Decarbonizing Industry with Nuclear Energy

A Review of Nuclear Industrial Applications

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ABSTRACT

This technical brief presents a high-level perspective of the industrial applications of nuclear power plants (NPPs) through a review of past projects and provides an overview of the current state of NPP industrial applications. The paper also addresses other ideas that are being investigated with respect to the direct use of nuclear energy for industrial purposes through heat and/or electricity. This use case can improve economic viability for NPPs and contribute to decarbonization of industry.

The review was conducted by literature search and included 34 different nuclear projects from 13 countries. The projects include a wide range of circumstances including 1) NPPs presently operating and supporting industry, 2) NPPs previously operating but now closed, and 3) projects being cancelled before operations. Key insights from this review include the following:

- There is a large amount of experience for NPPs operating with industrial applications, with applications including direct electricity for aluminum smelters and process heating for a cardboard factory. A strong factor in their success is location, including factors such as the local community's perception of nuclear, nearby industrial consumers and resources, and political support for nuclear.
- The barriers to nuclear-powered industrial applications are mainly economical. Funding issues, competition from other energy resources, and difficulties in contract agreements led to many industrial application projects failing to start up or shutting down prematurely.
- Many developments are on the horizon for nuclear-powered industrial applications: Data centers are coordinating with NPPs for carbon-free energy, hydrogen demonstration projects are planning to show the feasibility of hydrogen as another revenue stream (and potential industrial product) for NPPs, and ongoing research for advanced nuclear reactors may enable a higher range of temperatures for nuclear-powered process heating.

Keywords
Decarbonization
Flexible operations
Operating reactors

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OPPORTUNITIES FOR DECARBONIZATION IN INDUSTRY

Addressing climate change requires substantial decreases in greenhouse gas emissions. These emissions are primarily due to the use of fossil fuels for electricity, heat, and transportation, as seen in Figure 1-1 below.

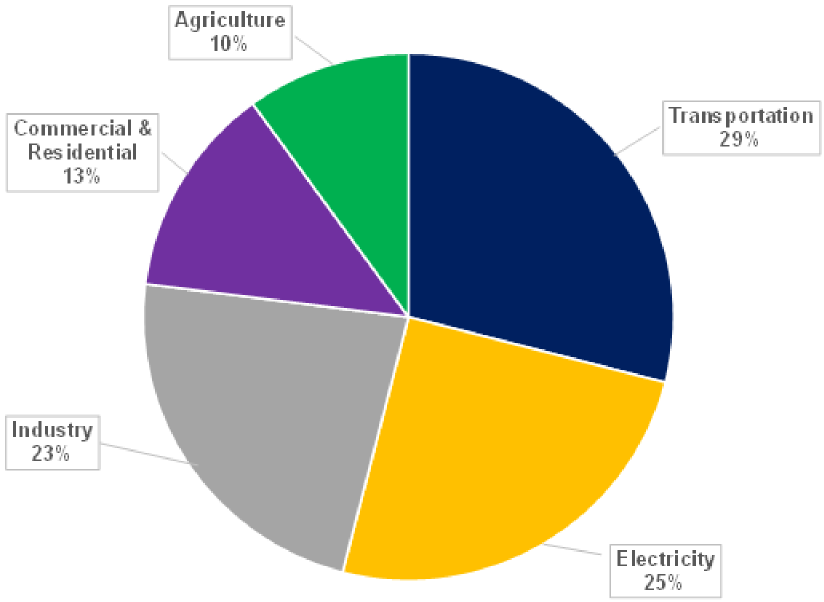

Figure 1-1
Total U.S. greenhouse gas emissions by economic sector in 2019 [1]

Nuclear power plants (NPPs) are a solution for reducing greenhouse emissions in the electricity and industrial sectors, as they can replace fossil fuel resources and provide carbon-free electricity, process heat, and district energy. Currently, however, most NPPs only provide power directly to the electrical grid. This business model is seeing increased competition from other generation types because of increasing penetration of renewable generation and the recent history of low natural gas prices. To maintain economic viability and ensure a sustainable business model for the future, utilities and other stakeholders are exploring alternative use cases for NPPs, such as providing heat for industrial applications.

The types of NPP industrial applications include:

- Direct use of electricity generated by a NPP coordinated with end users
- Use of steam from the power cycle for heating applications
- Combined heat and power (known as cogeneration)

Each of these applications can directly reduce reliance on fossil fuels and reduce carbon emissions in industrial applications. For direct electricity, NPPs can coordinate with consumers to receive steady demand while consumers receive cheaper rates. Industrial consumers typically require large amounts of reliable steam and/or electricity; NPPs are in a good position to support industrial consumers due to their typically large capacities and reliable output.

NPPs are capable of decarbonizing heating applications in addition to providing electricity directly to industrial consumers. Existing light water reactors (LWRs) and heavy water reactors (HWRs) can provide heat for low temperature applications, and future-deployed advanced reactors can potentially reach the higher temperatures for further applications. Based on a European study [2], 30% of industrial heating processes require temperatures below 100°C, with 57% requiring temperatures below 400°C; the existing nuclear fleet, capable of supplying temperatures up to around 300°C, is feasible to support a significant amount of heating applications.

Nuclear-powered industrial applications have been explored by many organizations around the world. This review covers 34 NPPs from 13 different countries, offering a representative collection of different regulatory environments, industrial applications, and heat and electricity transfer conditions. Information was gathered through a literature review including international and domestic sources. The review is intended to provide a summary of plant operational experiences and lessons learned that can be leveraged for future nuclear-powered industrial applications.

2
CURRENT STATE OF NUCLEAR INDUSTRIAL APPLICATIONS

Currently operating NPPs that are supporting industrial applications were reviewed to explore the reasons for their success and the representative operating conditions for different industrial applications. This portion of the review is summarized with relevant information on heat transfer, temperature range, and timeline in Appendix A and includes 21 NPPs from seven different countries.

Summary

All of the 21 operating plants included in the review operate in a cogeneration mode; these plants provide heat for applications including process heating for industrial partners and heavy water production, desalination for plant use and off-site customer use, and district heating [3]. The process of water for on-site use is reviewed as process heat was used, and in some applications, the production amount was significant.

Of the plants included in the review, heat-providing plants are mostly pressurized water reactors (PWRs) or pressurized heavy water reactors (PHWRs) that maintain radiological separation from the reactor core through a secondary coolant loop. An additional coolant loop (that is, tertiary loop) is used to provide the heat to the end user. This configuration provides an additional barrier for radiological separation for the end user and allows the NPP complete control of the secondary loop. The conditions of the tertiary loop are dependent on the application; the highest temperatures supplied were for process heating applications (up to 250°C) [4].

The Gösgen Nuclear Power Plant in Switzerland is an example of these process heating applications. The NPP provides heat for a nearby cardboard factory and paper mill, and it has the longest lifespan of relationship between the NPP and its industrial partners (from 1979 for the NPP and cardboard factory). The NPP supplies 220°C steam at 70 tons/hour through a 1.8-km steam line and, in total, provides 220 GWh of thermal energy per year to the industrial partners [5, 6, 7].

Of the NPPs conducting desalination, most plants use the desalinated water for plant use, so the NPP is also the end user. Desalination methods vary and include multistage flash (MSF), multiple-effect distillation (MED), vapor compression (VC), and reverse osmosis (RO). For methods requiring process heat, heat is provided through steam with temperatures up to 125°C [3, 8].

NPPs supporting district heating operate in countries with district heating networks (such as countries in Eastern Europe but not the United States). In this function, the district heating network functions as an independent loop from the nuclear reactor. The heat is provided through steam or hot water, but supply temperatures vary based on weather conditions. For the NPPs reviewed, supply temperatures are up to 153°C [9].

Success Factors

The NPPs included in this portion of the review have all successfully supported their industrial applications and continue to operate today. Although the reasons for their success are varied, the following key insights were gathered from the review:

- Favorable state support can improve NPP economics.
- Location-specific considerations were important drivers of success.
- Longer NPP lifetimes enable greater returns on investment when paired with district energy or industrial partners.

Several nuclear-powered industrial applications can owe their success to state support. NPPs in five of the eight countries included in the review are state owned and operated. The state provides financial support and vertically integrates the nuclear industry with the ultimate industrial application, streamlining operations from mining/fuel procurement to construction to end use. Furthermore, state-supported NPPs are likely driven by their respective national strategic economic and foreign policy goals, which can incentivize the state to further invest in nuclear energy to support industrial applications. This can be seen from Russia's (formerly the Soviet Union's) early investments into nuclear-powered district heating, which was intended to replace the usage of fossil fuel resources in heating applications [10].

Additionally, when implementing nuclear-powered industrial applications, location is a large factor for success. For process heating, desalination, and district heating, situating an NPP requires close proximity to end customers or saltwater resources. Without close proximity, the industrial application economics would not be favorable due to the large pipelines and infrastructure investments necessary to transfer resources. For all NPPs that support desalination, obtaining water for plant use was more economically favorable through desalination than other approaches. However, commercial deployment of nuclear-powered desalination depends primarily on economic factors and local freshwater needs [11]. Process heating and district heating follow the same location constraints; close proximity to industrial partners or district heating networks is required because thermal heat degrades in quality when transported long distances [12]. For example, the Gösgen plant uses a 1.8-km tertiary loop steam line to provide process heat to nearby facilities [5], and the Temelín Nuclear Power Station in the Czech Republic uses the nearby district heating network as a tertiary loop to provide heat to a town 5 km away [13].

Lastly, the process heating and district heating NPPs included in the review all have long expected lifetimes. Long lifetimes of reliable energy increase confidence in NPP investment, especially for process heating or district heating applications, where the source of heating would otherwise be provided by fossil fuel resources, which incurs larger variable fuel costs than nuclear power. For example, the Haiyang Nuclear Power Plant in China, which provides district heating to the local community, is expected to have a 60-year operating life [14, 15].

3 PAST NUCLEAR-POWERED INDUSTRIAL APPLICATION PROJECTS

Past projects that are not currently operating offer perspective on the challenges that were faced by NPPs in implementing industrial applications. Several of the projects included in this review have successfully operated for some time but were ultimately driven to close earlier than expected, while others were unable to operate at all. The review of past nuclear-powered industrial applications projects is included in Appendix B with information on each project, including heat transfer conditions and reasons for cancellation or discontinuation. The appendix includes 13 NPPs from seven different countries.

Summary of Review

The 13 NPPs included in this portion of the review covered support for industrial applications by NPPs producing electricity only, heat only, and both electricity and heat (that is, cogeneration). Reactor types included PWRs, HWRs, high-temperature gas reactors (HTGRs), and a liquid metal fast reactor (LMFR). For heat-producing plants, NPPs transferred or planned to transfer heat through steam in an independent loop to the end user. The conditions of the steam vary per application, with the highest pressure and temperature planned for the United States' next-generation nuclear plant (NGNP), at 566°C and 16.7 MPa [16].

Of the 13 NPPs included in this portion of the review, seven operated with industrial applications but ended earlier than planned. These applications included electricity provided directly to aluminum smelters at reduced rates and heat provided for local needs, district heating, desalination, and salt refining. For the electricity-only applications, the aluminum smelters required large and reliable supplies of electricity and coordinated with nearby NPPs. Both smelters shut down earlier than expected, mainly due to contract issues between the smelter and NPP that could not ensure reduced rates of electricity to the smelter [17]. The NPPs continued operating after the smelters shut down. The heat-providing NPPs shut down for similar economic reasons, including large and uneconomical investments needed to meet increased security and redundancy requirements for the Ågesta Nuclear Plant in Sweden [18] and high maintenance costs for the Stade Nuclear Plant in Germany [19] and Calder Hall Power Station in the United Kingdom [20].

The remaining six NPPs in this review did not operate and were cancelled at varying stages. The planned industrial applications included providing heat for district heating networks, desalination, and process heat for industries, including the food and chemical industries. The projects were not cancelled due to NPP technical concerns. Reasons for cancellation included public opposition [21, 22], siting disputes and cost-sharing issues between public and private entities for the NGNP plant [23], nuclear insurance concerns with tritium isolation in the Fort Calhoun–Cargill project [24], and funding issues for several projects.[1]

Challenges to Continued Operation and Implementation

Although the reasons for cancellation or discontinuation varied for the NPPs included in this review, several factors contributed greatly to early closures or failures in implementation, such as:

- Poor business cases
- Issues between NPPs and partners
- Local opposition to nuclear

The majority of industrial applications in this review were faced with economic challenges. These challenges included problems in initial NPP funding, such as issues with raising capital for the Bolsa Island Nuclear Power and Desalting Project in the United States [25]. High electricity costs for industrial partners and high maintenance costs for NPPs are examples of postoperational economic challenges, such as for the Stade Nuclear Power Plant and nearby salt refinery [19].

Workable agreements between the NPP and industrial partner were also a challenge in several cases. Although these challenges are mainly driven by the economic challenges discussed previously, an additional challenge is related to the ownership model for the NPP. In the case of the United Kingdom's aluminum smelters, the smelters made capital contributions to NPP construction but did not ultimately receive decision-making ability for how the electricity was distributed and at what rates. Difficulties in receiving reduced rates led to early closures for the smelters [17].

Lastly, opposition to nuclear presented a challenge to several of the NPPs included in the review. For example, the Voronezh and Gorky heat-only reactors in Russia were faced with increased opposition and were deemed infeasible to complete due to the post-Chernobyl political climate. Although these projects attempted to continue construction after public sentiment improved, the plants ultimately never operated [21, 26].

These past nuclear-powered industrial application projects show potential challenges for usage of nuclear power in industrial applications. Challenges with project economics, business agreements, and public opposition remain today for nuclear-powered industrial application projects. It is important for NPPs to establish and understand the business case for pursuing industrial applications, enter into mutually beneficial business agreements with industrial partners, and invest in areas where public perception for nuclear is more favorable.

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[1] The nuclear insurer for the Fort Calhoun–Cargill project had concerns about the legal liability resulting from tritium detections in food. Tritium is found in foods naturally, so proving that detected tritium was not due to the reactor was difficult [24].

4 FUTURE APPLICATIONS

The projects reviewed in this paper show how nuclear energy can be utilized for industrial applications, district energy, and desalination. Ideas for using nuclear power for industrial applications are currently being studied and planned. Applications include NPP coordination with data centers, NPP coordination with renewable energy resources and energy storage, and nuclear-powered hydrogen production projects, all of which support decarbonization and can provide a new revenue stream for NPPs.

Data centers require large amounts of energy to support business applications and activities, such as e-mail and file sharing, databases, and communication services. Additionally, the data center industry continues to grow due to increasing demands for computing power and storage [27]. NPPs can provide these data centers with reliable, carbon-free power; in fact, several data centers are planning to or have already implemented direct electricity from nuclear power, such as Talen Energy in the United States, with its plans to develop a nuclear-powered data center next to Susquehanna Steam Electric Station [28], and Rostelecom in Russia, with its Udomlya data center powered by the Kalininskaya Nuclear Power Plant [29].

Additionally, research into NPP coordination with renewables and energy storage is being explored through numerous research organizations, such as the U.S. Department of Energy. Current research being performed by Idaho National Laboratory is focused on the economic and technical feasibility of using energy from an integrated nuclear-renewable system to create products such as potable water or hydrogen [30]. Additional nuclear-powered hydrogen production projects, such as the projects underway in the United States [31, 32] and around the world [33, 34], may further demonstrate the feasibility and economics of producing hydrogen. The outcomes of these studies will demonstrate the feasibility of several industrial applications and nuclear-renewable coordination.

EPRI is actively working to improve the business case for NPPs through research support for NPPs in industrial applications and several other initiatives. For nuclear technology specifically, EPRI is leading research efforts through the Nuclear Beyond Electricity initiative [35]. The initiative is exploring ideas for using NPPs for purposes other than full power operation solely for providing electricity to the grid. Additionally, for advanced nuclear plants, EPRI's Advanced Nuclear Technology (ANT) program has provided leadership and guidance for advanced nuclear projects and is now investigating non-electricity-generation use cases.

NPPs have already demonstrated success in industrial applications of process heating, desalination, and district heating, and there are numerous efforts underway to demonstrate the economics of providing direct energy to data centers, coordinating with renewable resources, and producing hydrogen. Much of the success of NPPs in existing applications can be attributed to their large, reliable energy output. Future applications could expect the same success, if lessons learned from previous challenges are incorporated into their implementation. Although economics and location constraints may present challenges to some nuclear-powered industrial applications, NPPs can leverage their high-capacity factors and existing operational experience from around the world to meet the needs of many industrial applications.

5
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A

CURRENTLY OPERATING NUCLEAR-POWERED INDUSTRIAL APPLICATION PROJECTS

Table A-1
List of Projects

Plant/Project	Application	Design MWe/MWth/load	Method of heat transfer, heat transfer conditions	Notes on timeline
Gösgen Nuclear Power Plant (PWR, Switzerland)	Cogeneration: electricity to grid and process heat to nearby facilities (cardboard factory and paper mill) and for district heating	1010 MWe / 3002 MWth 190 GWh_th annual (50 MWth load) to nearby paper mill, 30 GWh_th annual (7 MWth load) to nearby cardboard factory, 12 GWh_th annual (12 MWth load) to nearby district heating network	PWR secondary loop steam is used to heat a tertiary loop (a 1.8-km steam line) to nearby facilities. This line is extended for nearby district heating networks. Tertiary steam loop conditions: 70 tons/hour, 1.2 MPa, 220°C supply, 100°C return Cardboard production is suspended during fuel outages (reserve steam generators are heated with heating oil when there is shorter-term unavailability). District heat conditions: 120° C supply, 70° C return	Start: 1979 Gösgen has an unlimited-duration operating license, as long as safety can be demonstrated to regulator. Shutdown plans: expected to shut down by 2040

Table A-1 (continued)
List of Projects

Plant/Project	Application	Design MWe/MWth/load	Method of heat transfer, heat transfer conditions	Notes on timeline
Rajasthan Atomic Power Station Unit 2 (PHWR, India)	Cogeneration: electricity to grid and process heat to produce heavy water for plant use	207 MWe/693 MWth 160 MWe/85 MWth loads	Steam conditions: 110 tons/hour 4 MPa (this steam is reduced to 0.6 MPa in the heavy water plant) 250°C supply	Start: 1980 Had several hiatuses related to coolant channel replacement and heavy water leakage.
Karachi Nuclear Power Plant Unit 1 (PHWR, Pakistan)	Cogeneration: electricity to grid and desalination plants and process heat used for desalination through MED	125 MWe/337 MWth MED plant requires 121 kWe to produce 1600 m^3/day of water for domestic and industrial uses.	An intermediate pressurized water loop separates the power plant and MED plant. MED Plant consumes 11.1 tons/hour, saturated steam at 75°C.	Start: 1971 Desalination began in 2010. Had hiatuses related to vendor support. Vendor's policies and the political climate resulted in the plant requiring indigenous support. Shutdown plans: Permanent shutdown of the plant was planned for 2021. Shutdown has not started yet.

Table A-1 (continued)
List of Projects

Plant/Project	Application	Design MWe/MWth/load	Method of heat transfer, heat transfer conditions	Notes on timeline
Japanese Nuclear Power Plants with Desalination Experience (PWRs): Ohi 3,4 Ikata 3 Genkai 3–4 Takahama 3–4	Cogeneration: electricity to grid or desalination plants and process heat used for desalination (MSF, MED, VC). Potable water is used to supply high-quality make-up for nuclear power stations.	Varies per plant: from 890 (Ikata 3) to 2360 MWe (Ohi and Genkai). Water desalination capacity varies as well, from 2000 to 3900 m^3/day per site.	Steam is taken off the turbine and is used to heat an intermediate heat exchanger loop. The intermediate loop is used to separate the seawater from the power plant steam and maintain a pressure boundary to reduce risks of contaminated release.	Start: varies per plant, from 1984 to 1996 Many plant shutdowns are attributed to increased safety requirements for relicensing following the Fukushima Daiichi nuclear incident. Shutdown plans: Japan currently has policies limiting reactors to 60-year life spans.
Madras Atomic Generating Station (PHWR, India)	Cogeneration: electricity to grid and desalination and process heat for desalination through MSF RO plant requires electricity only.	410 MWe/1620 MWth (two units) 4 MWe penalty to total electric capacity due to desalination retrofit RO 1800 m^3/d capacity Requires 1MWe MSF 4500 m^3/d capacity Requires 3 MWe from total electric capacity (which is a 12-MWth load)	Steam is taken off turbine and transported to the MSF plant at 20 tons/hour, 0.3 MPa, and 125°C and returned to the feedwater heater.	Start: 1983 Desalination began in 2008. Shutdown plans: expected shutdown by 2033/2036.

Table A-1 (continued)
List of Projects

Plant/Project	Application	Design MWe/MWth/load	Method of heat transfer, heat transfer conditions	Notes on timeline
Beznau Nuclear Power Plant (PWR, Switzerland)	Cogeneration: electricity to grid and process heat to nearby Refuna district heating network	730 MWe/2260 MWth (two units) 150 GWh_th annual (up to 74.5 MWth load). The heat taken out of the power cycle decreases the electricity output by up to 7.5 MWe.	Secondary steam is used to heat a tertiary district heating loop (35-km main network). District heat conditions: 1.6 MPa, 80–125°C supply, 50°C return Oil-fired backup boilers feed the district-heating network when Beznau is offline.	Start: 1969 Closed for repairs in 2015 due to safety risks in the steam generator caused by age. Restarted in 2018. Shutdown plans: expected shutdown by 2030
Haiyang Nuclear Power Plant (PWR/AP-1000, China)	Cogeneration: electricity to grid and process heat to district heating network	2340 MWe/6830 MWth (two units)	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.	Start: 2018 District heating began in 2020. Shutdown plans: AP-1000 reactors have an expected 60-year operating life.
Temelín Nuclear Power Station (PWR, Czech Republic)	Cogeneration: electricity to grid and process heat to district heating networks	2056 MWe/6240 MWth (two units)	District heating network functions as a tertiary loop from the NPP. Heat is supplied to local town Týn nad Vltavou 5 km away. District heat conditions: 153°C supply, 67°C return	Start: 2000 Shutdown plans: expected 40-year lifetime.

Table A-1 (continued)
List of Projects

Plant/Project	Application	Design MWe/MWth/load	Method of heat transfer, heat transfer conditions	Notes on timeline
Russian NPPs with district heating experience: Bilibino 2–4 (light-water-cooled graphite reactor [LWGR]) Balakovo 1–4 (PWR) Beloyarsk 3, 4 (LMFR) Kalinin 1–4 (PWR) Kola 1–4 (PWR) Kursk 1–4 (LWGR) Leningrad 2–1, 2 (PWR) Novovoronezh 4 (PWR) Novovoronezh II 1, 2 (PWR) Smolensk 1, 2 (LWGR)	Cogeneration: electricity to grid and process heat to district heating networks	Varies per plant, including ranges from 48-MWe and 76-MWth heat output (Bilibino 1–4) to 3800-MWe and 800-MWth heat output (Balakovo 1–4)	District heating networks function as an independent loop from the NPPs. District heat conditions: 130–150°C supply, 70°C return	Start: varies from 1973 (Kola 1) to 2021 (Leningrad 2–2) Shutdown plans: expected closures for some plants by 2050

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B
CURRENTLY OPERATING NUCLEAR-POWERED INDUSTRIAL APPLICATION PROJECTS

Table B-1
List of Projects

Plant/ Project	Application	Design MWe/MWth/ load	Method of heat transfer, heat transfer conditions	Reason for cancellation or discontinuation
Midland Nuclear Power Plant (PWR, United States)	Cogeneration: electricity and industrial steam for Dow Chemical Company	~1300 MWe/~2500 MWth (two units) Current Dow Chemical load is 1633 Mwe, and steam requirement is 750 tons/hour.	Tertiary steam heated from PWR secondary loop, 4.65 MPa	Construction problems (sinking foundation due to poor soil preparation); public opposition; cost overruns
Bolsa Island Nuclear Power and Desalting Project (PWR, United States)	Cogeneration: electricity and some heat used for desalination (150 million gallons per day)	~1900 MWe/3250 MWth (two units)	Steam sent to a backpressure turbine generator used for electricity and in desalting plant brine heaters, 5.55 MPa	Southern California Edison was unable to raise sufficient capital to begin construction.
Fort Calhoun–Cargill Project (PWR, United States)	Cogeneration: electricity and industrial steam to nearby corn-milling operation	478 Mwe/1500 MWth Cargill required 400 tons/hour of steam, which required an increase of 1755 MWth.	A tertiary steam loop was to provide superheated steam. Steam would be transported via ~2.3 km of pipeline to Cargill site, 4.14 MPa gauge.	Nuclear insurance issue: Cargill could not sufficiently isolate food-process lines. Liability concerns of tritium sources in food (food has natural sources of tritium, and it would be difficult to prove the reactor was not the source).

Table B-1 (continued)
List of Projects

Plant/ Project	Application	Design MWe/MWth/ load	Method of heat transfer, heat transfer conditions	Reason for cancellation or discontinuation
NGNP Plant (HTGR, United States)	Cogeneration: electricity for plants located 1–1.5 miles away and excess to grid; heat used for hydrogen production, district heating, and industrial steam	500 MWe to industry, 750 MWe to grid/3600 MWth	An independent steam loop would interface with the NGNP plant for process heat. Steam conditions in loop: 16.7 MPa 566° C	Terminated due to disputes over site location and the selection of a private-sector partner.
Wylfa Nuclear Power Station and Anglesey Aluminium (Magnox Reactor, United Kingdom)	Electricity provided to grid and directly to aluminum smelter at reduced rates.	980 MWe (two units) 255 MWe to smelter	N/A	Anglesey Aluminium could not renegotiate its power contract with Wylfa and was unable to receive electricity at reduced rates, leading to its closure in September 2009, after operating since 1971.
Hunterston B Nuclear Power Station and Invergordon Aluminium (advanced gas-cooled reactor, United Kingdom)	Electricity provided to grid and directly to aluminum smelter at reduced rates	1220 MWe (two units) 200 MWe to smelter	N/A	After 10 years of operation, the Invergordon smelter closed in 1981 due in part to the high price of electricity and difficulties in contract agreements.

Table B-1 (continued)
List of Projects

Plant/ Project	Application	Design MWe/MWth/ load	Method of heat transfer, heat transfer conditions	Reason for cancellation or discontinuation
Calder Hall Plant (Magnox reactor, United Kingdom)	Cogeneration: electricity and steam to nearby Sellafield site for building heating, nuclear fuel reprocessing, and hypodermic needle sterilization Also generated isotopes for industrial, medical, and research uses	184 MWe/728 MWth (four units)	Steam was taken off from the turbine building. Steam conditions into turbine building: High pressure steam: 519 tons/hour, 3.9 MPa, 366°C Low pressure steam: 252 tons/hour, 0.95 MPa, 349°C.	Calder Hall closed in 2003 due to high maintenance costs and the falling price of electricity, after operating since 1956.
Stade Nuclear Power Plant and Salt Refinery (PWR, Germany)	Cogeneration: electricity to grid and process steam for nearby salt refinery Backup power during outages was provided by nearby heavy oil-fired power plant and on-site fired boiler.	640 MWe/1892 MWth Delivered steam (30 MWth) to nearby salt refinery External steam decoupling reduced net electricity production by around 10 MW.	Steam provided through external steam decoupling and through a 1.5-km pipeline loop. Steam conditions: 60 tons/hour, 0.8 MPa, 190°C supply, 100°C return	Nuclear plant was shut down in 2003 for economic reasons, after operating since 1972 (1984 with salt refinery). The salt refinery also shut down with the nuclear plant.

Table B-1 (continued)
List of Projects

Plant/ Project	Application	Design MWe/MWth/ load	Method of heat transfer, heat transfer conditions	Reason for cancellation or discontinuation
Bruce A Nuclear Generating Station (CANDU reactors, Canada)	Cogeneration: electricity to grid and process heat for nearby buildings, industrial park, and heavy water production	3212 MWe/11328 MWth (Bruce A only) Bruce Bulk Steam Supply (BBSS) could produce 5350 MWth medium pressure steam. 750 MWth used for heavy water production; 15 MWth used for heating on site. 72 MWth delivered to Bruce Energy Centre industrial park.	Bruce A delivered high-pressure steam to a steam supply plant, where a tertiary steam line provided steam to customers (6-km piping). Steam conditions to Bruce Energy Centre: ~250 tons/hour, 1.04 MPa, 180°C supply Emergency backup steam provided from oil-fired boilers.	BBSS was demolished in 2006 due in part to Bruce A's shutdown. Additionally, BBSS's largest user of steam, the heavy water plant, also shut down, which reduced BBSS steam use significantly. Bruce A units were temporarily shut down starting in 1995 so that the station owner, Ontario Hydro, could focus on its other generation resources. The heavy water plant was shut down because sufficient stockpiles of heavy water were produced for CANDU reactor usage. Bruce Power's refurbishments focused on providing full-power electricity instead of selling steam and resulted in BBSS's demolishment.
Aktau Nuclear Power Station Desalination (LMFR, Kazakhstan)	Cogeneration: electricity to grid and desalination through MED and MSF distillation.	135 MWe/350 MWth 200 MWth was used for desalination plant, with 80,000 m^3/day water desalination capacity. 135 MWe to grid	The steam discharged from the backpressure turbine located in the tertiary system was fed to the brine heater of the desalination system. Steam conditions: 0.6 MPa, 230°C supply	The plant was discontinued due to the lack of funds to buy fuel and its expired operating license in 1995. The site was permanently shut down in 1999, after operating commercially since 1973.

Table B-1 (continued)
List of Projects

Plant/ Project	Application	Design MWe/MWth/ load	Method of heat transfer, heat transfer conditions	Reason for cancellation or discontinuation
Voronezh and Gorky AST-500 Projects (PWR, Russia)	Heat-only reactors: district heating for local cities	Both plants were designed for 1000 MWth (two units)	Three-loop heat transport scheme, with pressure barrier between second (intermediate) and third (district heating network) District heat conditions based on AST-500 operation: 1.6 MPa, 150° C supply, 70° C return	Construction started on both projects but was infeasible to complete in the post-Chernobyl political climate. The first units of Voronezh and Gorky were more than 30% and 83% complete, respectively. Cities already pursued other heating methods.
Ågesta Nuclear Power Plant (HWR, Sweden)	Cogeneration: electricity to grid and district heating for Stockholm suburb Farsta	68 MWth, 12 MWe loads Max steam flow of 2400 tons/hour to district heating network	Steam supplied to tertiary heating circuit (Farsta's district heating network). District heat conditions: 78-115°C supply, 55-60°C return	Major investments were needed to meet increased redundancy and security requirements. Investments could not be procured, so the site shut down in 1974, after operating since 1963.

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