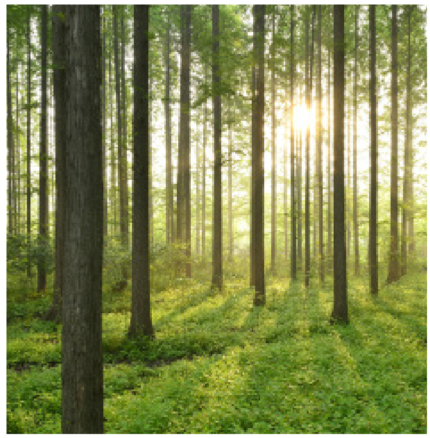
NUCLEAR BEYOND ELECTRICITY



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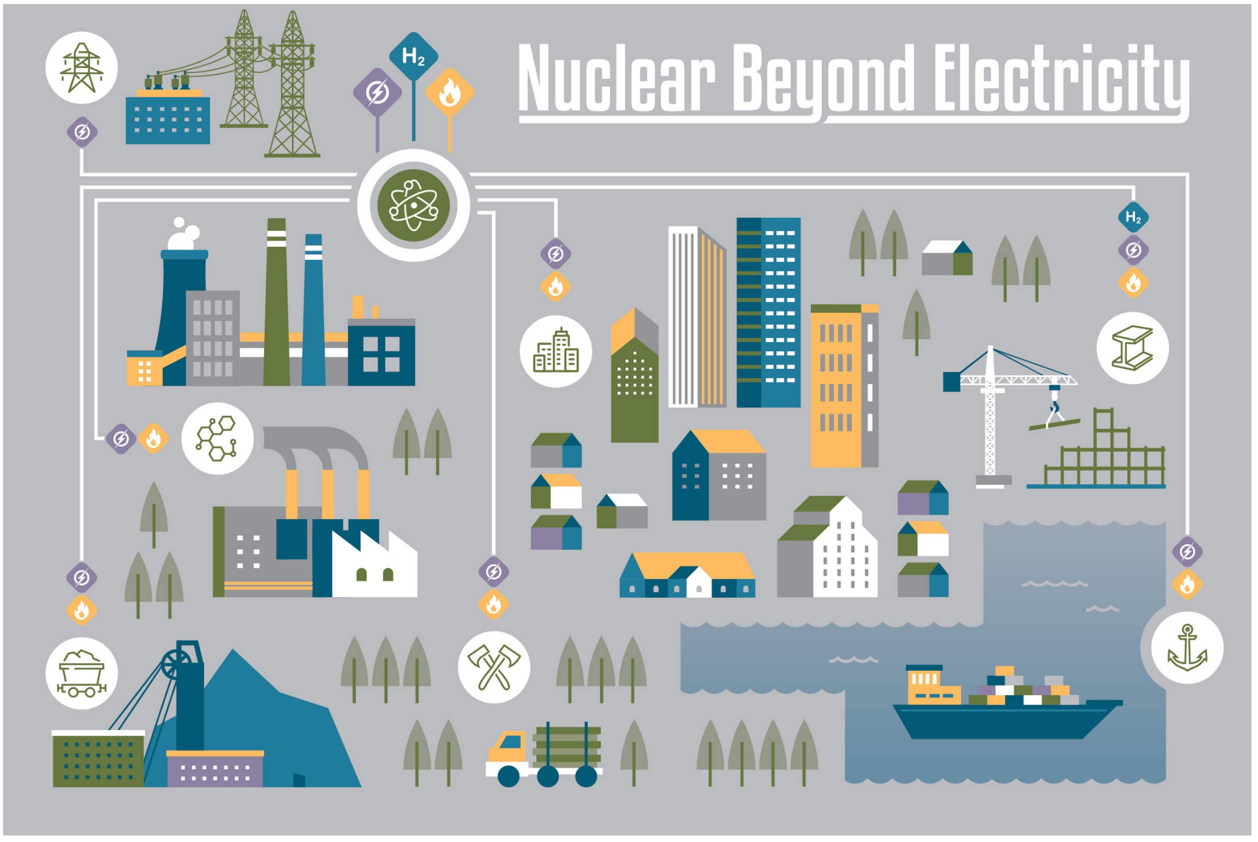


Nuclear Beyond Electricity

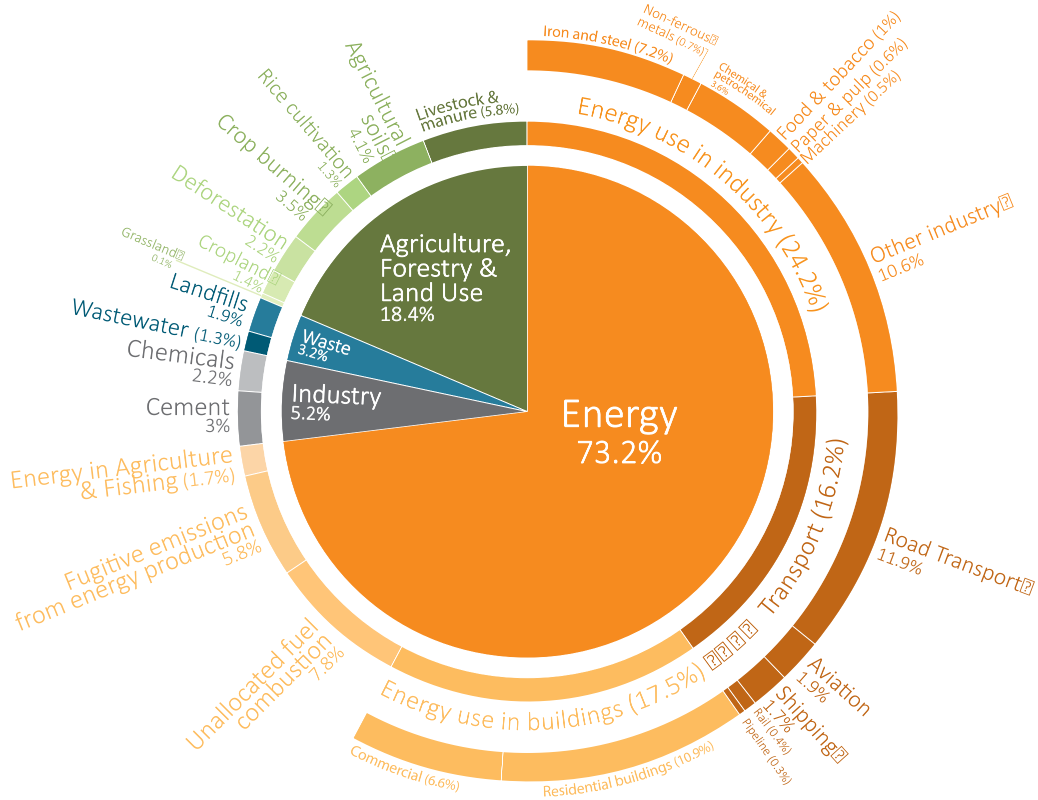
Energy is at the heart of the climate challenge, but energy is more than just electricity. Nuclear reactors fundamentally produce heat, and a lot of it. This heat can be used for more than producing electricity.

This brochure investigates a number of questions about the potential role of nuclear energy beyond electricity. Can new and advanced reactors bring new possibilities, what are the possibilities for existing reactors, and where and when can we see nuclear integrated in sectors beyond electricity production?

MAIN POINTS

- Energy is at the heart of the climate challenge. Heat is the largest energy end-use, accounting for half of the world's total energy consumption.
- Nuclear energy already produces a significant amount of clean electricity and holds vast potential to aid decarbonisation beyond electricity while also decreasing the overall need for electricity and de-risking the decarbonisation journey.
- There are opportunities for both existing and new reactors, but advanced reactors can also play a role in high temperature applications.

The full report is available on Energiforsk's website.



The climate challenge is an energy challenge

Decarbonising energy and non-energy sectors will require an immense effort in electrification as well as beyond electricity.

The increasingly pressing urgency of the climate challenge demands swift action to address and dramatically reduce carbon emissions, which are currently still increasing. Energy is at the heart of the climate challenge, contributing around three-quarters of global greenhouse gas emissions.

A large part of energy consumption will need to be met through electrification, which in many cases provides not only a low-carbon pathway but also significant efficiency gains compared to the fossil-fuelled alternatives of today. Electrification of transportation and fossil-free steel are two examples where the low-carbon alternative consumes less energy than when powered by fossil fuels.

Electricity makes up only around 20% of final energy consumption. Heat is the largest energy end-use and heating for our homes, industry and other applications accounts for half of the world's total energy consumption. Heat use is also responsible for 40% of global carbon dioxide emissions.

In 2018 about half of the total heat was used in industrial processes and the other half was used in buildings for space and water heating (as well as for cooking). A small part was used in agriculture, primarily for heating greenhouses.

Nuclear reactors have provided useful heat since the first commercialisation of nuclear energy. In 2020, 71 of the world's 457 reactors were used to supply non-electricity products in 11 countries. From low-grade heat to district heating and industrial process heating, nuclear energy can supply, and is sometimes already supplying, the heat necessary to decrease emissions in these sectors.

Advanced reactors are already operating

Several advanced, high-temperature reactors have been researched and operated for over 50 years. Several types of advanced reactors can provide temperatures over 500 °C and in some cases higher than 900 °C.

Years of development aided by modern technology and modern design tools have brought about the development of a host of new and advanced reactors, with almost 100 different reactors at various stages of design, licensing and construction.

Several reactors able to provide combined heat and power as well as high-temperature heat for industrial processes are already in operation or scheduled for operation before or around 2030.

TURNING UP THE HEAT

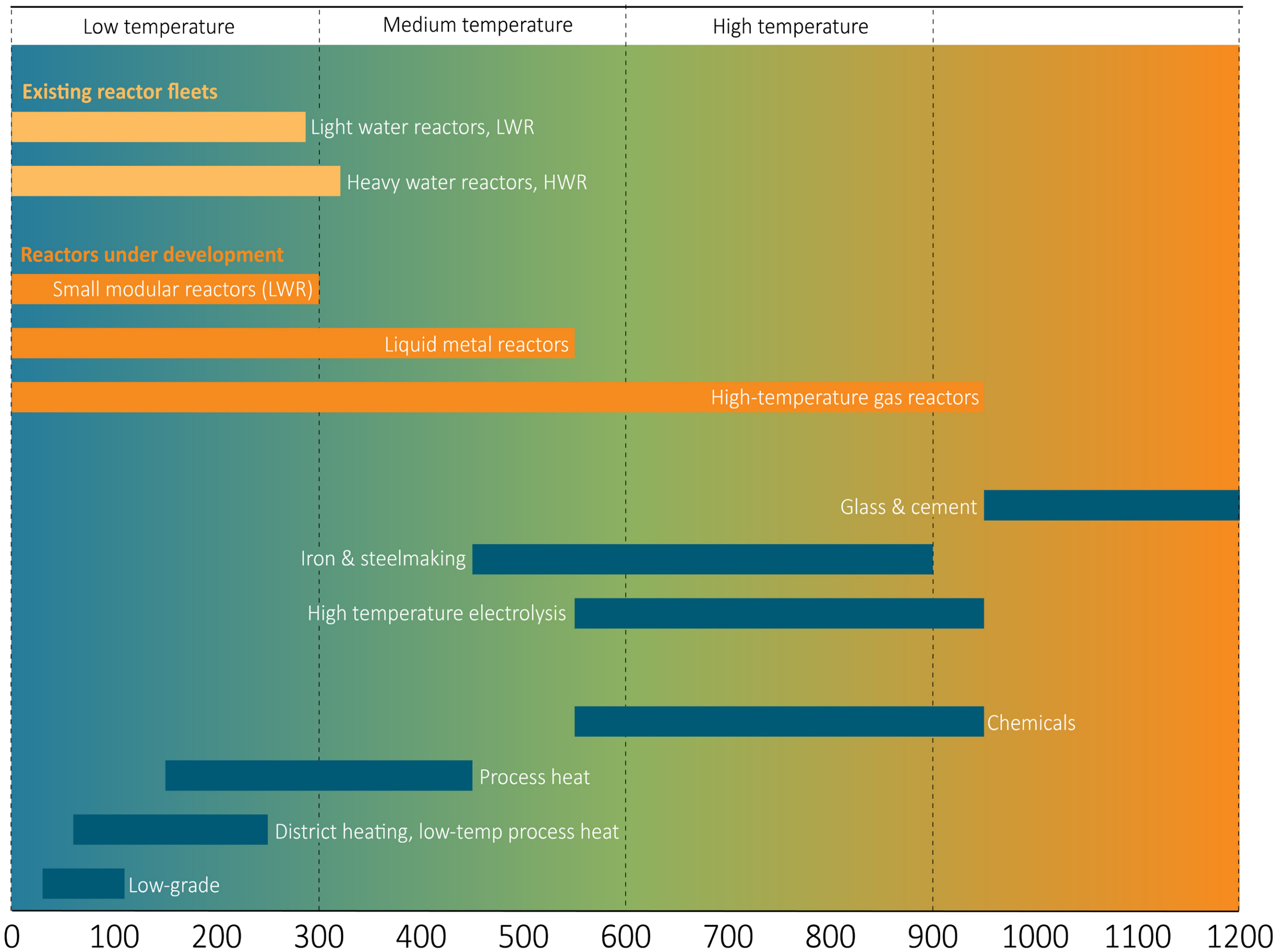
Several types of advanced reactors can operate with a peak primary coolant outlet temperature of more than 500 °C and in the case of high-temperature gas reactors (HTGRs) higher than 900 °C. The Japanese High-Temperature Test Reactor (HTTR) has operated since 1999 with a demonstrated steady coolant outlet temperature of 950 °C.

The German Arbeitsgemeinschaft Versuchsreaktor (AVR), in operation 1967-1988, formed the basis of the Chinese HTR-10 and High-Temperature gas-cooled Reactor Pebble-bed Module (HTR-PM) reactors.

Two HTR-PM reactors entered operation in January 2022. With a thermal output of 250 MW_{th} each they feed a single steam turbine to produce 210 MW_e.

A non-exhaustive sample of the many reactors small and advanced reactors in operation and under development. Temperatures indicated with a star are approximate.

Reactor type	Company	Reactor	Temperature [°C]
BWR	GE Hitachi	BWRX-300	287
PWR	Holtec	SMR-160	321
PWR	NuScale	NPM	321
PWR	Rosatom	RITM-200 & 400	300*
PWR	CNNC	ACP100	323
Liquid metal (sodium)	ARC-100 Canada	ARC-100	510
Liquid metal (sodium)	Oklo	Aurora	500*
Liquid metal (sodium)	TerraPower & GE Hitachi	Natrium	500*
Molten salt reactor	Moltex	SSR-W	600
Molten salt reactor	Terrestrial Energy	IMSR	600-700
Molten salt reactor	Seaborg	cMSR	700
High-temperature gas-cooled reactor (HTGR)	Ultra Safe Nuclear Corp.	MMR	600-900
High-temperature gas-cooled reactor (HTGR)	X-Energy	Xe-100	750
High-temperature gas-cooled reactor (HTGR)	CNNC	HTR-PM	750



A non-exhaustive sample of the many reactors small and advanced reactors in operation and under development.

A NOTE FROM HISTORY

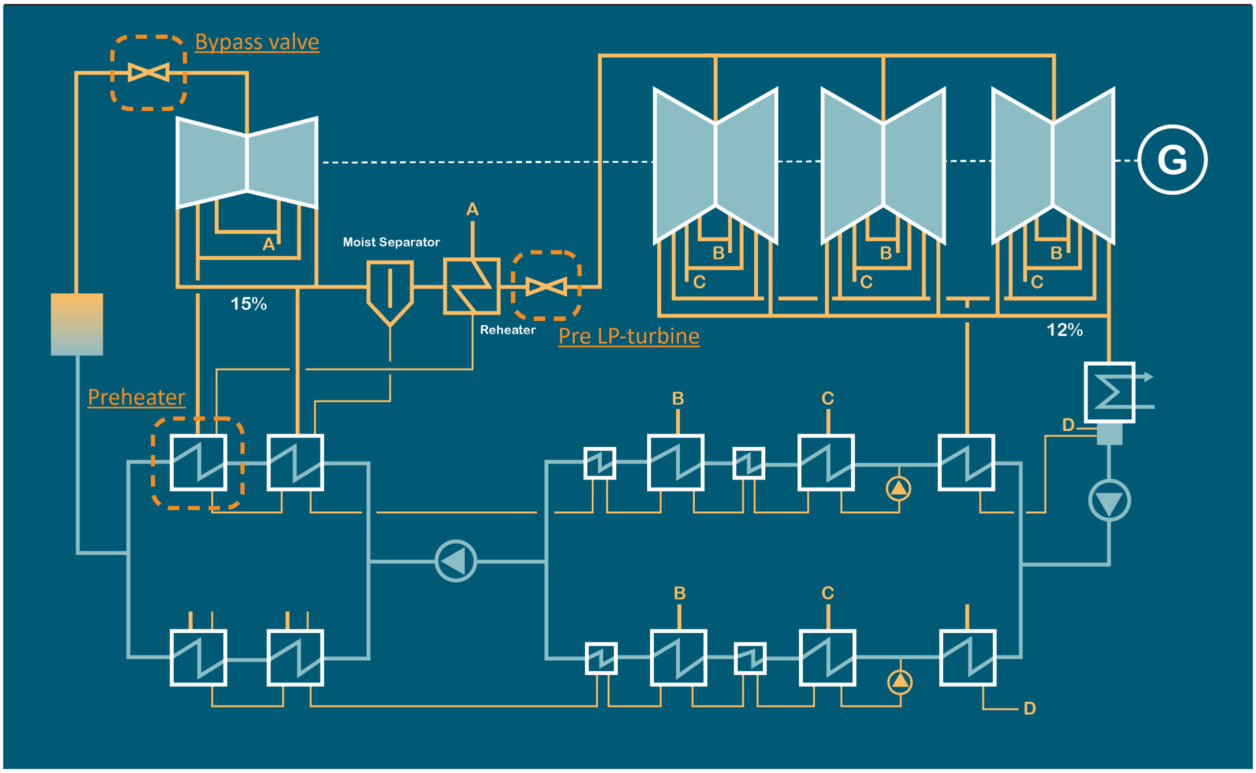
The full report describes the development and diversification of Sweden's energy supply at the height of electrification during the period from the 1940's to the 1960s. That historical situation is not entirely unlike today's, with electricity demand forecast to rapidly increase and new and changing consumption patterns developing.

Three points – the scale of the decarbonisation and electrification challenge, the vast role that heat plays in energy, the possibility of disruption or scarcity in supply – combine to make a compelling case to consider lessons of the past on how to de-risk our decarbonisation journey.

Reactors produce a lot of heat

With high-temperature reactors this heat is available at higher temperatures which are well suited for a range of different applications.

Typical temperatures for different reactor technologies and some applications are shown in the figure above.



Schematic showing a typical 2nd generation BWR cycle with possible steam extraction points marked.

Combining heat and power

To produce both heat and power, heat must be extracted in some way. There are several ways in which steam can be extracted from both new and existing reactors.

The most apparent way is to divert fresh steam from a turbine bypass system. This bypasses the turbine entirely. There are also other ways to extract steam. Depending on how steam is extracted and where, somewhere between 10 - 60% of the total thermal power can be extracted for non-electricity use.

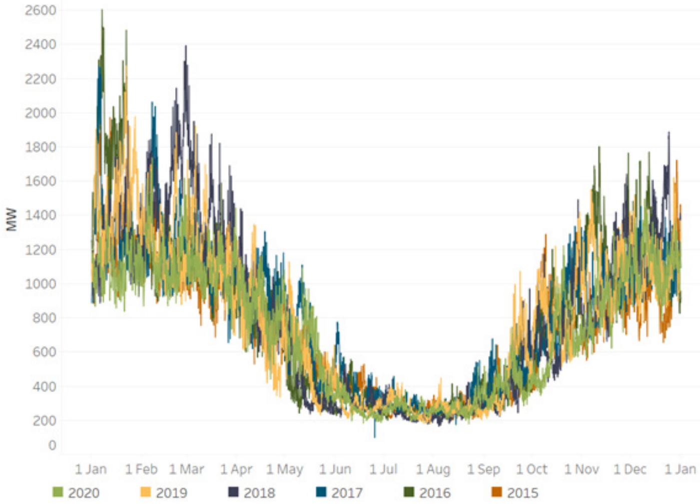
1960's logotype for Stockholm Energi, which managed the district heating network for Farsta where the Ågesta combined heat and power reactor was located.

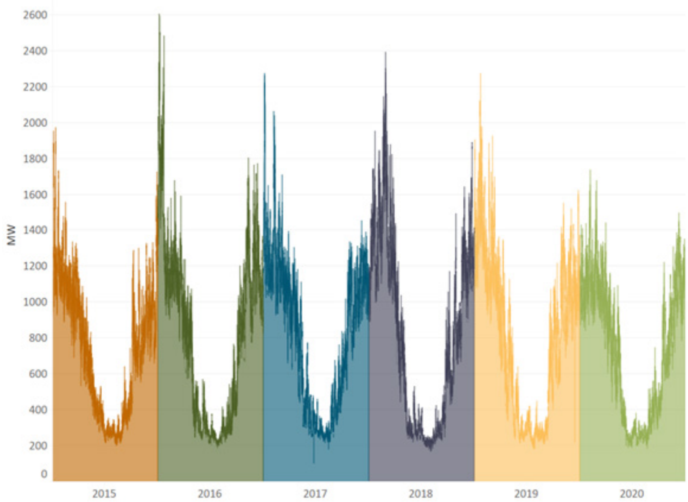
District heating

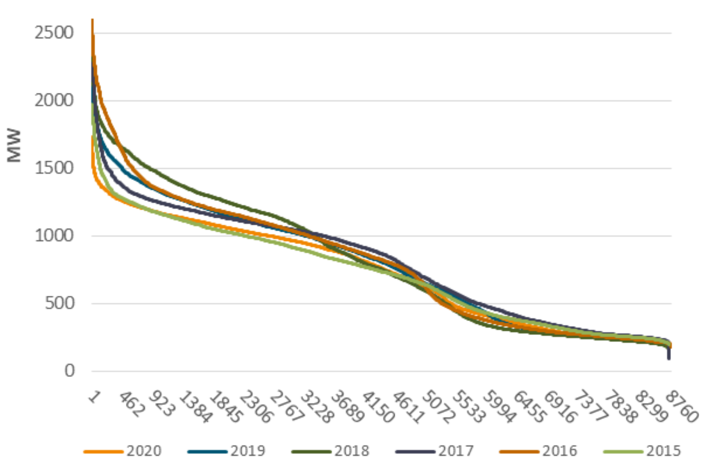
In 2020, nuclear energy provided district heating in 8 countries. Several district heating projects are underway in China, Russia and the Czech Republic to expand nuclear heat use for district heating.

District heating is especially relevant in the Nordic countries. Significant and sustained demand with strong economic benefits of scale offer advantages, while strong seasonal variability poses a potential problem. A significant share of European and Nordic district heating is provided fossil fuels, which will need to be phased out.

Projected costs of nuclear heat in district heating are very competitive with other alternatives. Estimates for conventional, small modular reactors indicate that they should be able to provide district heating for between 20 - 30 EUR/MWh. Early estimates (or cost targets) for heating-only reactors which are currently under development in Finland and China are around 30 EUR/MWh.







District heating data from Helen Oy, which supplies district heating to around 90% of Helsinki.

The first figure shows raw data for the years 2015 to 2020

The second figure shows continuous data for the same five years.

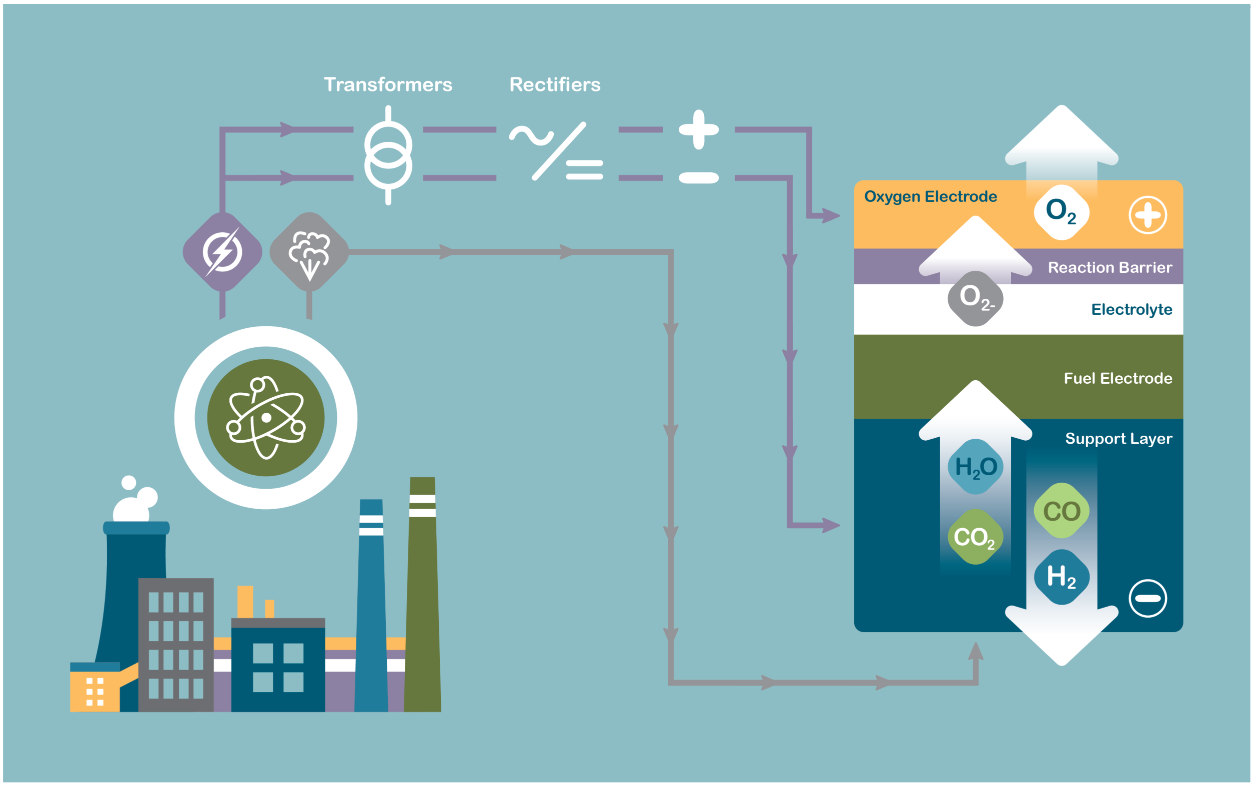
The third figure show the same data as duration curves for all five years.

Stable demand over time, but high seasonal variability

While the supply trend is stable, district heating displays high annual variability. There is high weekly and monthly variability, but seasonal and annual variability is especially significant.

This seasonal variability is a significant barrier for a nuclear reactor, which is capital intensive and benefits from maximising the utilisation factor. However, seasonal variability may be possible to solve with seasonal thermal storages. With a storage equal to about 25% of total demand, it could be possible to remove all or almost all seasonal variation. This would allow nuclear reactors to meet demand at all times, both at peak loads and when the reactor is in a maintenance outage.

Another challenge is the size of the market for nuclear in district heating. Very few cities have district heating grids with a sufficiently high demand for a sufficiently high number of hours.



A schematic of hydrogen production from high temperature steam electrolysis power by nuclear energy.

Hydrogen production

Hydrogen has become the de facto Swiss army knife of the energy transition as countries around the world firm up their commitments to cut carbon emissions. From an energy carrier and a fuel in aviation, shipping and heating to a feedstock in industrial processes and as energy storage to firm up the power grid – hydrogen holds the promise to do it all. However, questions over supply of low-carbon hydrogen has resulted in emerging consensus that the role of hydrogen will be crucial but secondary to other measures such as direct electrification. Nuclear energy may offer advantages in the production of low-carbon hydrogen, if promises of cost reductions and technological development can be fulfilled.

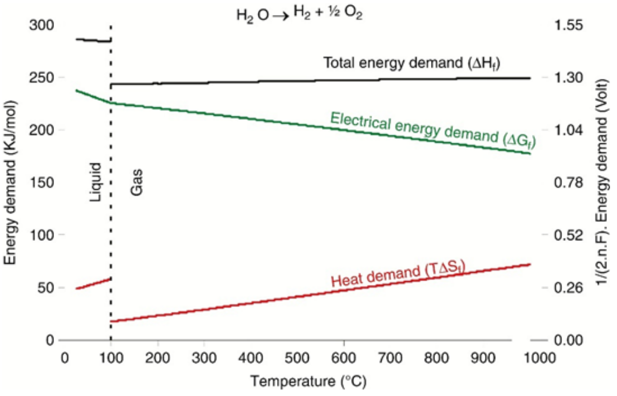
Most hydrogen is produced from fossil fuels

Most of the world's hydrogen is produced from steam methane reforming. Hydrogen produced from fossil gas or coal will always release carbon dioxide both from the chemical reaction and from the combustion required for heating. In theory, it is possible to capture and store (or utilise) most or all of the CO2.

However, in practice it is not possible to capture all emissions.

The energy required to separate water in hydrogen and oxygen consists of both electrical energy and thermal energy.

The relationship between electrical energy demand and heat demand is roughly linear. This means that the more heat is used, the less electricity is required.



The figure shows energy demand in electrolysis, split into electrical and heat demand. Figure from M. B. Mogensen et al., "Reversible solid-oxide cells for clean and sustainable energy," Clean Energy, vol. 3, no. 3, pp. 175–201, Nov. 2019, doi: 10.1093/CE/ZKZ023.

More heat, less electricity

There are several different types of electrolysers. The choice of electrolyser will depend on many different factors, such as the size of the hydrogen demand and project, access to storage infrastructure, access to high temperature heat and more.

For high-temperature reactors with an output close to the SOEC operating temperature range of 600 – 850 °C, Solid Oxide Electrolyser Cells (SOEC) is a very attractive alternative.

The advantage of SOEC is the possibility of significantly reducing the amount of electricity required, while also being able to supply hydrogen at high temperatures, around 900 °C.

Significantly reduced electricity demand

By using more heat and being more efficient, significant reductions in the amount of electricity that is required can be achieved. For applications such as fossil-free steel production, this could have major implications.

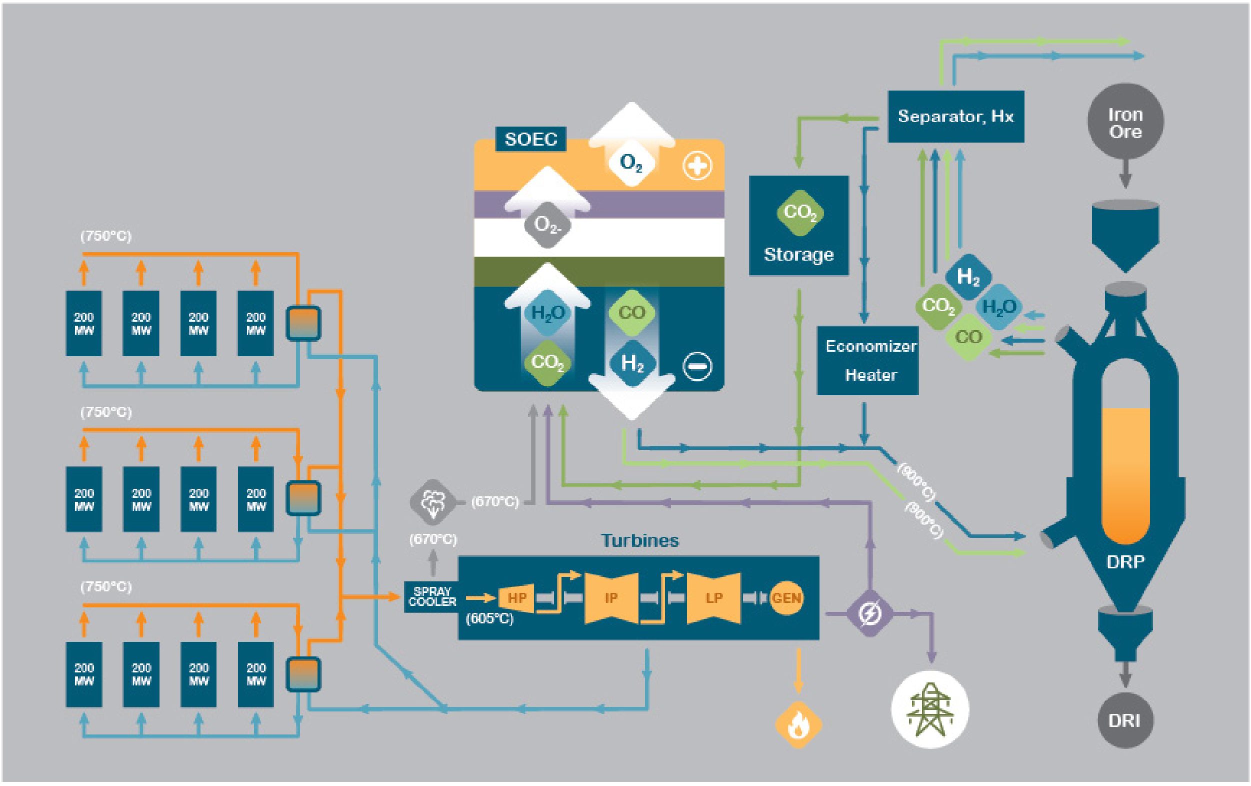
Integration into fossil-free steel production

The iron and steel industry is one of the largest emitters of greenhouse gases. Direct reduction of iron ore is one of several potential routes to produce fossil free steel without any carbon emissions.

While the switch to carbon free reduces the overall energy consumption of the process it also dramatically increases the amount of electricity required. In addition to the technical challenge of establishing a working direct reduction process there is also a massive practical and technical challenge in securing the required clean electricity. Through integrating small modular reactors with high temperature electrolysis it is possible to dramatically reduce the electricity and energy needed.

However, there are several questions that need solving to produce fossil-free at a large scale. Integrating nuclear energy could bring significant benefits, but also several more considerations, both technical and practical.

A schematic illustrating what integration of small, high temperature reactors in fossil-free steel production might look like.



Integration into fossil-free steel production, cont.

Reducing the amount of electricity required doesn't only make operations cheaper, it also has side-effects - perhaps most significantly on the generation capacity, electrolyser capacity and transmission capacity required to supply and use the electricity. The table below shows rough estimates of the amount of electricity and electric power needed to reduce 25 million tonnes of direct reduced iron, DRI, per year.

Electricity and power required for reduction of iron, based on different electrolyser assumption.

kWh_e per kgH_2	**50**	**40**	**35**
TWh_e PER YEAR	62.5	50	43.75
MW_e OF 24/7 POWER PRODUCTION	7,150	5,700	5,000

The full load (8760 hours per year) required to supply 62.5 TWh with the highest electrolyser consumption is equal to almost half of Sweden's total demand in summer. Relying on producing only when prices are low, perhaps 25% of all hours, would require a generation capacity, electrolyser capacity and transmission capacity that is four times larger, almost 30 GW. This poses a significant challenge.

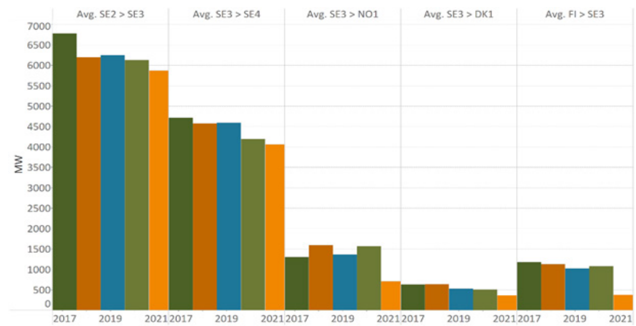
DE-RISKING THE TRANSITION

There is a growing concern over the cost and access to materials with the increasing adoption of new clean technologies, with rising costs for batteries and electrolysers as demand outstrips supply.

At the same time, power grids in several countries are showing signs of strain when it comes to keeping up with the transition. Scarcity may appear not only in terms of materials, but also in terms of transmission capacity and access to grid connections.

Sweden has seen dramatically rising balancing costs as well as price differences and congestions incomes for the grid operator. The large price differances and volatility of power prices present a risk for consumers.

Nuclear energy beyond electricity could help de-risk the transition, by providing heat and grid services to ease the strain and enable faster deployment of clean technology.



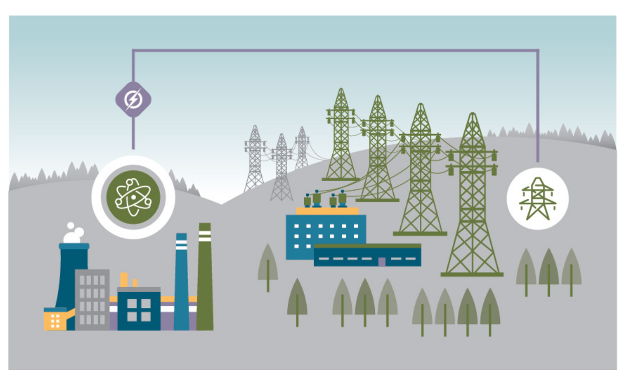
Average transmission capacities between Nordic price areas have been falling.

Enabling a faster transition

Transmission capacity allocated to the market has been steadily falling for the past five years in Sweden.

Restriction in transmission capacity are increasingly correlated with reactor outages as the power system has become more sensitive to disturbances. Some new markets for grid services have been introduced and the Swedish grid operator has dramatically increased spending on balancing. However, there is still now compensation for several of the ancillary services that nuclear power plants provide beyond supplying electricity to the grid.

Existing nuclear power plants could theoretically greatly expand the amount of services they provide within areas such as energy storage, grid services and operational flexibility. However, most actions require investments and often result in



Enabling Nuclear Beyond Electricity

Energy is at the heart of the climate challenge, but energy is more than just electricity. This study aims to evaluate the potential of nuclear energy beyond electricity from a Nordic perspective and with a focus on de-risking the energy transition.

The largest energy end-use is heat and nuclear holds vast potential to contribute to decarbonising our heat use. Several international organisations have dedicated considerable effort to investigate and develop nuclear heat applications, both practically and theoretically. Many reports and tools are publicly available, with technologies and use cases ranging from early research to fully implemented projects already in commercial operation today.

Advanced, high-temperature reactors have been researched and operated for over 50 years. Several new advanced, high-temperature reactors are under development or licensing, and some are in already operation.

Decarbonising energy and non-energy sectors will require an immense effort in electrification as well as beyond electricity. Nuclear energy already produces a significant amount of clean electricity and holds vast potential to aid decarbonisation beyond electricity and decrease the overall need for electricity.

The incorporation of nuclear beyond electricity can de-risk the energy transition while contributing positively to security of supply, competitiveness and sustainability goals.

NEGATIVE EMISSION NUCLEAR

There is broad consensus that Negative Emission Technologies, or NETs, will be needed alongside other measures to keep global average temperature increase below 2 °C and in line with the Paris Agreement.

There are several different NETs, most of which are energy-intensive and require large amounts of clean electricity as input.

Powering direct air capture technology with low grade nuclear heat could offer a cost competitive and efficient option for capturing carbon emissions.

Opportunities beyond flexibility

While much attention is focused on flexible operations and hydrogen production, several other strategies and applications are also worth pursuing.

Nuclear energy can be, and is already, integrated in many different non-electricity applications. However, many potential markets for nuclear beyond electricity applications could either be described as risky or chronically undervalued (e.g. fresh water and power grid services).

With adequate policies and fair valuation in these and other sectors, nuclear energy could provide significant help in decarbonisation beyond electricity.

DESALINATION

There are three main desalination methods, two based on distillation and one based on membrane filtration.

Desalination plants are often hybrid plants, and utilise more than one method to achieve the desired water quality.

Both existing and new and advanced reactors are very well suited to integrate in the desalination process by providing low-carbon heat and electricity.

LONG-RANGE DISTRICT HEATING

Nuclear energy is often said to be poorly suited for district heating as plants are located far from cities and transmission of heat is not well suited for long distances. There are however projects in the EU with district heating pipes ranging upwards of 100 km and Chinese projects where district heating pipes upwards of 200 km long are being considered.

For very large district heating pipes over large distances, the heat losses are covered by friction losses which means that the feedwater may arrive warmer than when it first entered the pipe.

NUCLEAR BEYOND ELECTRICITY

Energy is at the heart of the climate challenge, but energy is more than just electricity. This folder provides you with a quick overview of the potential role of nuclear beyond electricity.

The broschure gives an overview of nuclear technology developments and the possibilities and challenges in a number of different applications, from district heating to district heating and ancillary services, for both existing and new reactors.

Energiforsk is the Swedish Energy Research Centre – an industrially owned body dedicated to meeting the common energy challenges faced by industries, authorities and society. Our vision is to be hub of Swedish energy research and our mission is to make the world of energy smarter!

Energiforsk

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