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Opportunity for Cogeneration in Nuclear Power Plants

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ABSTRACT

Current thermal efficiency of electric power generation from nuclear power plants is about 33%, which is rather low since the rest of the energy is dissipated to the environment as heat. Such efficiency could be increased up to 80% through cogeneration of electricity and other applications such as seawater desalination, hydrogen production, district heating or cooling, or any energy-demanding industrial application. The development of innovative reactors and fuel cycles with further enhanced safety features, improved economics and reduced generation of waste, the need for prudent use of fossil energy sources and increasing requirements to curtail the production of greenhouse gases (GHGs), and the benefits of cogeneration provide additional reasons for the revival of nuclear power in the years to come. These reasons are also expected persuade the public in favour of nuclear power.

Despite the fact that no energy conversion system is free from risk, nuclear power production has demonstrated high standards of safety, low impact on health and the environment. It is also a reliable, clean, and economic energy option with a variety of possibilities beyond electricity production. This paper discusses benefits of cogeneration of nuclear power and aspects of exploiting nuclear energy for non-electric applications aiming at drastic reduction of GHG, hence combating global warming. The paper will argue on how cogeneration for different non-electric applications could enhance further the role of nuclear energy not only to encounter global warming but also to improve quality of life allowing industrial, social and economic development.

Keywords: cogeneration; nuclear energy; non-electric applications, improving efficiency

1. INTRODUCTION

Cogeneration, also known as combined heat and power (CHP), is a very efficient; clean; and reliable approach to generate power and thermal energy from a single fuel source. Typically, cogeneration plants recover percentage of the “waste heat” that is otherwise discarded from conventional power generation. The recovered waste heat is effectively utilised in other thermal energy applications. Current nuclear power plants have low thermal efficiencies generally in the range of 30 to 35% compared to other steam cycle energy conversion systems. Such efficiencies could be increased to reach up to 80% through cogeneration of electricity with other applications such as seawater desalination, hydrogen production, district heating or cooling, or any industrial application. Countries embarking on nuclear power should consider co-generation and the use of waste heat from a NPP to increase energy utilization and overall efficiency. At the same time, if considered during prefeasibility studies, some applications of cogeneration e.g., seawater desalination, in areas of water scarcity, could provide an added benefit during NPP construction and operation. For example, a large quantity of industrial quality pure water is needed during the operation of a NPP e.g., for cooling the plant equipment, energy conversion systems, and replenishment of makeup water for steady consumption. In the absence of an inexpensive water supply source a desalination plant should be considered at an early stage.

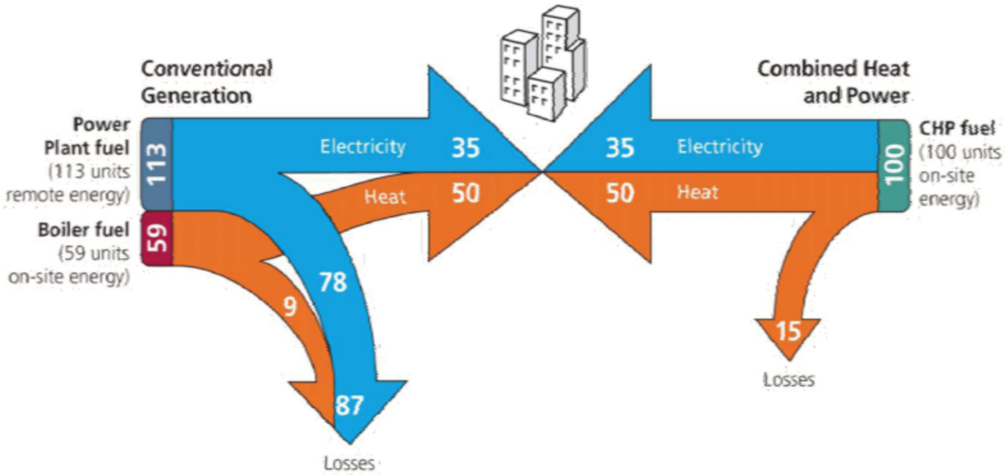

Fig. 1 Comparison primary energy savings due to cogeneration compared to conventional separate energy production

In a number of countries, co-generation and heat production using nuclear reactors is already an effective way to meet different types of energy needs. There is a considerable incentive to make use of the capacity of most nuclear plants to provide steam and heat for residential and industrial purposes. Currently, there are 79 reactors operating in cogeneration mode and the potential for applying this technology more widely appears promising. Interest at the international level is again emerging as environmental and other problems raise concerns about the burning of fossil fuels for other applications.

Heat applications cover a wide range of specific temperature requirements starting from low temperatures i.e., just above room temperature for applications such as hot water and steam for agro-industry, district heating, and sea water desalination; reaching more than 1000° Celsius for process steam and heat applications i.e., for chemical industry and high-pressure injection steam, enhanced oil recovery, oil shale and oil sand processing, oil refinery, refinement of coal and lignite, and water splitting for the production of hydrogen (see Fig. 2Fig.). Steam system could provide heat up to 550° Celsius. The upper limit of 1000° for nuclear-supplied process heat is set as a threshold based on the demonstrated properties of the metallic reactor materials.

With the rapid increase in energy demand (for both electricity and heat), concern over global warming could pave the way for nuclear energy to exert a major positive impact on energy security and climate change. Such concern could allow expansion of nuclear power to penetrate into other areas currently dominated by conventional fossil fuel such as hydrogen production for transportation sector, seawater desalination, district heating and other industrial process heat applications. Nuclear energy is a good supplier of energy for non-electrical application for the same reason that is for electricity as previously mentioned. That is, energy security, stable base-load electricity, predictable costs when compared with other volatile fuels, low-carbon footprint etc.

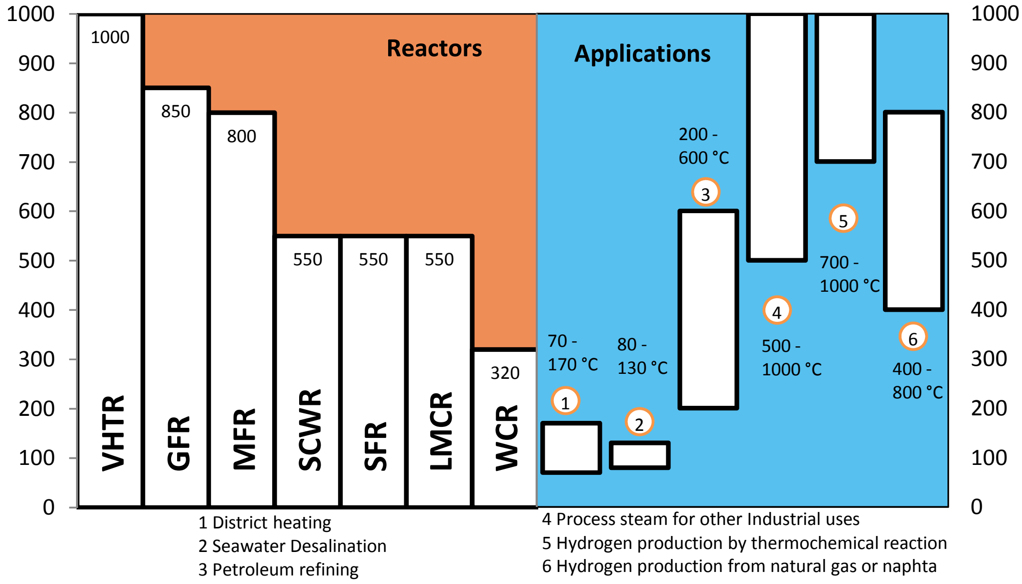

Fig. 2 Range of applicability between reactors and applications

All existing reactor types can be used in cogeneration mode. In principle, any portion of the heat can be extracted from cogeneration reactors, subject to design limitations. Cogeneration plants, when forming part of large industrial complexes, can be readily integrated into an electrical grid system to which they supply any surplus electricity generated. In turn, they would serve as a backup for assurance of the electricity supply or supplementary source for peak load periods thus providing a high degree of flexibility. Heat-only reactors, on the other hand, have only the objective of heat production, not electricity generation. This limits their operational flexibility, during times when heat is not needed (International Atomic Energy Agency 2007).

For countries having rather small grids and embarking on large capacity NPPs for economic reasons i.e., the net power output of the reactor is too big for the existing infrastructure, and at same time they are in need for process steam or heat distribution demands which also are much smaller than the output of the existing commercial water cooled reactors, then an ideal solution could be the combining process steam or heat distribution loads with electrical generation to operate in cogeneration mode, or co-locating a number of process steam users on a common site to match the available heat output from the nuclear power plant. This can help in the integration of the nuclear power plant to the existing country infrastructure, and the cogeneration of electricity and process steam may allow the consideration of other more economical alternatives during the technology assessment, while providing process steam more efficiently.

2. CONSIDERATION FOR COGENERATION

Cogeneration could be considered in the following circumstances:

- There is big demand for other energy-intensive non-electric products.
- The net electrical output of the reactor selected is too big for the electrical grid.
- There is need to secure the energy supply for industrial complexes
- The electricity demand has big seasonal variations.

Cogeneration can also be applied for off-peak period i.e., when electricity demand is low to produce desalinated water, production of hydrogen, etc. The environmental footprint of cogeneration is almost carbon-free since it is based on the nuclear fuel cycle. Depending on the type of non-electric application considered with cogeneration, there are other synergies achieved by the coupling of non-electrical application. Significant Important savings can also be achieved by sharing the resources (e.g., cold water in-take and return facilities, technical staff, etc.), utilizing waste heat from the condenser, or even enhancing overall safety aspects by establishing a possible redundant water supply in the case of desalination. When a nuclear reactor is used to supply steam for any other process the method of coupling has a significant technical, safety and economic impact. The exact method of coupling depends upon the type of reactor and type of desalination plant. It is thus crucial to consider a proper plan during the design phase in order to select the most appropriate technical solution that will allow the safest and more economical integration of the reactor with the non-electric application.

3. IMPROVING EFFICIENCY WITH COGENERATION

Having an average efficiency of 33, this means that two-thirds of the energy in the fuel is lost—vented as heat—at most nuclear power plants in the world. Using waste heat recovery technology to capture a significant proportion of this wasted heat; CHP systems typically achieve total system efficiencies of 60 to 80 percent for producing electricity and thermal energy. Higher efficiency translates into:

- Lower operating costs
- Reduced emissions of all pollutants
- Increased reliability and power quality
- Reduced grid congestion and avoided distribution losses

Through “waste heat recovery,” cogeneration power plants achieve typical effective electric efficiencies of 70% to 90% — a dramatic improvement over the average 33% efficiency of conventional fossil-fuelled power plants (REI). Improving efficiency means the production of more end-use energy with the same amount of primary fuel and consequently the earnings rise proportionally. The question is whether the improved income could payback the investment. Internal Rate of Return varies from 12-16% and payback period is 5-6 years (EPRI 2007). CHP can offer a variety of economic benefits for large energy users. The economic benefits of CHP can include (EPA):

- Reduced energy costs: The high efficiency of CHP technology can result in energy savings when compared to conventional, separately purchased power and onsite thermal energy systems.
- Offset capital costs: CHP can be used in place of boilers or chillers in new construction projects, or when major heating, ventilation, and air conditioning (HVAC) equipment needs to be replaced or updated.
- Protection of revenue streams: Through onsite generation and improved reliability, CHP can allow businesses and critical infrastructure to remain online in the event of a disaster or major power outage.
- Hedge against volatile energy prices: CHP can provide a hedge against unstable energy prices by allowing the end user to supply its own power during times when prices for electricity are very high.

4. SITING CONSIDERATIONS FOR COGENERATION FACILITY

In addition to the typical siting of nuclear plants, close location to the load centres has a strong incentive. However, the trend is to choose remote, but accessible, locations for siting nuclear plants in order to mitigate the consequences of an accident. Locating a new plant far from densely populated areas makes it easier to comply with regulatory requirements. Furthermore, plants need to be located near a ready supply of cooling water, which may not necessarily correspond to the location of the population centre. The supply of steam to an industrial process by a nuclear plant generally implies the need to have the nuclear facility in close proximity to the industrial process. This is due to the technical and economic characteristics of steam transmission. For existing industrial facilities, the co-location or proximate location of a nuclear plant may be further complicated by the likelihood of nearby population centres. For the design and the site selection of the following rule of thumbs can be used:

- For a given steam delivery pressure, the unit energy cost of steam transmission increases with distance and decreases with transmission capacity and inlet pressure.
- Steam transmission costs decrease as the steam delivery pressure is decreased.
- The use of compressors in a steam transmission system is generally not economical.
- Heat in the form of hot water can be delivered at a distance of up to about 150 km with a reported loss of 2%.

The need to locate a nuclear facility near industrial plants, and perhaps population centres, implies additional efforts towards licensability and public acceptance. Potential issues include:

- Requirements for additional safety features.
- The need of plans for the safe and orderly shutdown of the industrial process and sheltering or evacuation of the industrial facility staff in the event of accidents.
- The need of detailed plans for public notification, sheltering or evacuation in the event of accidents.
- Increased requirements for public education and programs encouraging public

acceptance.

The specific requirements will be determined by such factors as the reactor type, the nature of the industrial process, the distances of the industrial facility and population centres from the nuclear plant, and prevailing public attitudes. It should be noted that the new generation of smaller reactors with passive safety features should at least partly mitigate the above sitting issues (International Atomic Energy Agency 1991).

5. TECHNICAL ISSUES TO BE CONSIDERED FOR COGENERATION SYSTEMS

The possible coupling schemes to use steam affect the feasibility study since they define the cost of steam and the investment cost. Design of the coupling configuration along with the entire plant is always better than retrofitting, both for the investment and the operational costs. The most common way to supply steam is either from the back pressure or from extraction/condensing turbine. The optimal coupling usually depends on many parameters. The most important of them, which should be examined during a feasibility study, are:

- Relative sizes of the power plant to the non-electrical application (heat/power ratio)
- Required temperature range and quality of heat needed.

Special attention should be given to the safety of coupling. In the case of cogeneration of nuclear heat and electric power, the steam is bled-off at a suitable place in the secondary circuit of the plant. The technique of the heat extraction from the steam cycle of the NPP is identical to that of the fossil-fired plant, the main difference being the necessity to shield any potential carryover of the radioactivity from the primary to the other circuits is to be prevented. The “protective barriers” and the level of protection should be included in all cogeneration plants. An appropriate pressure reversal should be considered so that in the case of any leak all contaminants are trapped in the power plant side. Fig. 3Fig shows a typical example of this concept. This usually affects the economics of the plant because heat has to be extracted at a higher quality than the application needs.

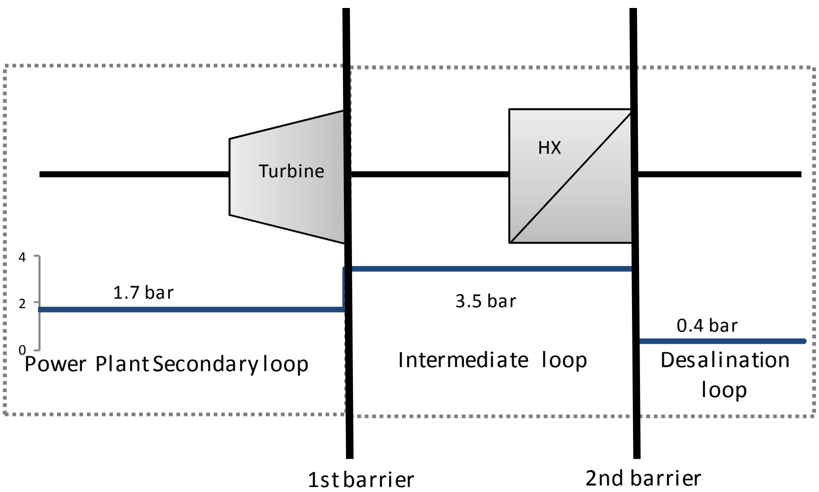

Fig. 3 Conceptual diagram of protective barriers

6. ECONOMIC ISSUES TO BE CONSIDERED FOR COGENERATION SYSTEMS

Cogeneration economic benefits do not come only from the increased overall efficiency but also from harvesting all the benefits from the synergies of cogeneration with advanced , planning. The most important element of a feasibility study has to be a comparison of the viability of the plant with and without cogeneration. Nuclear electricity generation, as well as the infrastructure for the transportation and distribution of hot water and steam, are capital intensive technologies. While nuclear power plants have proved to be economically competitive for electricity generation alone, different cost factors are involved for co-generation and heat production modes. The rule of thumb: the cost of co-generated heat is equal to the electricity cost divided by the coefficient of plant performance, a factor which depends on the type of reactor under consideration and other parameters.

Appropriate methodology to compare the economics to rank different integrated plants has to be developed, in which the annual overall expenditures of the plant, the outputs of electricity and heat recovery cost for specific application are considered. The most common methodology called equivalent electricity generation cost method enables the comparison of different plants with the heat demand and with similar net base load power capacities. Other methods include the calorific, proportional, exergetic etc. with the latter being reported as the most accurate (International Atomic Energy Agency 2005).

Utilization factor is another parameter to consider with economic impact. If the demand for the non-electrical application is seasonal, the large capital investment is left stranded during the period of non-utilization e.g., district heating is seasonal and as a result with a low utilization factor, while the seasonal factor can be removed for desalination because of the easy storage capabilities. The distance between the reactor and the industrial user is an important economic consideration in nuclear process heat applications due to the cost of the piping to connect them. The specific design of a steam transmission system must be based upon an economic evaluation of the entire system, including the cogeneration plant, transmission system and the steam plant equipment. In summary, the variables to be considered during a feasibility study are the following:

- Average electrical load
- Average steam load
- Average purchased fuel cost in case of separate production
- Average total annual operating hours
- Average purchased power cost as a result of co-generation option
- Standby charge of power as a result of co-generation option
- Estimated O&M cost of a non-electrical application

7. ENVIRONMENTAL ISSUES TO BE CONSIDERED FOR COGENERATION SYSTEMS

Use of cogeneration for desalination could help alleviate the environmental impact of the desalination plant using the specific characteristics of cooling systems of the

NPPs. A coupled plant can reduce the greenhouse gases emission compared to separate conventional production. New considerations should exist for the non – electrical application as if it was an independent plant. Generally, there is no added impact to the environment because of the more restrictive regulations that apply to the nuclear power plants.

8. CONCLUSIONS

Cogeneration in nuclear power plants of electricity and other applications such as seawater desalination, hydrogen production, district heating or cooling, or any energy-demanding industrial applications could well accelerate the revival of nuclear power. Indeed, cogeneration could not only improve the overall efficiency of the plant but also help enhance the economics and reduce environmental impacts of GHG.

REFERENCES

International Atomic Energy Agency (1991), *TECDOC 615 - Nuclear applications for steam and hot water supply*, Vienna.

International Atomic Energy Agency (2005), *TECDOC 1444 - Optimization of the coupling of nuclear reactors and desalination systems*, Vienna.

International Atomic Energy Agency (2007), *TECDOC 1561 - Economics of Nuclear Desalination: New Developments and Site Specific Studies*, Vienna.