Nuclear power applications: Supplying heat for homes and industries

More countries are interested in applying smaller sized nuclear reactors to help meet industrial and urban heating needs

by Bela J. Csik and Juergen Kupitz

When the first nuclear power reactor at Calder Hall in the United Kingdom came into commercial operation in October 1956, it provided electricity to the grid and heat to a neighboring fuel reprocessing plant. After more than 40 years, the four 50 megawatt-electric (MWe) Calder Hall units are still in operation. In Sweden, the Agesta reactor provided hot water for district heating to a suburb of Stockholm for a decade, starting in 1963.

These examples show a side of nuclear energy that is unfamiliar to many people — its capacity to deliver heat for industrial processes and urban needs. Such applications started at a very early date, practically at the same time when nuclear power reactors were first applied to electricity generation.

Since these early days of nuclear power development, the direct use of heat generated in reactors has been expanding. Countries such as Bulgaria, Canada, China, the Czech Republic, Germany, Hungary, India, Japan, Kazakstan, Russia, Slovakia, Sweden, Switzerland, and Ukraine have found it convenient to apply nuclear heat for district heating or for industrial processes, or for both, in addition to electricity generation. Though less than 1% of the heat generated in nuclear reactors worldwide is at present used for district and process heating, there are signs of increasing interest in these applications.

The direct use of nuclear heat is nothing new. After all, the result of the nuclear fission process is the generation of heat within the reactor. The heat is removed by the coolant circulating through the core, that can then be applied to the generation of electricity or used in providing hot water or steam for industrial or space heating purposes. There are, however, substantial differences between the properties and applications of electricity and of heat, as well as between the markets for these different forms of energy. These differences as well as the intrinsic characteristics of nuclear reactors are the reasons why nuclear power has predominantly penetrated the electricity market and had relatively minor applications as a direct heat source.

Mr. Csik is a senior staff member in the IAEA's Section on Nuclear Power Technology Development, of which Mr. Kupitz is the Section Head.

The energy market

About 33% of the world's total energy consumption is currently used for electricity generation. This share is steadily increasing and is expected to reach 40% by the year 2015. Of the rest, heat consumed for residential and industrial purposes, and the transport sector constitute the major components, with the residential and industrial sectors having a somewhat larger share. Practically the entire heat market is supplied by burning coal, oil, gas, or wood.

Overall energy consumption is steadily increasing and this trend is expected to continue well into the next century. Conservation and efficiency improvement measures have in general reduced the rate of increase of energy consumption, but their effect is not large enough to stabilize consumption at current values.

A modest increase in the generation of nuclear electricity is expected during the next couple of decades. In the transport sector, practically no application of nuclear energy is foreseen, except indirectly through the increased use of electricity.

The heat market is an open challenge. Though nuclear energy has been used to supply a portion of the heat demand, it has not yet achieved significant penetration. How far and how fast it could capture part of this market will depend mainly on how the characteristics of nuclear reactors can be matched with the characteristics of the heat market, in order to successfully compete with alternative energy sources.

Characteristics of the heat market

Transport of heat is difficult and expensive. The need for a pipeline, thermal isolation, pumping, and the corresponding investments, heat losses, maintenance, and pumping energy requirements make it impractical to transport heat beyond distances of a few kilometers or, at most, some tens of kilometers. There is also a strong size effect. The specific costs of transporting heat increase sharply as the amount of heat to be transported diminishes. Compared to heat, the transport of electricity from where it is generated to the end-user is easy and cheap, even to large distances measured in hundreds of kilometers.

The residential and the industrial sectors constitute the two major components of the overall heat market. Within the residential sector, while heat for cooking has to be produced directly where it is used, the demand for space heating can be and is often supplied from a reasonable distance by a centralized heating system through a district heating transmission and distribution network serving a relatively large number of customers.

District heating. District heating networks generally have installed capacities in the range of 600 to 1200 megawatt-thermal (MWth) in large cities, decreasing to approximately 10 to 50 MWth in towns and small communities. Exceptionally, capacities of 3000 to 4000 MWth can be found. Obviously, a potential market for district heating only appears in climatic zones with relatively long and cold winters. In western Europe, for example, Finland, Sweden, and Denmark are countries where district heating is widely used, and this approach is also applied in Austria, Belgium, Germany, France, Italy, Switzerland, Norway, and the Netherlands, though to a much lesser degree. The annual load factors of district heating systems depend on the length of the cold season when space heating is required, and can reach up to about 50%, which is still way below what is needed for base load operation of plants. Also, to assure a reliable supply of heat to the residences served by the district heating network, adequate back-up heat generating capacity must be provided. This implies the need for redundancy and generating unit sizes corresponding to only a fraction of the overall peak load. The temperature range required by district heating systems is around 100 to 150° C.

In general, the district heating market is expected to expand substantially. Not only because it can compete economically in densely populated areas with individual heating arrangements, but also because it offers the possibility of reducing air pollution in urban areas. While emissions resulting from the burning of fuel can be controlled and reduced up to a point in relatively large centralized plants, this is not practical in small individual heating installations fueled by gas, oil, coal, or wood.

Industrial processes. Within the industrial sector, process heat is used for a very large variety of applications with different heat requirements and with temperature ranges covering a wide spectrum. While in energy intensive industries the energy input represents a considerable fraction of the final product cost, in most other processes it contributes only a few percent. Nevertheless, the supply of energy has an essential character. Without energy, production would stop. This means that a common feature of practically all industrial users is the need for assurance of energy supply with a very high degree of reliability and availability, approaching 100% in particular for large industrial installations and energy intensive processes.

Regarding the power ranges of the heat sources required, similar patterns are found in most industrialized countries. In general, about half of the users require less then 10 MWth and another 40% between 10 and 50 MWth. There is a steady decrease in the number of users as the power requirements become higher. About 99% of the users are included in the 1 to 300 MWth range, which accounts for about 80% of the total energy consumed. Individual large users with energy intensive industrial processes cover the remaining portion of the industrial heat market with requirements up to 1000 MWth, and exceptionally even more. This shows the highly fragmented nature of the industrial heat market.

The possibility of large-scale introduction of heat distribution systems supplied from a centralized heat source — which would serve several users concentrated in so-called industrial parks — seems rather remote at present, but could be the trend on a long term. Contrary to district heating, the load factors of industrial users do not depend on climatic conditions. The demands of large industrial users usually have base load characteristics.

The temperature requirements depend on the type of industry, covering a wide range up to around 1500° C. The upper range above 1000° C is dominated by the iron/steel industry. The lower range up to about 200 to 300° C includes industries such as seawater desalination, pulp and paper, or textiles. Chemical industry, oil refining, oil shale and sand processing, and coal gasification are examples of industries with temperature requirements of up to the 500 to 600° C level. Non-ferrous metals, refinement of coal and lignite, and hydrogen production by water splitting are among applications that require temperatures between 600 and 1000° C.

All industrial users who require heat also consume electricity. The proportions vary according to the type of process, where either heat or electricity might have a predominant role. The demand for electricity can either be supplied from an electrical grid, or by a dedicated electricity generating plant. Co-generating electricity and heat is an attractive option. It increases overall energy efficiency and provides corresponding economic benefits. Co-generation 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 back-up for assurance of electricity supply. Such arrangements are often found to be desirable.

Characteristics of nuclear heat sources

From the technical point of view, nuclear reactors are basically heat generating devices. There is plenty of experience of using nuclear heat in both district heating and in industrial processes, so the technical aspects can be considered well proven. There are no technical impediments to the application of nuclear reactors as heat sources for district or process heating. In principle, any type and size of nuclear reactor can be used for these purposes.

Potential radioactive contamination of the district heating networks or of the products obtained by the industrial processes is avoided by appropriate measures, such as intermediate heat exchanger circuits with pressure gradients which act as effective barriers. No incident involving radioactive contamination has ever been reported for any of the reactors used for these purposes.

Regarding the temperature ranges, up to about 300° C are obtained in light- and heavy-water reactors, up to 540°C in liquid metal-cooled fast reactors, up to 650°C in advanced gas-cooled reactors, and up to about 1000° C in high temperature gas-cooled reactors.

For applications to district or process heating, there are basically two options. Co-generation of electricity and heat, and heat-only reactors. Co-generation has been widely applied, while there is not much experience in heat-only reactors. In principle, any amount of heat can be extracted from co-generation reactors, subject to design limitations. Whatever heat is not needed to supply the heat demand can be used for electricity generation, which means a high degree of flexibility. Heat-only reactors, on the other hand, have only one objective, as they are not intended for generating electricity.

The availability of nuclear reactors is, in general, similar to fossil-fuelled power plants. As shown by experience, availability factors of 70% to 80% or even 90% can be achieved. The frequency and duration of unplanned outages can be kept very low with good preventive and predictive maintenance. Availability and reliability of a reactor, however, can never reach the nearly 100% levels required by most large heat users. Consequently, as for fossil-fueled heat sources, redundancy is needed. Multiple unit co-generation power plants, modular designs, or back-up heat sources are suitable solutions.

Nuclear reactors are capital intensive. The influence of the fixed cost component is predominant in the final cost of energy. Therefore, base-load operation with load factors as high as achievable is needed for competition with alternative sources. This is only possible when the demand of the heat market to be supplied has base-load characteristics, or when the combined electricity and heat market enables overall base-load operation of a co-generation plant.

Nuclear reactors can be technically proven, safe, reliable and environmentally clean energy sources, but for commercial deployment they also have to be economically competitive with alternative energy sources. Compared to fossil-fuelled sources, nuclear reactors are characterized by higher investment costs compensated by lower fuel costs. The penetration of nuclear power into the electricity market would not have been possible without having fulfilled the condition of economic competitiveness. Even with prevalent low fossil fuel price levels, nuclear power has retained its competitive position in most parts of the world. Should fossil fuel prices increase, as is expected to occur, the economically competitive position of nuclear power, both for electricity generation and for heat supply, will improve.

Due to the size effect, nuclear economics are, in general, improved for larger units. This has led to the development and predominant deployment of large-size reactors in industrialized countries with very large interconnected electrical grid systems. Nevertheless, there has been and there continues to be a market for small- and medium-sized power reactors (SMRs). Current design SMRs are not scaled down versions of large commercial reactors, and they are intended to be economically competitive.

Siting of nuclear plants has become a major issue, even in those countries which are proceeding with their nuclear programmes by initiating new projects. Building additional units at existing nuclear sites has been standard practice lately, and opening up new sites for nuclear plants are a rare occurrence. Economic factors promote siting as close as possible to load centers even for electricity generating power plants. For co-generation or heat-only reactors, this is practically a necessary condition to be fulfilled. The NIMBY (not in my back yard) syndrome, however, is an important factor affecting site selection. It promotes a trend to choose remote but accessible locations, in order to avoid potential conflicts and opposition. Remote siting far from densely populated areas makes it also easier to comply with regulatory requirements, which are getting more and more demanding. Advanced reactor designs, in particular in the SMR range with improved safety features, could be perceived as acceptable for close siting by the public. They also could more easily meet regulatory requirements and could maintain heat transmission costs at reasonable levels.

In nuclear power, unlike in many industrial undertakings, the long-term viewpoint is predominant. The planning, design, project preparatory activities, and licensing takes years to be completed for any nuclear reactor. Reactors are designed and built to last for about 40 years or more, and to achieve the economic benefits expected, they have to be operated with high load factors during their economic lifetime. There are also infrastructure requirements, which require time and considerable development efforts, if not already available. These efforts are only justifiable under a long-term perspective directed to a nuclear programme.

Prospects for nuclear heat applications

The technical viability of employing nuclear heat sources for district heating or for industrial processes has existed since the very start of nuclear development. A substantial penetration into the commercial heat market, however, has not yet taken place. Prospects will mainly depend on where and how the demand characteristics of the heat market can be matched by what nuclear reactors are able to offer.

District heating market. For the district heating market, co-generation nuclear power plants are one of the supply options. In the case of medium to large nuclear reactors, due to the limited power requirements of the heat market and the relatively low load factors, electricity would be the main product, with district heating accounting for only a small fraction of the overall energy produced. These reactors, including their siting, would be optimized for the conditions pertaining to the electricity market, district heating being, in practice, a byproduct. Should such power plants be located close enough to population centers in cold climatic regions, they could also serve district heating needs. This has been done in Russia, Ukraine, the Czech Republic, Slovakia, Hungary, Bulgaria, and Switzerland, using up to about 100 MWth per power station. Similar applications can be expected for the future wherever similar boundary conditions exist.

For small co-generation reactors corresponding to power ranges of up to 300 MWe and 150 MWe, respectively, the share of heat energy for district heating would be larger. But electricity would still be expected to constitute the main product, assuming base-load operation, for economic reasons. The field of application of these reactors would be similar to the case of medium or large co-generation reactors. Additionally, however, they could also address specific objectives, such as the energy supply of concentrated loads in remote and cold regions of the world.

Heat-only reactors for district heating are another option. Such applications have been implemented on a very small scale (a few MWth) as experimental or demonstration projects. Construction of two units of 500 MWth was initiated in Russia in 1983-85, but later interrupted. There are several designs being pursued, and it is planned to start construction of a 200 MWth unit soon in China. Clearly the potential applications of heat-only reactors for district heating are limited to reactors in the very small size range. These reactors are designed for siting within or very close to population centers so that heat transmission costs can be minimal. Even so, economic competitiveness is difficult to achieve due to the relatively low load factors required, except in certain remote locations where fossil fuel costs are very high and the winter is very cold and long.

In summary, the prospects for nuclear district heating are real, but limited to applications where specific conditions pertaining to both the district heating market and to the nuclear reactors can effectively be met. The prospects for co-generation reactors, especially in the SMR range, seem better than for heat-only reactors, mainly because of economic reasons.

Industrial process heat. The characteristics of the market for process heat are quite different from district heating, though there are some common features, particularly regarding the need for minimal heat transport distance. Industrial process heat users, however, do not have to be located within highly populated areas, which by definition constitute the district heating market. Many of the process heat users, in particular the large ones, can be and usually are located outside urban areas, often at considerable distances. This makes joint siting of nuclear reactors and industrial users of process heat not only viable, but also desirable in order to drastically reduce or even eliminate the heat transport costs.

For large size reactors, the usual approach is to build multiple unit stations. When used in the co-generation mode, electricity would always constitute the main product. Such plants, therefore, have to be integrated into the electrical grid system and optimized for electricity production. For reactors in the SMR size range, and in particular for small and very small reactors, the share of process heat generation would be larger, and heat could even be the predominant product. This would affect the plant optimization criteria, and could present much more attractive conditions to the potential process heat user. Consequently, the prospects of SMRs as co-generation plants supplying electricity and process heat are considerably better than those of large reactors.

Several co-generation nuclear power plants in operation already supply process heat to industrial users. The largest projects implemented are in Canada (Bruce, heavy-water production and other industrial/agricultural users) and in Kazakstan (Aktau, desalination). Other power reactors which currently produce only electricity, could be converted to co-generation. Should there be a large process heat user close to the plant interested in receiving this product, the corresponding conversion to co-generation would be technically feasible. It would, however, involve additional costs, which would have to be justified by a cost/benefit analysis. Some such conversion projects could be implemented but, in general, prospects for this option seem rather low.

Installing a new nuclear co-generation plant close to an existing and interested industrial user has better prospects. Even better would be a joint project whereby both the nuclear co-generation plant and the industrial installation requiring process heat are planned, designed, built, and finally operated together as an integrated complex.

Current and advanced light- or heavy-water reactors offer heat in the low temperature range, which corresponds to the requirements of several industrial processes. Among these, seawater desalination is presently seen as the most attractive application. Other types of reactors, such as liquid metal-cooled fast reactors and high temperature gas-cooled reactors can also offer low temperature process heat, but in addition, they can cover higher temperature ranges. This extends their potential field of application. These reactors still require substantial development in order to achieve commercial maturity. Should they achieve economic competitiveness as expected, their prospects seem to be promising in the medium to long term, especially for high temperature industrial applications.

Heat-only reactors have not yet been applied on an industrial/commercial scale for the supply of process heat. Several designs have been developed and some demonstration reactors have been built. Economic competitiveness seems to be an achievable goal according to many studies which have been performed, but this is something yet to be proven in practice. The potential market for such heat-only reactors would be limited to the very small size range, i.e. below about 500 MWth.

The prospects for applying nuclear energy to district and process heating are closely tied to the prospects of deploying SMRs. A recent market assessment for SMRs found that 70 to 80 new units are planned in about 30 countries up to the year 2015. It was also found that about a third of these units are expected to be applied specifically to nuclear desalination. Of the rest, a substantial share could very well supply heat in addition to electric energy, while a few are expected to be heat-only reactors. ❐