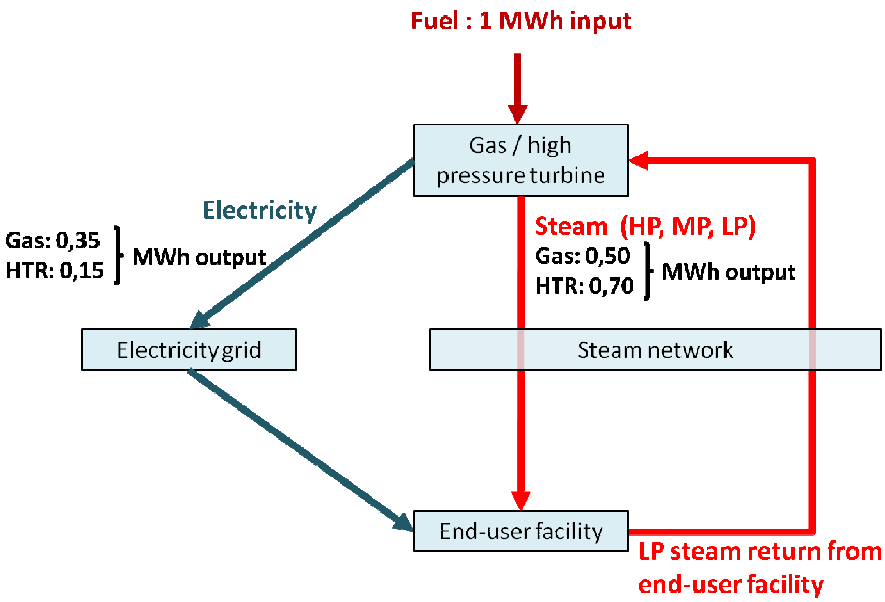

Figure 4 Assumption on the cogeneration scheme for gas and nuclear cogeneration plants

As noted in part 1, this assumption represents a specific arrangement and therefore a specific heat production cost. It is not representative of all cogeneration schemes, nor does it allow evaluating the overall energy cost for the end-user.

2.3. Capital costs

Overnight Construction Costs

Table 2 Assumed overnight construction costs for each technology

Plant type	Overnight Construction Cost estimates (€/kW thermal input)
Prismatic HTR 625 MWth	1 500 - 2 250
Pebble bed HTR 250 MWth	2 100 - 2 900
CCGT 750 MWth	500 – 700
Boiler Gas	200

The gas technology is clearly cheaper to build but the total production cost depends also on the costs during the operation of the cogeneration plant, including the fuel costs.

It must be noted the following:

- As presented in part 1, these cost estimates depend on numerous assumptions which should be investigated in more details. In particular, the influence of external economic factors should be assessed in details.
- HTR plants have been built in several places but the designs considered include several advances compared to the historical demonstrators. The R&D costs should be considered, at least partly, in the construction costs and the comparison with past HTR should be carried out carefully.
- The above construction costs would concern plants to be built in Europe

The HTR prismatic reactor has lower overnight construction costs than the pebble bed reactor because it is assumed to take benefit from economies of scale of a large installed capacity partially counterbalanced by a series effect for the same power installed. The capital cost data for the CCGT plant is rather certain, since this technology is today well established.

Project financing

The financing of the construction project can have different schemes. Independently from the debt/equity ratio, a weighted average cost of capital (WACC) is assumed to be 8% which is an averaged figure used in international economic study.

A standard spending profile would generate a financial burden during the construction period; due to difference in construction durations (5 years for HTRs, 2-3 years for CCGT).

Nuclear power is capital intensive investment so every modifications during the project in terms of time and cost definitely has a strong impact on financing cost and then in production costs. The sensitivity of the total capital cost should be assessed against the possible financial structures of the project. Although nuclear financing was widely analysed in the past, the sensitivity analysis for HTRs may be different: 1/ the financing structure (i.e. the cash flows over time) will depend on the construction planning, which depends on the design; 2/ the financing of a new technology is likely to be different from an established one; and 3/ the legal arrangement for a new nuclear cogeneration plant is likely to involve at least the nuclear vendor, the nuclear operator and the heat end-users, an arrangement which is not common for current nuclear power plants so the financing structure should have a specific sensitivity.

2.4. Costs during operation

The main cost assumptions during operation are the operation and maintenance costs, the expected operational lifetime and capacity factor, the fuel and fuel cycle costs and ultimately the decommissioning and dismantling costs. Other costs include taxations, fuel transport costs, regulatory provisions against accidents, raw material prices (e.g. gas), energy infrastructures and possible necessary refurbishment costs.

Gas is assumed to cost 40 €/MWh (equivalent to a price of 11,72 €/MBTu, in the highest part of current gas prices range (7-11 €/MBTu). The ratio LHV/HHV considered for fuel cost calculation is 9/10, gas prices in Europe are assumed to be expressed in HHV. The CO2 price under the Emission Trading Scheme is assumed to amount to 20 €/tCO2, which is in the range of CO2 prices observed in Europe.

The market price at which the generated electricity is integrally sold is assumed to be 55 €/MWh. This price corresponds to a baseload electricity price and is therefore in the low range of electricity gross market prices.

It is assumed that there is neither inflation nor taxes.

2.5. Illustrative results

The resulting heat production costs are reported in the graph below.

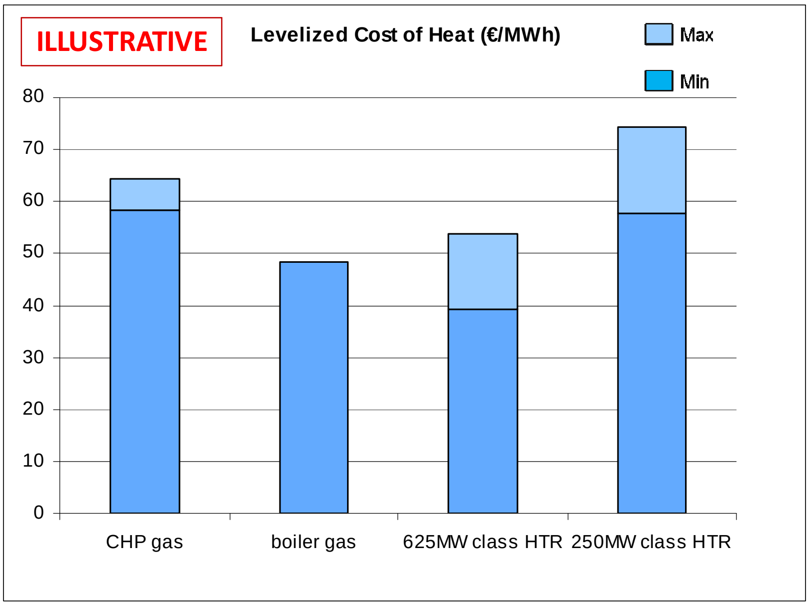

Figure 5 Illustrative results of the calculation of levelized cost of heat in €/MWh

On the gas technologies side, the gas boiler is more competitive for heat production than the gas cogeneration plant, which reflects the fact that the technology is simpler.

Regarding HTR systems, the prismatic design is found to be competitive to both gas technologies while the pebble bed design has similar heat production costs.

For gas, capital expenditures represent around 10% and operational expenditures 90% of the production costs, a sensibly different distribution than nuclear technologies which have CAPEX representing around 60% and OPEX 40% of the production costs.

2.6. General sensitivity analysis

The sensitivity of these results has to be assessed against all identified uncertainties in order to get a robust cost estimate range. Otherwise, the economic analysis remains only a partial vision of the issue.

As a matter of illustration, the sensitivity of all technologies against the price of gas is depicted in the following figure:

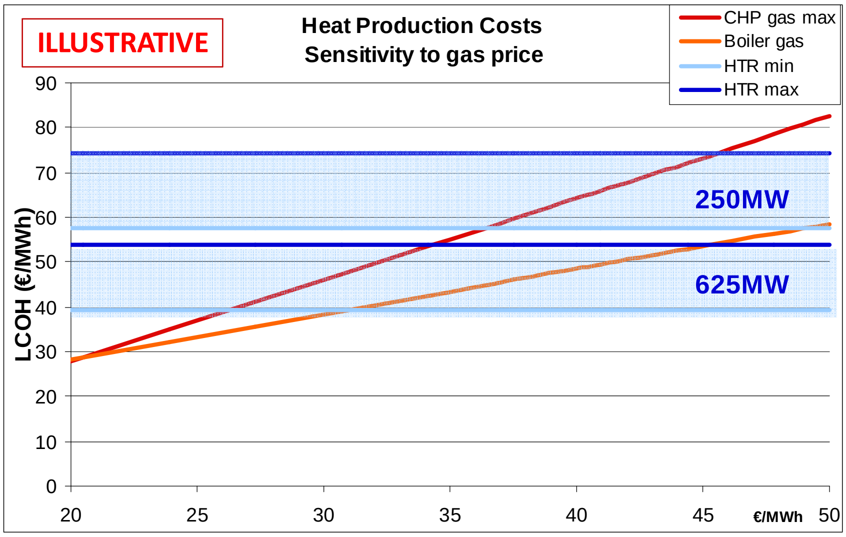

Figure 6 Heat production costs sensitivity against gas price

The prismatic HTR design is found to be competitive with a gas cogeneration plant between 26 and 38 €/MBWh and with industrial boilers between 35 and 45 €/MWh. The pebble bed design would become competitive with a gas cogeneration plant from approximately 36 €/MWh and with industrial boilers from around 49 €/MWh.

This sensitivity analysis illustrates how uncertainty can affect the economic viability of a nuclear cogeneration plant but it should be complemented by a full and detailed analysis on the context of gas and electricity.

First, electricity prices may be correlated to gas prices because gas power plants are used in many Member States as a marginal production capacity. The revenues from electricity sales are susceptible to increase with higher gas prices and this would ameliorate further the business case of cogeneration technologies, including nuclear cogeneration.

Considering a nuclear heat cost independent from gas price is therefore a first order approach that should be ameliorated with a correlation analysis of electricity and gas prices in relevant European countries. Indeed, the electricity generation mix may depend more or less on gas power plants and therefore depend more or less on gas prices.

Second, today's gas prices vary in the range of 25-40 €/MWh but the price trend is very unclear. Geopolitical tensions with gas-rich countries like Russia or Algeria as well as reserves depletions in Europe could push the gas prices up. On the contrary, the development of Liquefied Natural Gas infrastructures (LNG tankers and re-liquefiers) as well as the exploitation of new gas resources (like shale gas) could decrease the pressure on prices. Yet, it is difficult to foresee what will be the price of gas in Europe specifically.

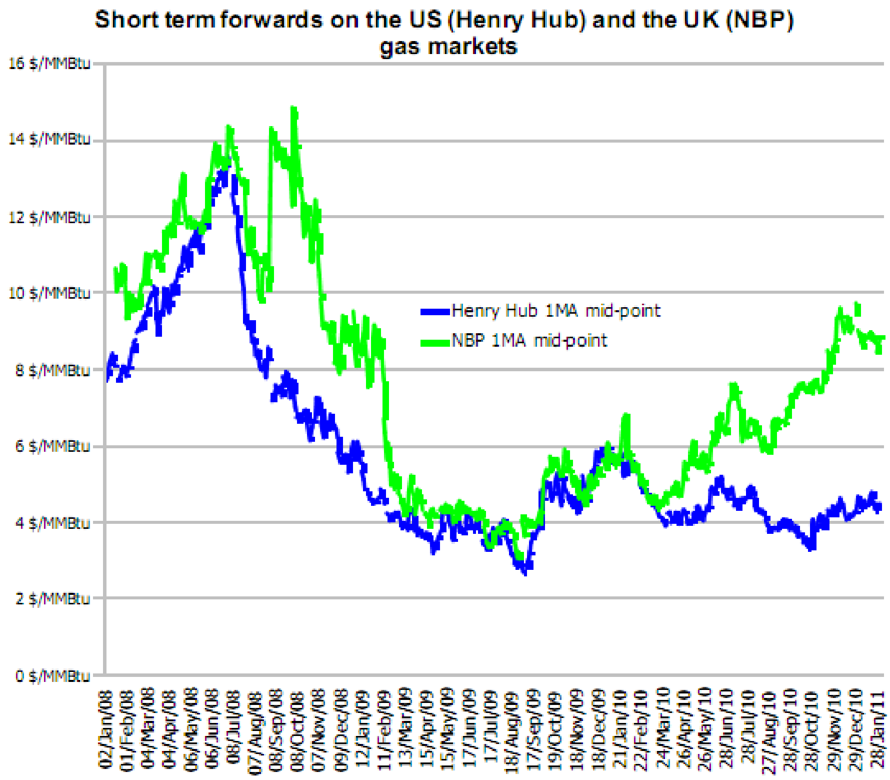

Figure 7 Quarterly report on European gas markets (Source: European Market Observatory for Energy)

Indeed, as an illustration, the US and European gas prices have been diverging since the uptake of shale gas in the US. This additional resource has made decrease the price of gas in the US but not in Europe, which does not produce any shale gas.

The price of gas in Europe may therefore diverge and keep up increasing. This situation would weaken significantly the European industry. If energy becomes too expensive, industry will have no choice but to delocalise its factories, as it has been the case for instance for the aluminium industry. This potential risk supports very much the development of an alternative low-carbon competitive technology like nuclear cogeneration.

3. Synthesis and recommendations

Synthesis

This report aims at listing the key cost items for a cogeneration project and at pointing out the numerous uncertainties of a cogeneration project, whether based on a nuclear or gas technology.

The project risk results not only from the intrinsic risk of the cogeneration technology and of the end-user industry but also from the relation between both and the site environment and from the overall political, environmental, economic, industrial, energy and raw material contexts. The overall risk results from the multiplication of every individual risks and their interrelations.

The advantage of nuclear is to concentrate most of the risk during construction and be rather secure after the commissioning of the plant, while gas cogeneration is highly uncertain during the plant operation due to the gas price volatility.

An illustrative calculation shows that nuclear high temperature reactors may be competitive with gas technologies, already at current gas prices.

A thorough economic evaluation of nuclear cogeneration should therefore reflect at least all uncertainties which were identified in this report.

Recommendations

In order to support future economic assessments from the preliminary findings of this report, it would be recommended to:

- Analyse the costs of each high temperature reactor design in order to limit the uncertainty margin on overnight construction costs, operation and maintenance costs, fuel and fuel cycle costs, dismantling costs

- Analyse the impact of economies of scale from the power capacity, the replication of in-series modular reactors and the construction experience (first-of-a-kind vs. nth-of-a-kind)

- Assess the possible cogeneration schemes (heat/electricity production ratios) and their impact on costs

- Analyse the influence of site-related issues and possibly establish a generic site boundary condition envelop that may help the evaluation of site-related economic aspects: average salaries, productivity, site characteristics, industrial surroundings, population distribution, distance between the cogeneration plant and the end-user facility, engineering needs

- Analyse the different project financing options and their impact on capital costs in comparison to the overnight construction costs

- Evaluate the mutual benefit of public private partnerships and original ownership arrangements (nuclear operator, heat end-user, joint ownership between several end-users, etc.)

- Analyse the external context of nuclear cogeneration and its impact on the project costs: international conventions, energy policies, environmental policies, tax incentives, nuclear safety regulations, local tax structures, electricity prices

- Evaluate the end-user related costs, possibly through selected case studies: process adaptation costs to nuclear cogeneration, energy infrastructures, facility operational characteristics, energy needs, industrial context, etc.; like for the site-related aspects, an operational boundary envelope could be established for end-user facilities in order to prepare the general engineering of FOAK projects.

- Assess the best alternative technologies over time: currently, gas cogeneration is the reference technologies and the overall context of gas should be taken into account (e.g. gas price, security of supply, gas infrastructures, carbon taxation, CCS deployment)

- Develop business cases in order to model the business opportunities of each stakeholder (nuclear vendor, nuclear operator, heat end-users, engineering companies, banks, public authorities, society, investment companies, etc.)

- Carry out comprehensive sensitivity analyses through dedicated methods like Monte Carlo cost benefit analysis or real options modelling

Bibliography

(GIF 2007) Cost estimating guidelines for generation IV nuclear energy systems, Economic Modelling Working Group, Generation IV International Forum , Revision 4.2, September 2007, http://www.gen-4.org/Technology/horizontal/EMWG_Guidelines.pdf

(Kumana, Al-Gwaiz 2004) Marginal cost of steam and power from cogeneration systems using a rational value-allocation procedure, Kumana J., Al-Gwaiz M., Saudi Aramco, April 2004, http://repository.tamu.edu/bitstream/handle/1969.1/6042/ESL-IE-04-04-31.pdf?sequence=4

(Kupitz, 2000) Small and Medium Reactors: Deveopment status and application aspects, Kupitz J., Nucler Power Technology Development Section, International Atomic Energy Agency, April 2000, http://users.ictp.trieste.it/~pub_off/lectures/lns005/Number_2/Kupitz.pdf

(Moses and Lanning, 1985) The analysis and evaluation of recent operational experience from the Fort St. Vrain HTGR, Moses D., Oak Ridge National Laboratory, Lanning W., US Nuclear Regulatory Commission, May 1985, http://www.osti.gov/energycitations/servlets/purl/5535126-kBPx7R/5535126.pdf

(Risto and Alja, 2008) Comparison of electricity generation costs, Faculty of Technology, Lappeenranta University of Technology, 2008, www.doria.fi/bitstream/handle/10024/39685/isbn9789522145888.pdf

(Van Heek 1996) INCOGEN: Nuclear cogeneration in the Netherlands, Van Heek A., ECN, Technical committee meeting on high temperature gas cooled reactor technology development, Johannesburg, South Africa, November 1996, http://www.iaea.org/inisnkm/nkm/aws/htgr/fulltext/29026668.pdf

(J.R. Geschwindt, L.J. Lommers1, F.H. Southworth, F. Shahrokhi, 2010) Performance and Optimization of an HTR Cogeneration System, Proceedings of HTR 2010 Prague, Czech Republic, October 18-20, 2010