Current and Past Use of District Energy Using Nuclear Power

A Review of Nuclear District Energy Facilities

Technical Brief—*Nuclear Beyond Electricity*

Nuclear-Powered District Energy

Heating makes up the largest proportion of energy end use, accounting for 50% of final energy consumption and 40% of energy-related carbon dioxide emissions globally. Close to half of the heating is used for building needs, such as space and water heating [1]. Building heat is typically provided through on-site furnaces and boilers powered by fossil fuel sources.

To reduce fossil fuel usage and improve energy efficiencies through economies of scale, heat can also be supplied through a centralized district energy network. A district energy network is comprised of pipes transferring heat from thermal power plants and industrial processes (in the form of water or steam) to areas of high energy demand, such as university campuses, health care facilities, and commercial complexes.

Heating for district energy networks can be supplied by carbon-free energy resources like nuclear power plants (NPPs) to further reduce fossil fuel usage and carbon emissions. In current commercial NPPs, the heat from nuclear fission is used to boil water into steam, which spins a turbine to generate electricity. This power cycle typically produces thermal efficiencies around 33–37% [2]. Alternatively, the steam can be extracted from the energy cycle and used to provide heat to a district energy network. While this operating strategy reduces electricity generation, this cogeneration mode (producing both electricity and heat as end products) offers NPPs several benefits, such as:

- ***Increased thermal efficiency:*** The overall thermal efficiency of an NPP could be increased by more than 30% [3].
- ***Economic benefits:*** A cogeneration mode could provide an alternative source of income for NPPs instead of electricity, which can be a challenging market for NPPs due to renewables penetration and changing energy costs. Cogeneration would have further advantage if reducing carbon emissions at end users is incentivized (such as through government policy).

There are many examples of nuclear reactors operating in a cogeneration mode; in 2019, there was a combined total of 750 reactor years of experience in cogeneration [4]. This review covers a representative portion of those reactors operating to provide district energy, including a collection of different reactor types, heat transfer conditions, countries, and environments. In total, 27 facilities from 11 different countries are included in the review, with NPP and district energy information gathered from both international and domestic sources. From this review, several technical and location based considerations for nuclear-powered district energy facilities were identified. For the full list of facilities, see Appendix A.

Technical Considerations

NPPs typically produce large amounts of heat energy, which are converted into electricity. For the NPPs covered in this review, heat sent to district energy networks is typically a small fraction of the total generated energy. On the energy-demand side, district energy network needs can vary greatly in size and energy requirements. Thus, the coordination of energy supply and demand will need to factor in multiple technical considerations.

Heat Transfer Considerations

The heat interface between NPPs and district energy networks for the applications included in this review varied with the following technical factors:

- Heat transfer medium conditions (phase [steam or water], temperature, pressure, flow rate)
- Distance from NPP to district energy network
- Network size and demand
- Network supply and demand variation due to plant outages and seasonal changes

District energy networks typically require heat within 80–130°C for the supply line from a heating source and 45–70°C for the return line to the heating source [5]. For district energy networks interfacing with NPPs, this heat is usually provided by water, which is pressurized so that higher temperatures can be reached without boiling.[1] The highest operating pressure for the facilities in this review is 2.86 MPa at the Greifswald Nuclear Power Plant in East Germany [6]. This NPP provides hot water to a district energy network at a max flow rate of 2600 tons/hour and max temperature of 180°C.

Steam can also be used to transfer heat in district energy networks [7]. Using steam results in higher heat losses than using liquid water as the heat transfer medium. Steam heat losses are due to several factors, including the higher temperature gradient with ambient conditions relative to hot water. Steam has an advantage as a heat transfer medium over hot water when high temperatures are needed or for applications where its latent heat can be utilized;[2] steam can transfer greater amounts of energy when condensing, which is useful in certain industrial processes [8]. Although NPP applications for district energy have been well-suited for using hot water as the heat transfer medium, usage of steam for this purpose is commonplace with other generation types. A comparison of district energy heat transfer mediums is presented in Table 1.

1 For example, water at atmospheric conditions boils at 100°C, but water pressurized to 2.9 MPa boils at 232°C.

2 A phase change from steam to liquid water at 100°C and 1 atmosphere results in 2257 kJ/kg. A change in hot water temperature from 130°C to 70°C, assuming constant specific heat of 4.2 kJ/kg, results in 252 kJ/kg.

Table 1. District Energy Heat Transfer Medium Comparison

Heat transfer medium	Advantages	Disadvantages
Steam	• Can be used for additional purposes beyond heating due to the potential for higher temperatures, including on-site cogeneration and chilled water production with steam-driven chillers • Can use steam's latent heat for higher-energy applications, such as industrial processes and sterilization • No pumping power required for distribution	• Heat loss—for example, due to higher temperature gradient with ambient conditions • More dangerous leaks than hot water leaks • Slower response time than hot water for district energy • Potential for explosions due to improper steam piping warm-up
Hot water	• Greater thermal efficiency and fewer heat losses due to lower temperatures • Less required maintenance • Lower-cost insulating materials	• Pumping energy required for distribution

In addition to differences in heat transfer medium conditions, district energy systems can vary in size and distance from the heating source. Of the facilities included in this review, the Cernavodă Nuclear Power Plant in Romania and Mühleberg Nuclear Power Plant in Switzerland are situated closest to their respective district energy networks at approximately 2 km away. The Kola Nuclear Power Plant in Russia is situated the furthest away from the district energy network, with the furthest served town's boundary at 64 km away (the most remote consumer is 72 km away from the NPP) [9]. Situating NPPs closer to district energy networks would produce the most favorable return on investment because large distances would require a larger capital cost for piping and would incur larger heat transfer losses. However, even with the higher costs, it is expected that nuclear heat can be delivered up to 150 km away in the form of hot water at a competitive price to alternative heat sources [10]. District energy network size information is limited for the facilities included in the review; heating demand includes values reported in area (700,000 m^2 of housing from the Haiyang Nuclear Power Plant in China) and values reported by number of residents (65,000 residents from the Leningrad 2 Nuclear Power Plant in Russia). Larger networks offer greater opportunity for carbon reduction and economic benefit due to the associated economies of scale but may also require more infrastructure and a larger source of thermal energy.

Heat transfer reliability is an additional consideration for district energy networks, including networks supplied by nuclear-powered facilities. Nuclear reactors typically refuel every 18 to 24 months, and during this time, no electricity or heat is generated. Therefore, either the outages should be aligned with periods of low district energy demand to minimize the effect of the outage or a backup source of energy should be provided to ensure a reliable output of heat for a district energy network. Multiunit NPPs can provide better continuity in energy supply by staggering unit-refueling outages so that at least one unit is available to provide heat; for single-unit NPPs, heat to the district energy network would be supplied from alternative sources, such as the oil-fired package boilers at the Beznau Nuclear Power Plant in Switzerland [11]. Beyond refueling outages, seasonal demand would also need to be considered. Unlike industrial process heat, which is a relatively constant heat demand, district energy demands vary based on local needs for heat, which would be higher in winter and lower in summer. The change in demand can be met through changes in supply temperature, as shown by the Beznau Nuclear Power Plant and district energy network, which supplies water at 125°C in winter and 80°C in summer [11].

Reactor Type

For all reactor types, a district energy network that uses the thermal energy from the plant is an independent heat transfer loop to maintain radiological separation between reactor plant systems and the district energy loop. Additionally, this approach allows the plant to maintain better control of the water used in plant systems, including the water chemistry. Several different reactor types are explored in this review:

- Pressurized water reactor (PWR)
- Pressurized heavy water reactor (PHWR)
- Boiling water reactor (BWR)
- Light-water-cooled graphite reactor (LWGR)
- Liquid metal fast reactor (LMFR)
- Pool-type reactor

Most of the facilities included in the review are PWRs or PWHRs. These plants are designed with a secondary water-coolant loop to maintain radiological separation from the reactor core. In nonheating applications, this loop generates steam to drive turbines and produce electricity. The PWRs and PWHRs in this review utilize extracted steam from this secondary coolant loop to provide heat through a heat exchanger to an independent district energy loop. Based on district energy needs and plant economics, steam can be extracted from many locations of the secondary loop.

The other reactor types are less prominent in district heating applications. Only three BWR-type reactors are included in the review, which include two AST-500 heat-only reactors from Russia that were never completed and the Mühleberg Nuclear Power Plant in Switzerland. These plants require a robust means for radiological separation since the steam is contaminated. For example, the AST-500 heat-only reactors are designed to include an intermediate loop between the primary loop and the district heating loop to provide radiological separation [9]. Russia also incorporates district energy from several LWGR-type reactors and an LMFR-type reactor. These reactors include an intermediate coolant loop as well; for the LWGR-type reactor, pressure is kept higher in the intermediate loop than the steam pressure but lower than the district energy network [12]. This approach minimizes the risk of any leakage resulting in exposure to the public, since flow would travel from higher pressures to lower pressures.

An additional reactor type explored in this review is the Canadian SLOWPOKE-3 demonstration reactor, which demonstrates that nuclear-powered district heating is competitive with that of conventional fossil fuels. This reactor is a pool-type reactor designed to be minimally operated with "walk-away safety" to provide heat to district energy networks. The design includes a reactor core with primary heat exchanger installed in a steel-lined concrete vault filled with water. The water serves as both heat transfer medium and radiation shielding, with natural circulation as the heat transfer method. A secondary loop is used to distribute the heat from the primary heat exchangers through the district heating network [13].

Location Considerations

Location is a primary factor in the feasibility of nuclear-powered district energy applications. Specific considerations include factors such as state support, public opinion, and local conditions of climate and resource availability.

State Support

All of the facilities included in this review have some form of state support. State support provides advantages to nuclear-powered district energy facilities mainly through financial support for large investments and long-term planning.

Financial support for nuclear-powered district energy is twofold; the state can help fund large capital investments for both NPPs and district energy networks. Both new-build NPPs and new-build district energy networks are typically associated with large up-front capital costs and are intended for long operational lifetimes. Private owners for either NPPs or district energy networks may not be willing to accept the potential financial risks associated with their development, such as cost and schedule overruns and long payback periods even for successful projects. For example, Europe's major district energy systems were developed with payback periods of over 20 years and were mostly state funded and owned [14]. State support can alleviate risks of large capital investment and can reduce the time pressure for becoming profitable. This state support also enables the public sector to further meet environmental objectives and support long-term energy goals [15]. States with large nuclear programs, such as China and Russia, may be further incentivized to invest in nuclear energy as part of strategic economic and foreign policy goals, such as using nuclear energy as an exportable product to other countries [16] or replacing fossil fuel resources used for heating [12].

District energy networks, much like NPPs, can have several ownership models, from fully public owned (state or local municipalities) to full private ownership to a mixture of the two. The ownership models differ in their ability to manage risk and control of district energy assets and are determined typically based on the expected return on investment and the level of risk local authorities are willing to accept. Typically, private ownership models require a high return on investment (usually between 12% and 20%); lower expected rates of return would be pursued by public ownership or a public-private partnership [15].

Public Opinion

Nuclear-powered district energy facilities may be affected significantly by public opinion. Proximity to population centers (which minimizes heat losses in transport and distribution) can amplify the effect of the NPP on public opinion. For antinuclear forces, the location of the plant can increase fear of an accident due to impact on more people. For pronuclear forces, the location of the plant provides jobs and tax revenue.

An example of public opinion affecting NPPs was in Germany, which has had a long history of antinuclear movements. In 1975, a group of 28,000 protesters occupied a construction site and managed to stop the construction of an NPP, and in 1979, 200,000 people protested the use of nuclear power in Hannover and Bonn. Antinuclear movements were a key factor in the formation of Germany's Green Party, and through political decisions, NPP lifespans were limited to 32 years [17]. Thus, even with suitable economic returns, nuclear-powered district energy facilities may encounter political hurdles.

Local Climate and Resources

The local climate is a crucial factor in the feasibility of a nuclear-powered district energy facility. All of the plants in this review are located in areas with cold weather conditions, particularly Russia and areas of northern Europe. Greater returns on investments for nuclear-powered district heating can be expected in colder regions. For example, temperatures in Russia's Kola peninsula typically vary between -15°C and 17°C [18]; the Kola Nuclear Power Plant provides heating for this area and was able to economically justify a 64-km heat transmission pipeline [9]. A pipeline of this length is expensive and would be less economically justifiable in warmer climates. Besides providing heat for space heating, district energy can supply heat for hot water, which is needed even in warmer seasons.

Alternative heat source availability also has an effect on the feasibility of nuclear-powered district energy. For example, the Canadian SLOWPOKE-3 was developed to reduce reliance on fossil fuel imports and to offer a pathway for urban nuclear-powered heating. Costs for the system were competitive with conventional fossil fuels for use in remote communities, but low natural gas prices caused market interest in the reactor to dissipate over time [19]. Alternative heat sources include waste heat from other cogeneration plants, geothermal energy, waste incineration, and solar-thermal energy, which could affect the feasibility of an NPP depending on their availability at a location. An advantage of district energy systems, however, is that multiple energy sources can be used to provide heat; as such, nuclear power may be able to coordinate with other energy sources to still see some benefits from cogeneration.

Future of Nuclear-Powered District Energy

Current nuclear-powered district energy operational experience only involves using generated heat for district heating. However, other possibilities are being explored, such as district cooling and NPP coordination with renewable energy resources, industrial applications, and energy storage.

Heat from an NPP can be used for cooling applications through absorption or adsorption chillers (for example, using steam to drive a steam chiller). In these chillers, heat gathered from a water loop is expelled through an absorption/adsorption refrigeration cycle, and the resulting chilled water is distributed to end users [20, 21]. District cooling can operate with distributed chillers at end-user locations that utilize heat from the district energy network or operate with a centralized chilling unit in a combined heat, power, and cooling unit, known as trigeneration [22]. Although experience on nuclear trigeneration is limited, several feasibility studies exist that suggest that centralized nuclear-powered district cooling is technologically feasible [21, 23]. The Krško Nuclear Power Plant in Slovenia, however, determined that it was not currently economically feasible to implement nuclear district cooling in their location due to low overall cooling demand [24]. Globally, cooling demands today are significantly lower than heating demands but are expected to grow significantly in the coming decades with growing populations, improved living standards in developing countries, and increases in global average temperatures [25]. District cooling networks and NPPs are likely to provide more value in the future and can contribute to net-zero carbon initiatives by providing economies of scale for district cooling and reducing carbon emissions.

NPP coordination with renewable energy resources, industrial applications, and energy storage is also an area of research. The consistent and reliable generation provided by NPPs can complement the less consistent generation of some renewable energy resources to provide heat for district energy networks and reduce the usage of fossil fuels. Industrial processes, such as paper and cardboard production, can also utilize heat from an NPP, either through on-site cogeneration, as is the case for many NPPs that produce desalinated water, or through a district energy network, such as for the Gösgen Nuclear Power Plant in Switzerland [10]. Additionally, NPPs can coordinate with energy-storage assets, like thermal energy storage, to stabilize supply and demand, such that the energy produced by the NPP does not need to be used immediately. The coordination of these resources is being explored by numerous research organizations around the world [10, 23, 26].

NPPs have successfully supported district energy applications in the past and will continue to do so in the future. Several new projects have started in recent years, including district heating from China's Haiyang Nuclear Power Plant (2019) and Russia's Leningrad 2 Nuclear Power Plant (2018). These developments show that nuclear-powered district energy is a feasible and cost-effective approach to decarbonization, and with many countries adopting net-zero carbon emission pledges, district energy networks and nuclear energy may see increased investment and interest in the future [27].

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Appendix A: Nuclear-Powered District Energy Facilities

See Table A-1 on pages 8–10.

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Table A-1. List of Facilities

Plant	Type of reactor	Years of operation	Location	End use	Size of district energy network	Heat transfer method from power cycle	District heat steam	District heat hot water	Cost to construct originally	Owned by
Kozloduy 5–6	PWR (VVER V 329)	Unit 5: 1988 to present Unit 6: 1993 to present	Bulgaria	Cogeneration: electricity to grid and process heat to district heating network	Units 5 and 6 have a heat output of 20 MWth to the local district heating network.	District heating network functions as a tertiary loop from the NPP.	N/A	150°C supply, 70°C return	Information not available	Bulgarian Energy Holding Company (state-owned enterprise)
Whiteshell SLOWPOKE-3	Light water pool-type reactor (SLOWPOKE-3 demonstration reactor)	1987–1990	Canada	Demonstrated that nuclear power could provide heat safely. Project terminated due to unfavorable market conditions (low natural gas prices).	N/A	District heating network functions as a tertiary loop from the NPP.	N/A	<100°C supply	\$5–\$7 million expected for commercial systems. These were expected costs for a small 10-MW commercial unit.	Atomic Energy of Canada Limited (AECL; state-owned enterprise)
Haiyang (heating from two AP-1000 units)	PWR (AP-1000)	Unit 1: 2018 to present Unit 2: 2019 to present (District heating: 2019 to present)	China	Cogeneration: electricity to grid and process heat to district heating network	Heat for at least 700,000 m^2 of housing	Extracts steam from secondary loop of NPP to supply a multistage heat exchanger on site (tertiary loop). The heat is then sent to an off-site district heating company, which directs heated water to consumers.	N/A	Heated water flows through municipal pipes to consumers. Further details on flow rate or pressure are not available.	\$6.3 billion (40 billion Chinese yuan)	State Power Investment Corporation (SPIC; state-owned enterprise)
Institute of Nuclear Energy and Technology (INET) at Tsinghua University NHR 5	Similar to PWR (NHR-5)	1989–1992 (district heating tested for three winters)	China	Supplied heat to INET campus, with heating availability of >99%	INET campus covers approximately 740,000 m^2.	District heating network functions as a tertiary loop from the NPP.	N/A	152 tons/hour 84°C supply, 56°C return	Information not available	Tsinghua University (public university)
Temelín 1, 2	PWR (VVER V-320)	Unit 1: 2002 to present Unit 2: 2003 to present	Czech Republic	Cogeneration: electricity to grid and process heat to district heating network	Heat is supplied to local town Týn nad Vltavou 5 km away.	District heating network functions as a tertiary loop from the NPP.	N/A	153°C supply, 67°C return	\$4.5 billion (98.6 billion Czech koruna)	CEZ Group (majority state-owned; includes some private entity ownership)
Greifswald 1–5	PWR (Units 1–4: VVER V-230, Unit 5: VVER V 213)	Unit 1: 1974 to 1990 Unit 2: 1975 to 1990 Unit 3: 1978 to 1990 Unit 4: 1979 to 1990 Unit 5: Nov. 1, 1989 to Nov. 24, 1989	East Germany	Cogeneration: electricity to grid and process heat to district heating network	22 km from plant (800-mm diameter pipe) to town of Griefswald, heat output 260 MWth	District heating network functions as a tertiary loop from the NPP.	Potentially could supply steam at 0.3 MPa to industrial users.	Max flow: 2600 ton/hour, max pressure: 2.86 MPa, max temperature: 180°C	Information not available	Energiewerke Nord GmbH (state-owned enterprise)
Paks 1–4	PWR (VVER V-213)	Unit 1: 1983 to present Unit 2: 1984 to present Unit 3: 1986 to present Unit 4: 1987 to present	Hungary	Cogeneration: electricity to grid and process heat to district heating network	Heat supplied to local town (Paks). Town is 6 km away from plant.	NPP turbines (on secondary loop) are connected to steam pipes feeding three heat exchangers. The heat exchangers heat the hot water district heating loop.	N/A	130°C supply, 70°C return	Information not available	MVM Group (state-owned enterprise)
Bilibino 1–4	LWGR (EGP-6)	Unit 1: 1974 to 2019 Unit 2: 1975 to present Unit 3: 1976 to present Unit 4: 1977 to present	Russia	Cogeneration: electricity to grid and process heat to district heating networks	Heat supplied to the plant and local residents, hot water to residential and public buildings. 3.5 km to heating network in Bilibino	District heating network functions as an independent loop from the NPP.	N/A	207–309 ton/hour 1.81 MPa, 150°C supply, 70°C return	Information not available	Rosenergoatom (state-owned enterprise)
Cernavodă 1, 2	PHWR (CANDU-6)	Unit 1: 1996 to present Unit 2: 2007 to present	Romania	Cogeneration: electricity to grid and process heat to district heating network	Heat supplied to town of Cernavodă, which is approximately 2 km away from the plant with ~20,000 inhabitants. 60,500 MWh was delivered to the town in 1999.	Steam supplied at 80 tons/hour from the main steam line is used to heat the tertiary hot water loop.	N/A	150°C supply, 70°C return	At least \$1.2 billion for both units	Nuclearelectrica S.A. (majority state-owned; includes some private entity ownership)

Table A-1. List of Facilities (continued)

Plant	Type of reactor	Years of operation	Location	End use	Size of district energy network	Heat transfer method from power cycle	District heat steam	District heat hot water	Cost to construct originally	Owned by
Balakovo 1–4	PWR (VVER V-320)	Unit 1: 1986 to present Unit 2: 1988 to present Unit 3: 1989 to present Unit 4: 1993 to present	Russia	Cogeneration: electricity to grid and process heat to district heating networks	12 km from the plant Heat requirement is over 1000 MWth.	District heating network functions as a tertiary loop from the NPP.	N/A	130°C supply, 70°C return	Information not available	Rosenergoatom (state-owned enterprise)
Gorky	Similar to BWR (AST-500 heat-only reactor)	N/A: never operated	Russia	Heat-only reactor: district heating for local city	According to design, would have been able to provide heat up to 2300 MW to support towns of 350,000–400,000 residents.	Three-loop heat transport scheme, with pressure barrier between second (intermediate) and third (district heating network)	N/A	Based on AST-500 operation: 1.6 MPa, 150°C supply, 70°C return	Information not available	Rosenergoatom (state-owned enterprise)
Kalinin 1–4	PWR (Units 1 and 2: VVER V-338; Units 3 and 4: VVER V-320)	Unit 1: 1985 to present Unit 2: 1987 to present Unit 3: 2005 to present Unit 4: 2012 to present	Russia	Cogeneration: electricity to grid and process heat to district heating networks	Heat supplied to local area through main pipeline that is 4 km long.	District heating network functions as a tertiary loop from the NPP.	N/A	130°C supply, 70°C return	Information not available	Rosenergoatom (state-owned enterprise)
Kola 1–4	PWR (Units 1 and 2: VVER V-230; Units 3 and 4: VVER V-213)	Unit 1: 1973 to present Unit 2: 1975 to present Unit 3: 1982 to present Unit 4: 1984 to present	Russia	Cogeneration: electricity to grid and process heat to district heating networks	Heat supplied to nearby areas through main pipeline that is 64 km long.	District heating network functions as a tertiary loop from the NPP.	N/A	130°C supply, 70°C return	Information not available	Rosenergoatom (state-owned enterprise)
Kursk 1–4	LWGR (RBMK-1000)	Unit 1: 1977 to present Unit 2: 1979 to present Unit 3: 1984 to present Unit 4: 1986 to present	Russia	Cogeneration: electricity to grid and process heat to district heating networks	Heat supplied to local area through main pipeline that is 3 km long.	Intermediate coolant circuit between the turbine extraction and district heating network. Pressure in the intermediate circuit is higher than steam pressure and lower than the district heating network.	N/A	130°C supply, 70°C return	Information not available	Rosenergoatom (state-owned enterprise)
Leningrad 2–1, 2	PWR (VVER V-491)	Unit 1: 2018 to present Unit 2: 2021 to present	Russia	Cogeneration: electricity to grid and process heat to district heating network	Heat supplied to local industrial park and town of Sosnovy Bor (5 km away). Supplies heating to more than 65,000 residents and hundreds of Sosnovy Bor businesses as well as educational, cultural, and medical institutions.	District heating network functions as a tertiary loop from the NPP.	N/A	Generic temperature range for district heating: 80–130°C supply, 45–70°C return	$5.8 billion (136-billion-ruble state contract in March 2008 for two units)	Rosenergoatom (state-owned enterprises)
Novovoronezh 3, 4	PWR (VVER V 179)	Unit 3: 1972 to 2016 Unit 4: 1973 to present	Russia	Cogeneration: electricity to grid and process heat to district heating networks	Heat supplied to nearby areas through main pipeline that is 50 km long.	District heating network functions as a tertiary loop from the NPP.	N/A	130°C supply, 70°C return	Information not available	Rosenergoatom (state-owned enterprise)
Novovoronezh II 1, 2	PWR (VVER V 392M)	Unit 1: 2017 to present Unit 2: 2019 to present	Russia	Cogeneration: electricity to grid and process heat to district heating networks	The distribution line from Novovoronezh is 55 km long.	District heating network functions as a tertiary loop from the NPP.	N/A	Generic temperature range for district heating: 80–130°C supply, 45–70°C return	At least $5 billion for both units	Rosenergoatom (state-owned enterprise)
Smolensk 1, 2	LWGR (RBMK-1000)	Unit 1: 1983 to present Unit 2: 1985 to present	Russia	Cogeneration: electricity to grid and process heat to district heating networks	Heat supplied to local area through main pipeline that is 5 km long.	Intermediate coolant circuit between the turbine extraction and district heating network. Pressure in the intermediate circuit is higher than steam pressure and lower than the district heating network.	N/A	130°C supply, 70°C return	Information not available	Rosenergoatom (state-owned enterprise)
Voronezh	Similar to BWR (AST-500 heat-only reactor)	N/A: never operated	Russia	Heat-only reactor: district heating for local city	According to design, would have been able to provide heat up to 2300 MW to support towns of 350,000–400,000 residents.	Three-loop heat transport scheme, with pressure barrier between second (intermediate) and third (district heating network)	N/A	Based on AST-500 operation: 1.6 MPa, 150°C supply, 70°C return	Information not available	Rosenergoatom (state-owned enterprise)

Table A-1. List of Facilities (continued)

Plant	Type of reactor	Years of operation	Location	End use	Size of district energy network	Heat transfer method from power cycle	District heat steam	District heat hot water	Cost to construct originally	Owned by
Beloyarsk 1–4	LWGR (Units 1 and 2) LMFR (Units 3 and 4) Unit 1: AMB-100 Unit 2: AMB-200 Unit 3: BN-600 Unit 4 BN-800	Unit 1: 1964 to 1983 Unit 2: 1969 to 1990 Unit 3: 1981 to present Unit 4: 2016 to present	Russia (formerly USSR)	Cogeneration: electricity to grid and process heat to district heating networks Delivers heat from the plant to supply heat and hot water to the buildings and structures on the plant site and to adjacent living areas	Supplies heat for locations 3–15 km from NPP.	District heating network functions as an independent loop from the NPP.	N/A	130°C supply, 70°C return	At least $14.4 billion (costs for Unit 4 alone; 1 trillion rubles for Unit 4)	Ministry of Medium Machine Building of the USSR (Units 1 and 2) Rosenergoatom (Units 3 and 4) State-owned enterprises
Ågesta	PHWR	1964 to 1974	Sweden	Cogeneration: electricity to grid and district heating for Stockholm suburb Farsta	Farsta is approximately 5 km away from the location of the plant.	Steam supplied to tertiary heating loop (Farsta's district heating network) 55 MWth load to Farsta	N/A	Max flow of 2400 tons/hour in district heating network 78–115°C supply, 55–60°C return	$26.7 million (230 million Swedish krona; estimated costs for the 80-MWth plant)	Vattenfall AB (state-owned enterprise)
Beznau 1, 2	PWR (Westinghouse two-loop)	Unit 1: 1969 to present (heating started in 1983) Unit 2: 1971 to present (heating started in 1984)	Switzerland	Cogeneration: electricity to grid and process heat to nearby Refuna district heating network	35-km main network, 85 km of local distribution pipelines	Secondary steam is used to heat a tertiary district heating loop.	N/A	District heating network 1.6 MPa, 80–125°C supply, 50°C return	$815 million (750 million Swiss francs)	Axpo Holding (owned by several public entities)
Gösgen	PWR (PWR three-loop)	1979 to present (Process steam supply began for a cardboard factory in 1979 and a paper mill in 2009. District heating started in 1996.)	Switzerland	Cogeneration: electricity to grid and process heat to nearby facilities (cardboard factory and paper mill) and for district heating	Heat provided through a 1.8-km steam line to cardboard mill. This line is extended for district heating network of Niedergösgen and Schönenwerd. Provides 232 GWh_th per year for all heating applications.	Secondary steam is used to heat a tertiary hot water district heating loop and industrial process steam line.	Tertiary loop steam conditions: 70 tons/hour, 1.2 MPa, 220°C supply, 100°C return	120°C supply, 70°C return	Information not available	Kernkraftwerk Gösgen-Däniken AG (private company with some state ownership)
Mühleberg	BWR (BWR-4)	1972–2019 District heating was short-lived. Information found only on heat supplied in 2008.	Switzerland	Cogeneration: electricity to grid and process heat to district heating network	1700 MWh_th consumed in 2008 in a 2-km hot water line.	Information not available	N/A	15.84 tons/hour (4.4 L/s) 125°C supply, 65°C return	Information not available	BKW Energie AG (majority state-owned; includes some private entity ownership)
Khmelnytskyi 1, 2	PWR (VVER V-320)	Unit 1: 1988 to present Unit 2: 2005 to present	Ukraine	Cogeneration: electricity to grid and process heat to district heating network	Information not available	District heating network functions as a tertiary loop from the NPP.	N/A	Based on other VVER V-320: 130°C supply, 70°C return	Information not available on Unit 1 or 2 costs. Units 3 and 4 (same reactor type) are expected to cost $2.6 billion (73 billion Ukrainian hryvnia)	Energoatom (state-owned enterprise)
South Ukraine 1–3	PWR (VVER V-302)	Unit 1: 1983 to present Unit 2: 1985 to present Unit 3: 1989 to present	Ukraine	Cogeneration: electricity to grid and process heat to district heating network	Heat supplied to local area through main pipeline that is 3 km long.	District heating network functions as a tertiary loop from the NPP.	N/A	150°C supply, 70°C return	Information not available	Energoatom (state-owned enterprise)
Zaporozhye 1–6	PWR (VVER V-320)	Unit 1: 1985 to present Unit 2: 1986 to present Unit 3: 1987 to present Unit 4: 1988 to present Unit 5: 1989 to present Unit 6: 1996 to present	Ukraine	Cogeneration: electricity to grid and process heat to district heating network	Heat supplied to local area through main pipeline that is 5 km long.	District heating network functions as a tertiary loop from the NPP.	N/A	Based on other VVER V-320: 130°C supply, 70°C return	Information not available	Energoatom (state-owned enterprise)

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Contact Information

For more information contact the EPRI Customer Assistance Center at 800.313.3774 (askepri@epri.com).

EPRI Resources

Chad Boyer, *Program Manager*
704.595.2450, cboyer@epri.com

The following organization, under contract to the Electric Power Research Institute (EPRI), prepared this report:

MPR Associates, Inc.
320 King St
Alexandria, VA 22314

Principal Investigator
A. Tran

This report describes research sponsored by EPRI.

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EPRI
3420 Hillview Avenue, Palo Alto, California 94304-1338 • PO Box 10412, Palo Alto, California 94303-0813 USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com