

NUCLEAR BEYOND ELECTRICITY

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NUCLEAR POWER – OUTLOOK
AND TECHNOLOGY DEVELOPMENT



Nuclear Beyond Electricity

A review of non-electricity energy applications

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Foreword

One mission of the Nuclear portfolio is to follow the developments in the nuclear field to understand the various opportunities and consequences of nuclear power. In the Nordic countries electricity is produced with very low CO₂-emissions, but with the climate challenge, a transition is needed for other parts of the energy sector, such as transportation and heavy industry.

Nuclear reactors fundamentally produce heat. This heat can be used for more than producing electricity and thereby satisfying other needs in the energy sector. This study investigates both the possibilities for existing reactors, and new and more advanced reactors. What are the new possibilities, where can they be put to best use and when can these applications be possible? This report presents a number of examples with nuclear integrated in sectors beyond electricity production, i.e., nuclear energy beyond electricity.

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These are the results and conclusions of a project, which is part of a research programme run by Energiforsk. The author/authors are responsible for the content.

Summary

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, thanks to the opportunity of sector coupling and integration across a range of difficult to decarbonise sectors. The incorporation of nuclear beyond electricity can de-risk the energy transition while contributing positively to security of supply, competitiveness and sustainability goals.

This study has reviewed applications and possibilities for nuclear beyond electricity from a Nordic perspective. The scope of the report has been limited to a number of topics. This is a summary of these topics and the most important conclusions.

Background and introduction. The first section serves as a background to provide some perspective on the energy transition as well as an introduction to the concept of nuclear beyond electricity. Energy is at the heart of the energy transition, but energy is more than just electricity. Historical efforts offer some lessons on the importance of diversification of energy supply.

The section also covers some different types of new and advanced reactors, nuclear heat production and steam extraction from existing reactors. Several new and advanced reactors are both operating and under development with planned deployment before or around 2030. District heating is an important part of the Nordic energy sector, which serves as a type of sector coupling between power and heat. Nuclear reactors are well suited to provide district heating, and cost estimates indicate they can do so competitively. Desalination is another energy-intensive process where nuclear energy could integrate well with hybrid desalination plants.

Direct air capture. 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. This report explores a novel method of powering direct air capture technology with low grade nuclear heat, which could offer a cost competitive and efficient option for capturing carbon emissions.

Hydrogen production. From low temperature electrolysis to high temperature steam electrolysis and different thermochemical cycles, there are many ways to produce low carbon hydrogen. Steam electrolysis, which doesn't require rare materials and offers greater efficiency with less electrical input compared to low temperature electrolysis, is an attractive option for nuclear hydrogen production.

Steel production. The report analyses steel production to find possible ways of integrating small and advanced reactors in steel production by providing

electricity, heat, and hydrogen for direct reduction of iron ore. This initial analysis explores some questions and recommends a focused effort on steel production.

Uses for existing nuclear power plants. New and advanced reactors offer more market opportunities, thanks to higher temperatures and the ability to integrate design considerations already in early design stages. However, existing reactors also offer opportunities beyond electricity production, e.g. industrial electricity, stabilising the power grid and low-grade heat applications for greenhouses.

Conclusions and recommendations for future work. Nuclear energy already plays an important role in global electricity production. It also holds vast potential in applications beyond electricity, where it can aid in the decarbonisation of otherwise hard to abate sectors. Nuclear energy can also contribute to ensuring security of supply, competitiveness, and sustainability. However, many potential markets for nuclear beyond electricity applications could be described as chronically undervalued, e.g. fresh water and ancillary services for the power grid. With adequate policies and fair valuation in these and other sectors, nuclear energy could provide significant help in decarbonisation beyond electricity.

Keywords

Nuclear Beyond Electricity, Small Modular Reactors, SMR, Nuclear Power, Hydrogen, Fossil-free steel, District heating, Direct Air Capture, Desalination of seawater

Kärnkraft bortom elproduktion, Små modulära reaktorer, SMR, Kärnkraft, Vätgas, Fossilfritt stål, Fjärrvärme, Koldioxidinfångning, Avsaltning av havsvatten

Sammanfattning

Denna studie avser att undersöka kärnenergens möjligheter bortom elproduktion från ett nordiskt perspektiv och med fokus på att begränsa risker i energiomställningen. Värme utgör den största delen av slutlig energianvändning och kärnenergi har stor potential att kunna bidra genom dess möjligheter till sektorskoppling och användningsområden inom sektorer som annars är svåra att minska utsläppen inom. Användningen av kärnenergi kan bidra positivt till försörjningstrygghet, konkurrenskraft och hållbarhetsmål.

Studien har undersökt tillämpningar och möjligheter för kärnkraft bortom elproduktion från ett nordiskt perspektiv. Rapportens omfattning har begränsats till ett antal huvudsakliga ämnen. Nedan följer en sammanställning av dessa ämnen och en sammanfattning av rapportens huvudsakliga slutsatser.

Bakgrund. Studiens första avsnitt tjänar som bakgrund för att ge perspektiv på energiomställningen samt en introduktion till begreppet kärnkraft bortom elektricitet. En historisk tillbakablick bjuder på några lärdomar om vikten av diversifiering av energiförsörjningen.

Avsnittet omfattar även olika typer av nya och avancerade reaktorer, kärnvärmeproduktion och bortledning av ånga från befintliga reaktorer. Ett antal nya och avancerade reaktorer finns redan i drift eller är under utveckling med planerad driftsättning före eller omkring år 2030. Kraftvärme och fjärrvärme utgör en viktig del av det nordiska energisystemet, inte minst som en typ av sektorskoppling mellan kraft och värme. Kärnreaktorer är väl lämpade för att producera värme och kostnadsuppskattningar visar att det skulle kunna göras konkurrenskraftigt. Avsaltning av havsvatten är en annan energikrävande process där kärnenergi lämpar sig väl, bland annat för hybridavsaltningsanläggningar.

Koldioxidinfångning. Det råder bred enighet att negativa utsläpp, tillsammans med en rad andra åtgärder, kommer krävas för att hålla den globala medeltemperaturökningen under 2 °C och i linje med Parisavtalet. Det finns flera olika tekniker för negativa utsläpp, varav de flesta är energiintensiva och kräver stora mängder el. Rapporten utforskar en ny metod för att driva koldioxidinfångning med låggradig kärnvärme, vilket skulle kunna utgöra en mer kostnadseffektiv och effektiv metod för koldioxidinfångning.

Vätgasproduktion. Från lågtemperatur elektrolys till ångelektrolys och olika termokemiska cykler – det finns många sätt att producera fossilfri vätgas. Ångelektrolys, som inte kräver sällsynta råvaror och som erbjuder högre verkningsgrad med mindre elektricitet jämfört med lågtemperatur elektrolys, skulle kunna utgöra ett bra alternativ för produktion av vätgas från kärnenergi.

Stålproduktion. Rapporten analyserar stålproduktion för att hitta möjliga sätt att integrera små och avancerade reaktorer i produktionen genom att producera el, värme och vätgas för direktereduktion av järnmalm. Denna inledande analys rekommenderar en särskild studie dedikerad till stålproduktion.

Befintliga kärnkraftverk. Tack vare högre temperaturer och möjligheten att integrera olika aspekter redan i tidiga designstadier erbjuder nya och avancerade reaktorer fler möjligheter än befintliga kraftverk. Men även för befintliga reaktorer finns en del möjligheter bortom elproduktion, bland annat för industriella elkunder som datacenter, stödtjänster till kraftsystemet och lågvärdiga värmetillämpningar som uppvärmning av växthus.

Slutsatser och rekommendationer för framtida arbete. Kärnenergi spelar redan en viktig roll i den globala elproduktionen. Den har också en enorm potential i tillämpningar bortom elproduktion, där den kan bidra till att minska koldioxidutsläpp inom sektorer som annars är svåra att ställa om. Kärnenergi kan också bidra till att uppnå mål inom försörjningstrygghet, konkurrenskraft och hållbarhet. Flera potentiella marknadsmöjligheter för kärnkraft bortom elproduktion skulle dock kunna beskrivas som kroniskt undervärderade, till exempel färskvattenförsörjning och stödtjänster för kraftsystemet. Med bättre policys och en mer rättvisande värdering av dessa och andra sektorer skulle kärnenergin kunna göra avsevärd nytta för att minska koldioxidutsläppen bortom elproduktion.

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Background – Energy is at the heart of the climate challenge

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 while also decreasing the overall need for electricity and de-risking the decarbonisation journey.

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. Figure 1 shows global carbon emissions by economic sector.

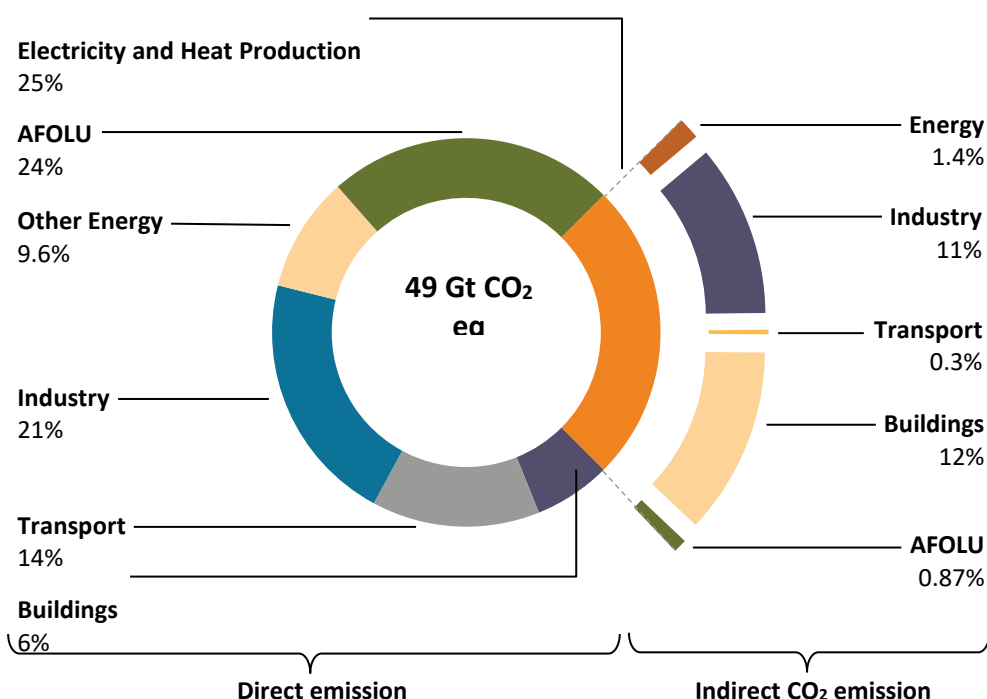


Figure 1.

Greenhouse gas emissions by economic sectors, as defined by IPCC [1] AFOLU is Agriculture, Forestry and Other Land Use.

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.

Nuclear power plays a significant role in electricity production. It produces around 10% of global electricity and is the leading low-carbon source in advanced economies¹. Together with hydropower, nuclear power has provided 90% of low-carbon electricity since the 1970s [2].

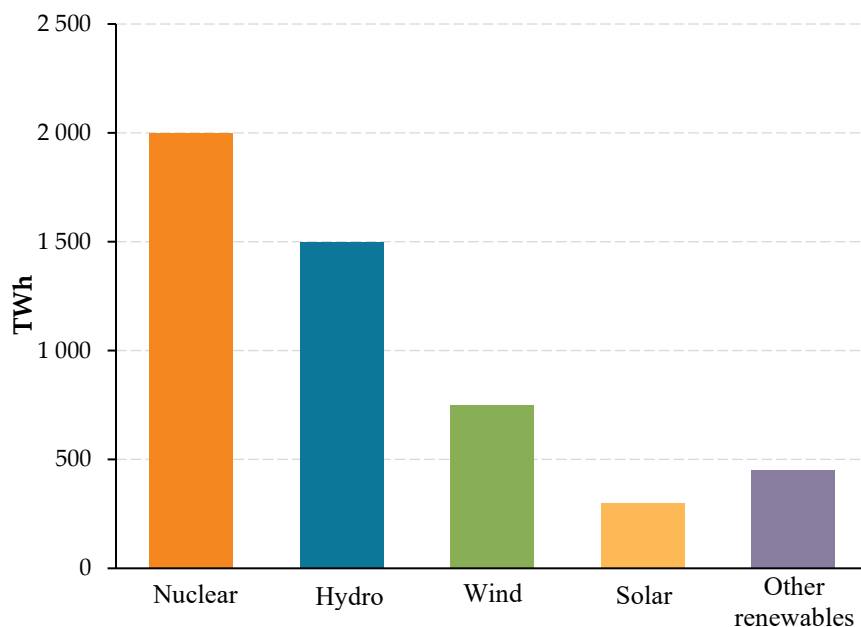


Figure 2.

Generation of low-carbon electricity in advanced economies by source, 2018. Data from IEA [2].

Over the past 50 years, nuclear power has provided approximately half of all low-carbon in advanced economies. In Europe, nuclear power is the main source of electricity. In both Europe and the U.S., nuclear power is the largest source of low-carbon electricity, providing about half of the low-carbon electricity in both.

Decarbonisation of electricity and energy is slow. The share of fossil fuels in electricity has remained largely constant at just over 60% for the past 20 to 30 years. The situation for overall energy use is similar, except the share of fossil fuels has remained stable at 80%.

In the same period, global electricity demand has more than doubled and global energy demand has increased by more than 50%.

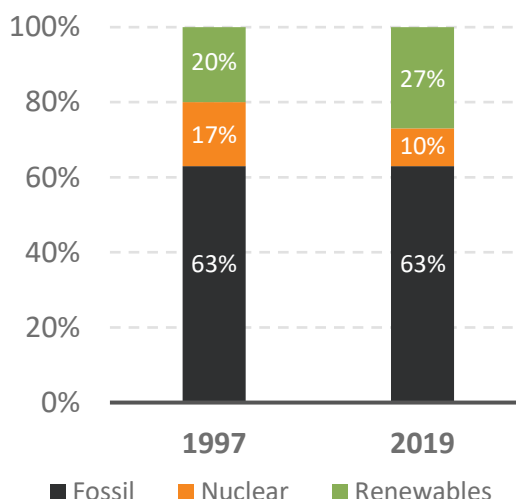


Figure 3.

Global electricity generation by source in 1997 and 2019. On 11 December 1997, the Kyoto Protocol was adopted.

¹ The term advanced economies includes Australia, Canada, Chile, the 27 members of the European Union and the United Kingdom, Iceland, Israel, Japan, Korea, Mexico, New Zealand, Norway, Switzerland, Turkey and the United States.

The energy transition will demand extraordinary amounts of clean electricity. This applies also to regions and countries where electricity supply is already or nearly fossil-free, e.g. Sweden, Norway and Finland, where the demand for clean electricity is set to increase dramatically as part of the transition away from fossil fuels.

In Sweden, electricity demand is set to rise by around 170 TWh, from 140 TWh today to around 310 TWh by 2045. Considering the possible closure of some existing generation, this will require somewhere between 200-250 TWh from new production. The situation is similar in Finland, where electricity demand is set to rise by 50 TWh to an estimated 135 TWh by 2050. This would require around 100 TWh of new electricity production.

Despite the seemingly large increases in electricity demand, neither the Finnish nor the Swedish forecast fully account for the necessary demand required to meet net zero goals, meaning both countries would still be emitting carbon dioxide in contradiction with their respective emissions targets.

Most greenhouse gas emissions are energy related and non-energy related emissions often require new, clean energy input as a way of reducing or limiting emissions. Additionally, negative emission technologies (NETs) necessary to address emissions from certain hard to abate sectors will require significant amounts of clean energy.

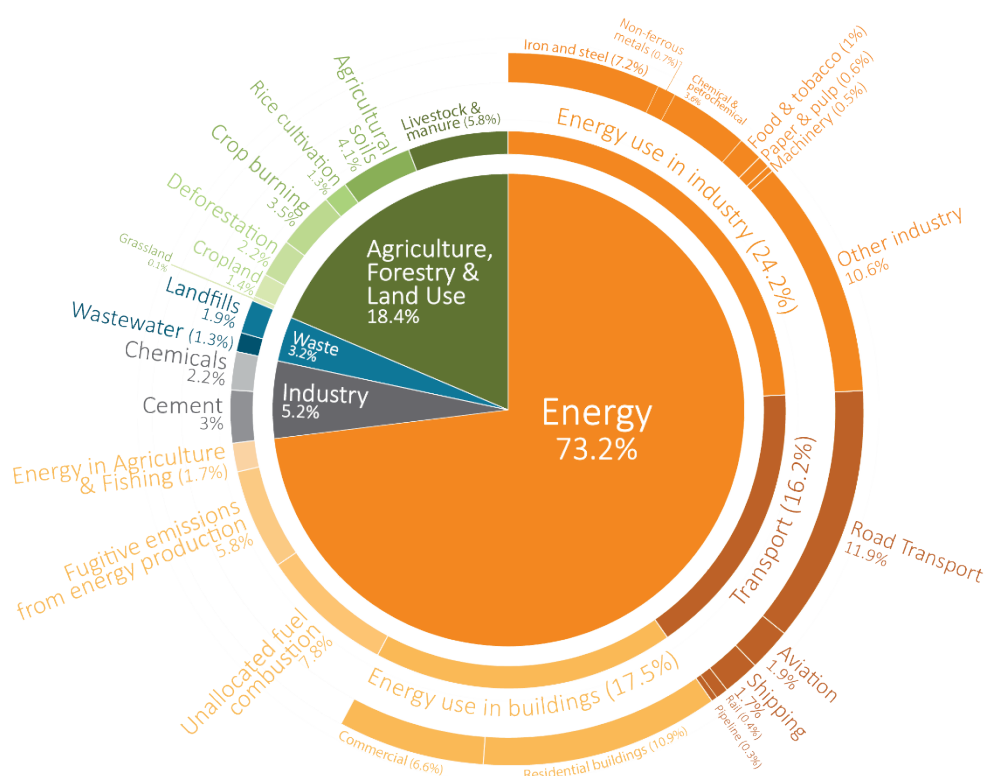


Figure 4. Global greenhouse gas emissions by sector, shown for the year 2016. Global greenhouse gas emissions were 49.4 billion tonnes CO₂eq. Data from Climate Watch and the World Resource Institute (2020) and adapted from Our World in Data [3].

HEAT IS THE LARGEST ENERGY END-USE

Energy is at the heart of the climate challenge, but energy is more than just electricity. Electricity makes up only around 20% of final energy consumption.

Heat is the largest energy end-use. Heating for our homes, industry and other applications accounts for half of the world's total energy consumption and is responsible for 40% of global carbon dioxide emissions [4].

Of this heat, around half is used for industrial processes. A little less than half is used for space and water heating in buildings, with a smaller part used for cooking. The remainder is used in agriculture, primarily for heating greenhouses [4].

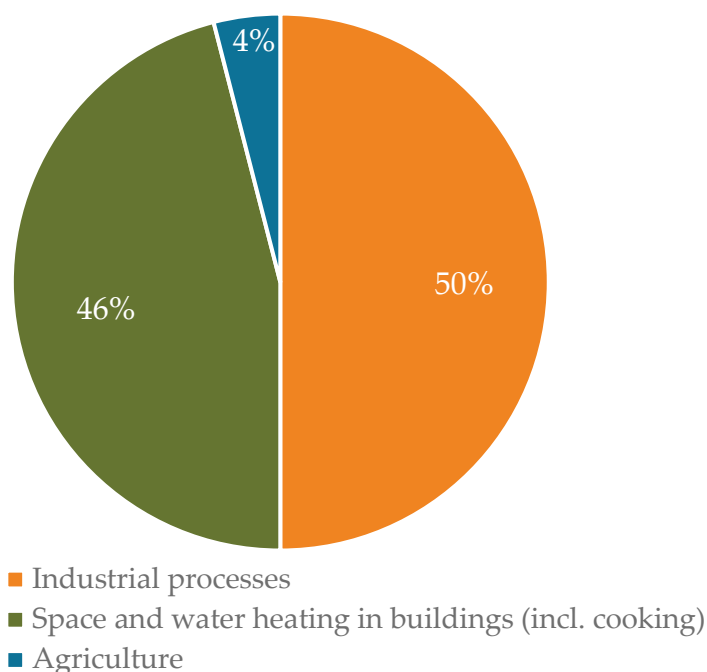


Figure 5.

Heat is the largest energy end-use. 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 greenhouse heating. Data from IEA [4].

Increasing electricity production to meet demand and decarbonise industry will be a central task, but it is not an easy one. The volatility in energy markets in the past year has demonstrated the delicate balance between the phase-out of fossil fuels and the deployment of clean energy alternatives.

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.

NUCLEAR ENERGY BEYOND ELECTRICITY FOR OVER 50 YEARS

Nuclear reactors have provided useful heat since commercial reactors were first deployed and rely on proven technology. Out of the 457 reactors in the IAEA Power Reactor Information System database, 71 reactors in 11 countries have been used for non-electricity energy products [5]. For 55 of these reactors, less than 2% of the reactor output is non-electric. Many now decommissioned reactors have also been used to produce heat, e.g. Stade² in Germany and Ågesta³ in Sweden.

Existing reactors are used in all kinds of heat applications, providing heat at different qualities and temperatures ranging from very low-grade heating for agricultural purposes to district heating and industrial process heat.

Several advanced, high-temperature reactors have also been researched and operated for over 50 years. 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 which recently entered operation.

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 72 reactors tracked by the IAEA at various stages of design, licensing and construction [6]. A number of reactors under development are not included among these.

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.

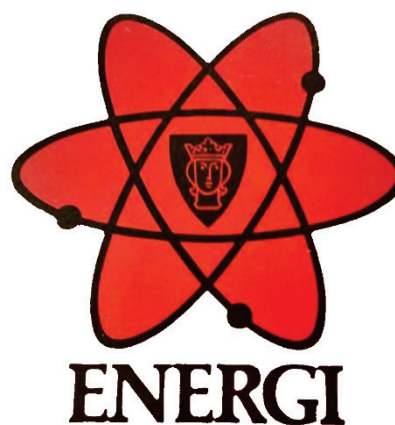


Figure 6. 1960's logotype for Stockholm Energi, which managed the district heating network for Farsta where the Ågesta combined heat and power reactor was located.

² The Stade nuclear power plant provided process steam to the nearby saltern to produce salt.

³ Ågesta was a combined nuclear heat and power plant built to primarily produce heat for the Stockholm suburb of Farsta, as well as a smaller amount of electricity.

TAKING A NOTE FROM HISTORY

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 pursue a multitude of different approaches.

Indeed, history offers lessons on how to de-risk the decarbonisation journey. Up until the period after the second world war, Sweden had been electrifying at a rapid pace – expanding hydropower during the second world war and especially up until 1942.

Then, in the late 1940s, Sweden experienced a number of severe years of drought which, when combined with rapidly increasing demand for electricity, necessitated rationing of electricity supplies [7].



Figure 7.
Kungsgatan with neon signs, looking west. Stockholm 29 December 1944 [8].

Sweden faced three major problems:

- The growth in demand for electricity was higher than ever before, following somewhat of an economic boom. This came as a surprise as energy demand slumped significantly after the first world war.
- The expansion of new power stations and power lines was behind schedule, both in the short term and long term.
- 1947 was a year with exceptional drought⁴.

⁴ It was one of the driest, if not the driest, year on record. The longest documented period without any rain at all was measured during this period, where the areas around Skövde went without any rain for 65 days in a row. Several heat records that still stand to this day were also recorded, among them 38 °C in Målilla on June 1947 [71]–[73].

In September 1947, rationing of electricity was introduced and lasted until May 1948. Rationing reduced electricity consumption in the autumn by around 20%.

However, the drought was not over and in September 1948, electricity rationing was again introduced and lasted until February 1949.

Scarcity in electricity supplies was compounded by urbanisation. Sweden changed rapidly after the war as people moved from rural areas to the growing cities for jobs and opportunities for growth.

The demand for both electricity and heating increased dramatically, risking that there would be a shortage within a few years. Hydropower resources were fundamentally limited, could not be expanded quickly enough to meet the demand, and were susceptible to droughts. Especially with regards to winter heating demand, the need for a more diversified energy policy was clear. Several measures alerted the public to the situation, among them a cartoon character. See Figure 8.

Sweden's first combined heat and power (CHP) plant started in October 1948 in Karlstad. It is soon followed by CHP plants Malmö, Norrköping, Göteborg, Sundbyberg, Stockholm, Linköping, Västerås and Örebro.

The realisation of the importance of security of supply and energy independence also lead to the establishment of *Atomkommittén*, the atomic committee, which was tasked with finding peaceful uses for nuclear energy. In 1947 AB Atomenergi was established based on recommendations by the committee. The recommendations were motivated by the security of supply issues and an electricity system based on several pillars would be significantly more robust. Nuclear energy would complement hydropower and solve the problem of drought years while meeting the increase in demand.

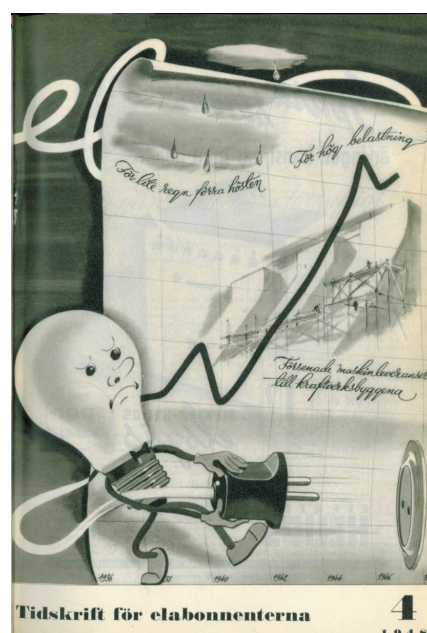


Figure 8.
A cartoon character nicknamed *Kalle Watt* encourages consumers to reduce their electricity consumption in 1948.

Sweden would go on to experience more drought years and after a year of drought in 1955-56, the hard situation was aggravated by the Suez crisis in 1956, which made it difficult for district heating plants to acquire fuel. Plentiful snow and rain luckily eased the worry about new shortages.

In 1959 the magazines were 86% full, the highest level in many years and enough to handle a dry year. However, the following months were exceptionally dry and thermal power plants had to cover 30% of the consumption, setting a new record.

However, the following months were exceptionally dry and thermal power plants now had to cover 30% of consumption, setting a new record. Thanks to the CHP plants, the situation is managed.

Ten years later, Sweden experiences two severe drought years in a row. Statistically two years of drought in a row was thought to happen with a thirty-year interval. For the first time since 1947, rationing is introduced again in 1970 to manage the situation. According to Lennart Lundberg, then vice president of Vattenfall, the drought years served as a real lesson and made the whole industry re-evaluate previous knowledge.

In the 1970s, the two oil crises served as a reminder of the importance of security of supply. By the end of the 1970s, Sweden had an increasingly diversified portfolio of electricity generation, aided by the expansion of district heating.

The historical situation is not entirely unlike today, with electricity demand forecast to rapidly increase, new and changing consumption patterns, and the increasing adoption of sector coupling between electricity, transportation, heating, and industry. Today's electricity system also faces several challenges with possible shortages or situations with scarcity both in terms of electricity generation and in terms of transmission capacity and access to grid connections. Access to grid connections for large industrial projects is far from guaranteed. There is also increasing concern over the cost and access to materials with the growing adoption of new clean technologies, with rising costs for batteries and electrolyzers as demand outstrips supply [9]–[11].

Nuclear heat holds extraordinary and untapped potential to provide district heating, hydrogen production, district heating and carbon capture. Nuclear energy can help diversify energy supply, especially within heat, and aid in de-risking the energy transition. Additionally, nuclear power plants can provide many important ancillary services to help provide grid stability, reliability, and resilience to increase transmission capacity and enable the adoption of further renewable electricity generation.

1 Introduction

Nuclear reactors can be used in many applications to decarbonize the energy sector, not just for large scale low-carbon electricity production. Several international projects are developing and investigating the potential benefits of integrating nuclear energy in the transport, industry-, commercial and domestic sectors. This report aims to provide a general overview of some ongoing initiatives, activities and general development as well as a deeper look at applications in hydrogen production, steel production and direct air capture of carbon dioxide as well as possible uses for existing nuclear power plants.

Nuclear energy holds vast potential beyond electricity production, with possible applications ranging from district heating to novel, high temperature industrial processes and non-stationary uses such as marine propulsion or space applications as well as production of isotopes for medical, research and industrial use. This report focuses on heat applications and possible uses for existing nuclear power plants, including the provision of ancillary services as an important pillar for grid stability.

1.1.1 Initiatives and activities

Several international organisations have dedicated considerable effort to investigate and develop nuclear heat applications, both practically and theoretically. Many results and tools are publicly available, with the technologies and use cases ranging from early research to fully implemented and already in use today. Large scale implementation projects are ongoing.

Some research projects aim to demonstrate new and advanced technology. One example is the Japanese HTTR, which aims to demonstrate sustained high temperature operation and integration with hydrogen production through the sulphur-iodine cycle (S-I cycle) [12].

Other research aims to find ways to integrate nuclear energy alongside variable renewable generation in complex energy systems with substantial sector coupling. This is the case at Idaho National Labs, where the Integrated Energy Systems project conducts research, development, and deployment activities to expand the role of nuclear energy beyond supporting the electricity grid [13].

Other projects focus on collecting information and experience from existing projects in order facilitate deployment of both existing and new technological solutions. Many nuclear heat applications aren't new *per se*, but have either been implemented previously, e.g. district heating, or rely on combining existing technological solutions in new applications, e.g. high-temperature steam electrolysis. Several reports and tools are publicly available without cost.

There are also international cooperation efforts such as the Nuclear Cogeneration Industrial Initiative (NC2I), established as one of three pillars of the European Sustainable Nuclear Energy Technology Platform (SNETP). Another project is the GEMINI+ project, a collaborative effort between European N2CI and American Next Generation Nuclear Plant (NGNP) Industry Alliance. EcoSMR is a Finnish project which aims to bring together nuclear suppliers and stakeholders to deploy small modular reactors for electricity and non-electricity energy production.

Some of the organisations working on projects related to nuclear beyond electricity include the IAEA, EPRI, OECD NEA, IEA, Energiforsk, VTT and INL. The following section describes some projects:

International Atomic Energy Agency - IAEA

The IAEA has a full suite of projects, tools and reports under the umbrella of *non-electric applications* [14]. This includes nuclear desalination, hydrogen production as well as industrial applications and nuclear cogeneration [15]–[17]. The IAEA reports range in depth from basic principles, describing the rationale for peaceful uses of nuclear energy, to guides, methodologies and technical reports which provide guidance and additional, detailed information. The IAEA also supplies several tools such as

- Desalination Economic Evaluation Program (DEEP),
- Desalination Thermodynamic Optimization Program (DE-TOP),
- IAEA Toolkit on Nuclear Desalination,
- Hydrogen Economic Evaluation Program (HEEP),
- Hydrogen Calculator (HydCalc), and
- IAEA Toolkit for Nuclear Hydrogen Production

are publicly and freely available.

IAEA also collects data and statistics on nuclear energy produced from non-electrical applications, available through the IAEA website [18].

Most recently, IAEA published the brochure *Nuclear Energy for a Net Zero World*, which details many ways in which nuclear is key to achieving global net zero objectives [19]. It also details several country-specific cases, showcasing how nuclear energy is deployed today in beyond energy applications in a few countries, including the Czech Republic, China and France.

- Czech Republic – Providing district heating from the Temelín nuclear power plant to the city of České Budějovice is one of the most important projects aimed at reducing carbon dioxide emissions in the Czech Republic. Since the 1980s the project has helped eliminate 22 medium sized coal fired heating plants and three large boiler facilities. A new project is underway to expand the use of nuclear heat and connect the city's largest housing estate to the district heating network.

- China – In Liaoyuan, China National Nuclear Corporation (CNNC) is preparing to build a pool type low temperature heating reactor to provide district heating. The 400 MW_{th} heat-only reactor would supply heat for 300 000 people. In another project in Rongcheng, China's State Power Investment Corporation (SPIC) aims transform Weihai on the east coast of China into a demonstration city for comprehensive utilisation of smart nuclear energy alongside wind and solar energy systems. This will optimise electricity generation and integrate heat in district heating, seawater desalination and hydrogen production.
- France – All of France's reactors can operate flexibly and on average each reactor in France performs 30 power variations per year. However, most variations in power are performed by a few units which may perform around 125 larger load modulations per year. A typical variation could consist of two large variations in one day, reducing power from 100 % to 20 % in thirty minutes while also providing frequency and voltage regulation to the system.

Electric Power Research Institute - EPRI

EPRI has undertaken research in nuclear energy within several areas for a long time. One of these areas is non-electricity markets and applications. Three recent reports explore the potential of nuclear beyond electricity

- *Rethinking Deployment Scenarios to Enable Large-Scale, Demand-Driven Non-Electricity Markets for Advanced Reactors* [20]
The report explores deployment paths required to meet the need for cost-effective, mature, and scalable technology options for decarbonising the world's energy consumption. Four conceptional scenarios illustrate how advanced nuclear heat sources can be configured and deployed to decarbonise global fuel and commodity markets.
- *Nuclear Beyond Electricity—Landscape of Opportunities: Initial Survey and Near-Term Actions* [21]
Applicable both to the existing reactors and new advanced reactors, the report provides a technical and rough economic basis for prioritising near-term development of particular technical opportunities. While utilities are focusing on flexible power operation and hydrogen production, other strategies and opportunities are worth pursuing, including thermal energy storage, water desalination, grid services and industrial electricity applications such as data centres.
- *Nuclear Beyond Electricity-Motivating and Valuing the Flexibility of Nuclear Energy Systems* [22]
The report focuses on three types of flexibility beyond electricity generation – operational flexibility, deployment flexibility and product flexibility – and finds that incorporation of flexibility aspects increases the competitiveness of nuclear energy. If flexibility is implemented and valued it enables nuclear energy systems to support clean energy development in many different scenarios and settings.

INL Integrated Energy Systems - IES

The IES is a program supported by the U.S. Department of Energy's Office for Nuclear Energy. The program aims to expand the role of nuclear energy beyond supporting the electricity grid through integration in complex energy systems with multiple energy inputs, multiple energy users and multiple energy storage options. IES has substantial portfolio of development projects and has produced a number of reports and simulation tools [23]. One of the simulation tools is HYBRID, a collection of process models capable of representing physical dynamics of integrated energy systems and processes. HYBRID is publicly available for free and is open source [24].

In addition to simulation laboratories such as the Dynamic Energy Transport and Integration Laboratory (DETAIL) where IES works to integrate different energy sources in complex systems, IES also participates in demonstration projects. Together with the Light Water Reactor Sustainability (LWRS) program and H2@Scale, IES is part of the nuclear-H₂ demonstration projects at the Davis-Besse, Nine Mile Point, Prairie Island and Monticello nuclear power plants. The projects aim to demonstrate low temperature electrolysis and high temperature steam electrolysis.

One of the resulting reports details the probabilistic risk assessment of heat extraction from a light water reactor (PWR and BWR) to produce hydrogen from high temperature electrolysis. The report concludes that, with the assumptions made, licensing criteria is met for a large electrolysis facility sited one km away from a generic reactor and that a shorter distance is viable [25].

INL and IES also work with the National Reactor Innovation Center (NRIC) and the Department of Energy to build and demonstrate several advanced nuclear reactors. There are at least 8 reactor projects aiming to demonstrate their projects before 2030 in the U.S., including MARVEL, the Hermes Kairos, the TerraPower MCRE, the X-Energy Xe-100, the TerraPower and GE Hitachi Sodium Reactor as well as the Aurora Oklo and NuScale VOYGR projects.

1.2 TECHNOLOGY

Several new and advanced nuclear reactor designs have either already been deployed or are planned for deployment of FOAK⁵ demonstration units before or around 2030. Advanced reactors are different from the conventional reactors and can be used in new, high-temperature applications.

Several types of small modular reactors (SMR) and advanced reactors are under development. These reactors are developed with the aim of offering improved economics, higher operational flexibility, a wider range of power plant sized and the ability to offer multiple energy services beyond electricity.

Reactors can be described as either conventional or advanced, where today's water moderated and water-cooled reactors are considered conventional. Advanced

⁵ First-Of-A-Kind

reactors are new reactor concepts which use liquid metal or gas as coolants. They can be either fast or thermal (slow) type reactors and use other types of fuel than uranium (e.g. spent fuel, depleted uranium, plutonium or thorium) and breed new fuel.

Advanced reactors are often designed to operate at high or very high temperatures, between 700 – 950 °C for high-temperature gas cooled reactors. Conventional light water reactors typically operate around 280 – 320 °C. A higher temperature allows for higher efficiency in electricity production and enables integration of nuclear heat in industrial processes that require higher temperatures.

1.2.1 Nuclear heat & temperatures

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.

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 which 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.

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, see Table 1.

Table 1.

A non-exhaustive selection of new and advanced nuclear reactors and their associated peak primary coolant temperature, grouped by reactor type. Reactors are either already in operation or have a planned deployment before or around 2030.

Reactor type	Company	Reactor	Temperature
BWR	GE Hitachi	BWRX-300	287 °C
PWR	Holtec	SMR-160	321 °C
PWR	NuScale	NPM	321 °C
PWR	Rosatom	RITM-200 & 400	~300 °C
PWR	CNNC	ACP100	323 °C
Liquid metal (sodium)	ARC-100 Canada	ARC-100	510 °C
Liquid metal (sodium)	Oklo	Aurora	~500 °C

Reactor type	Company	Reactor	Temperature
Liquid metal (sodium)	TerraPower & GE Hitachi	Natrium	~500 °C
Molten salt reactor	Moltex	SSR-W	600 °C
Molten salt reactor	Terrestrial Energy	IMSR	600-700 °C
Molten salt reactor	Seaborg	cMSR	700 °C
High-temperature gas-cooled reactor (HTGR)	Ultra Safe Nuclear Corp.	MMR	600-900 °C
High-temperature gas-cooled reactor (HTGR)	X-Energy	Xe-100	750 °C
High-temperature gas-cooled reactor (HTGR)	CNNC	HTR-PM	750 °C

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 Figure 9.

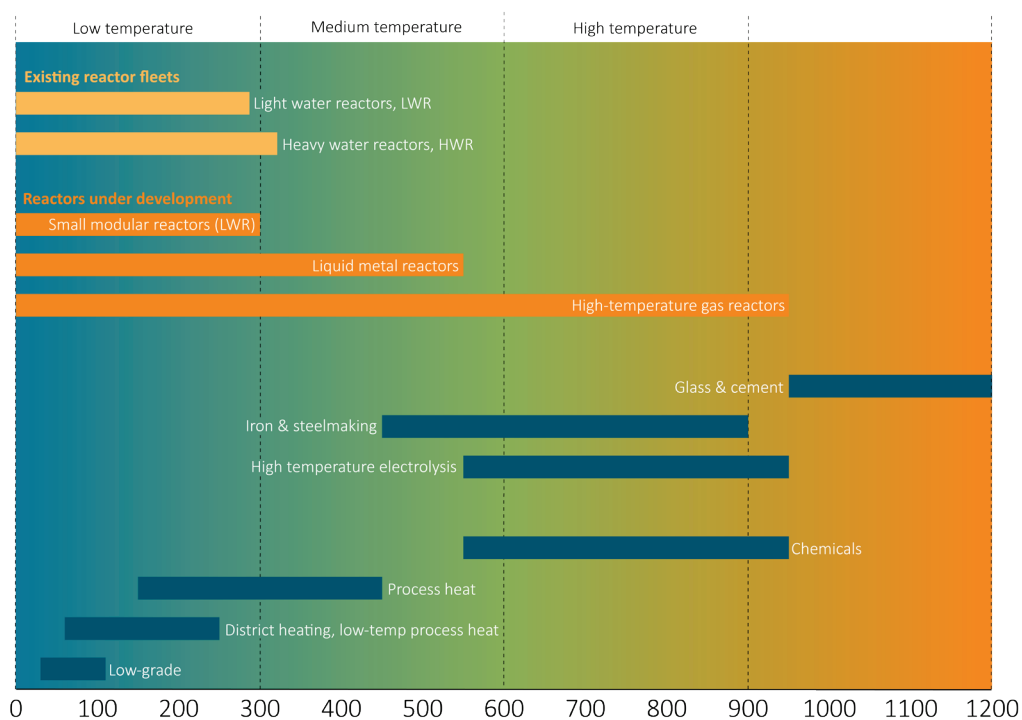


Figure 9.
Typical temperatures of different nuclear reactor categories and some applications.

1.2.2 Steam extraction

Extracting a steam flow to utilise heat from an existing reactor or a new reactor without considerable modifications is possible but must be done with caution as it may disrupt the turbine operation and result in various kinds of problems. It is more efficient to extract steam through multiple stages of heat exchange, as well as at the lowest possible pressures. This may however be difficult in practice. Depending on how the steam is extracted and on the extent of possible modifications, between 10 – 60% of the total thermal power can be extracted.

There are several ways in which steam can be extracted from a new or existing reactor. The most apparent way is to divert fresh steam from the turbine bypass system, which bypasses the turbine entirely. Extracting smaller amounts of heat, around 200 MW_{th} (or about 7 – 8% of the thermal power of Nordic BWRs), is not expected to cause any problems. The turbine may be simply operated slightly throttled to compensate, meaning the flow is reduced but pressure ratios stay the same.

Trouble occurs when pressure ratios in the last stages are reduced, which changes the velocity components of the working fluid and may cause numerous problems. Operating the turbine at 60% of nominal power should not lead to any increase in wear or maintenance. Operating around 30 % of nominal power or less can increase wear and maintenance and operation below 15 % should be avoided as it may cause problematic steam flow conditions [26].

A second option is to extract steam after the high-pressure turbine and moisture separator reheater, before the intercept valve and low-pressure turbines. This would be a relatively easy place to extract steam and by throttling the intercept valve the pressure ratios of the high-pressure turbine can be kept the same, essentially meaning the high-pressure turbine doesn't "see" the steam extraction.

A third way to extract steam, which is more difficult as it requires more detailed modelling of the turbine as well as more modifications, is to extract steam from the preheaters (high-pressure feed heater, HPFV). Extraction must then be done from the first or highest temperature preheater, otherwise other preheaters will compensate and use more energy⁶. Single point extraction means losing some efficiency compared to multi-point extraction but extraction from the preheaters does not interfere with the turbine operation. The first three options are illustrated in Figure 10.

A fourth option is the use of a back-pressure turbine, which requires the most design consideration and modification.

To summarise, steam extraction of between 10 – 60% of thermal power is possible with modifications ranging from minor to major, including new turbine configurations. Steam extraction carries a trade-off of lower electricity output, with

⁶ As condensate enters the following preheaters colder the following preheaters will heat it to the same outlet pressure.

an approximate ratio⁷ of 8:1 and 4:1 between thermal power (MWh_{th}) extracted and decreased electricity output (MWh_{e}). The exact ratio depends mainly on the number of points of extraction (single point versus multi-stage extraction) and the temperature.

Section 2.5.2 *Enabling steam-extraction for DAC from an existing reactor system* below contains a longer section on possible steam extraction points with examples.

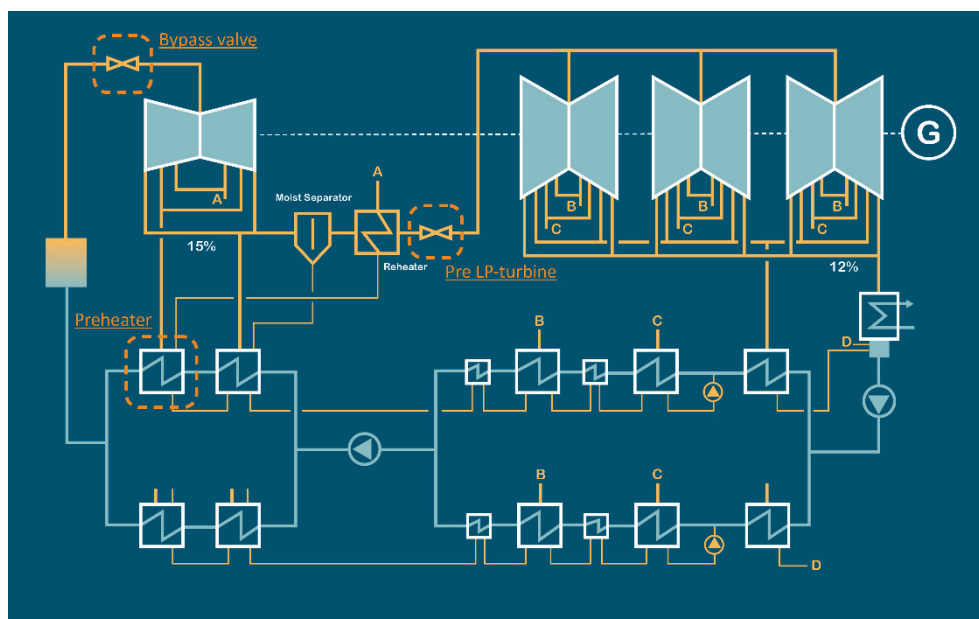


Figure 10.

Schematic of typical 2nd generation BWR cycle with possible stream extraction points marked. In addition to the extraction through bypass valve, preheater or pre-LP-turbine it is also possible to extract steam from LP turbine extraction points or through a back-pressure turbine configuration.

⁷ Meaning every 8 MWh_{th} to 4 MWh_{th} extracted comes at a "cost" of 1 MWh_{e} in decreased electricity generation.



1.3 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. Projected costs of nuclear heat in district heating are very competitive with other alternatives.

In 2020, nuclear power plants in 11 countries also provided heat for district heating, industrial processes, or desalination [18]. Several projects are underway in China, Russia and the Czech Republic to expand nuclear heat use for district heating.

The district heating consumption trend has been largely stable in Sweden since the early 2000s, see Figure 11. In Finland the district heating consumption has increased some in the same period, but demand is now fairly stable.

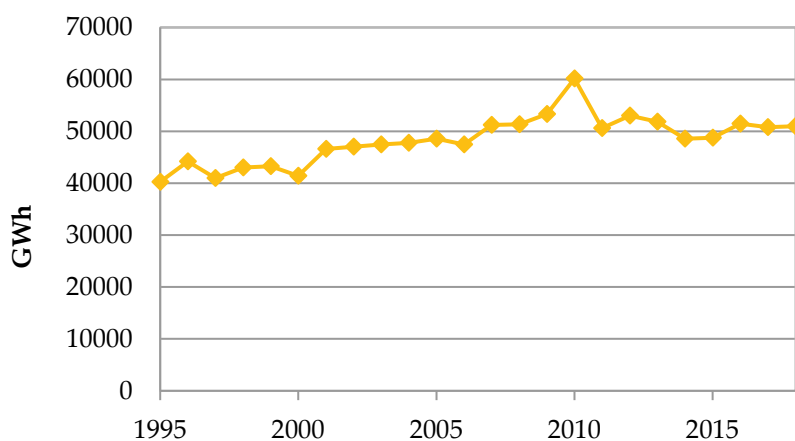


Figure 11.
District heating supply, Sweden, 1996-2018. Data from Energiföretagen [27].

Figure 12 and Figure 13 show fuel supplied for Swedish and Finnish district heating. A significant share of fuels are either fossil fuels (in Finland) or waste (in Sweden). Waste typically consists of about 35% fossil material. Carbon taxes on emissions and increasingly strict requirements on exhaust scrubbers to limit other emissions could constitute problems for continues firing of fossil fuels, waste and possibly biomass material. Increasing competition for biomass material is another factor.

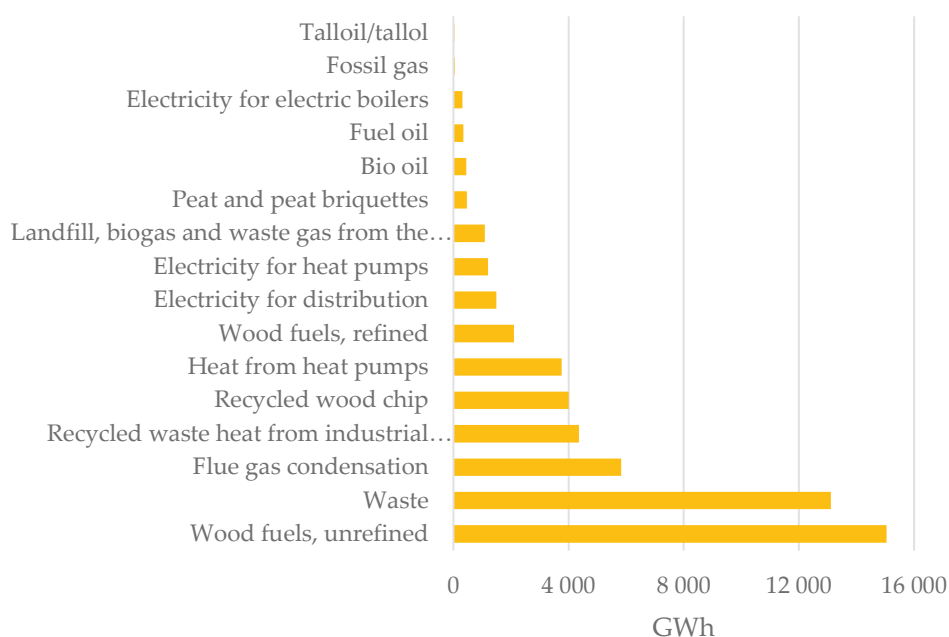


Figure 12.

Fuels supplied for district heating, Sweden, 2020. Data from Energiföretagen [27]. Some minor fuels (less than 40 GWh) removed for readability.

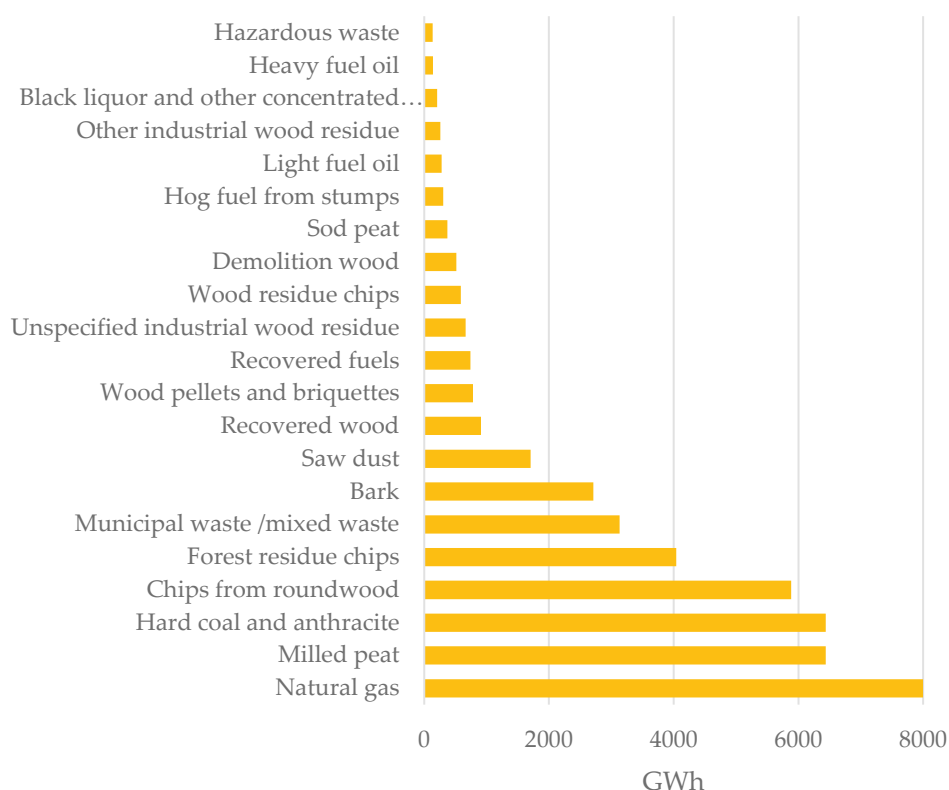


Figure 13.

Fuels supplied for district heating, Finland, 2020. Data from Energiategollisuus [28]. Some minor fuels (less than 100 GWh) removed for readability.

While the supply trend is stable, district heating displays high annual variability. Figure 15, Figure 14 and Figure 16 show data from Helen Oy, which supplies district heating to approximately 90% of Helsinki, for 2015 to 2020. There is high weekly and monthly variability, but seasonal and annual variability is especially significant.

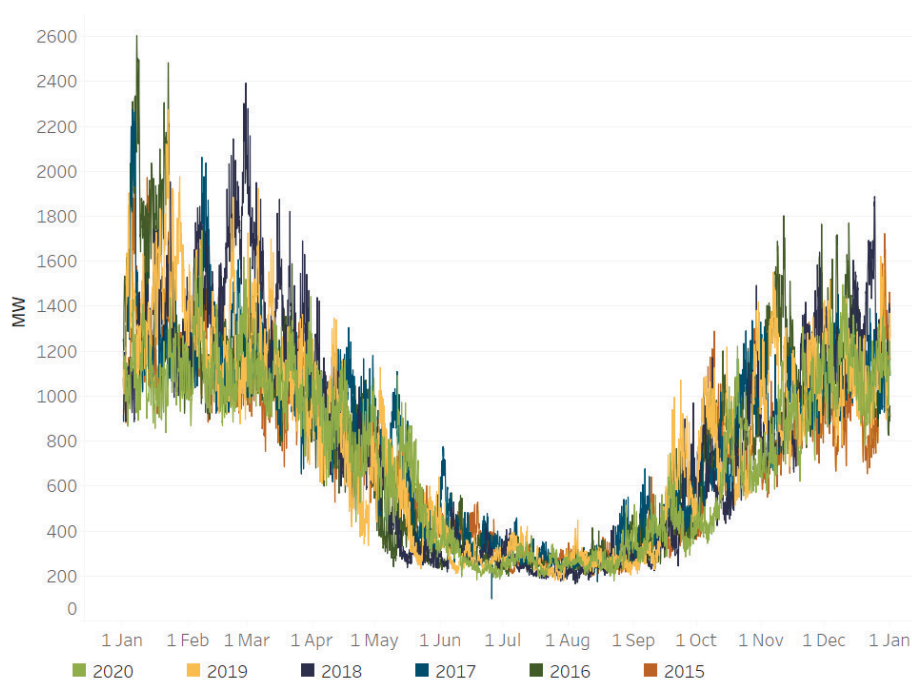


Figure 14.
District heating production 2015 to 2020, Helen Oy, Helsinki [29].

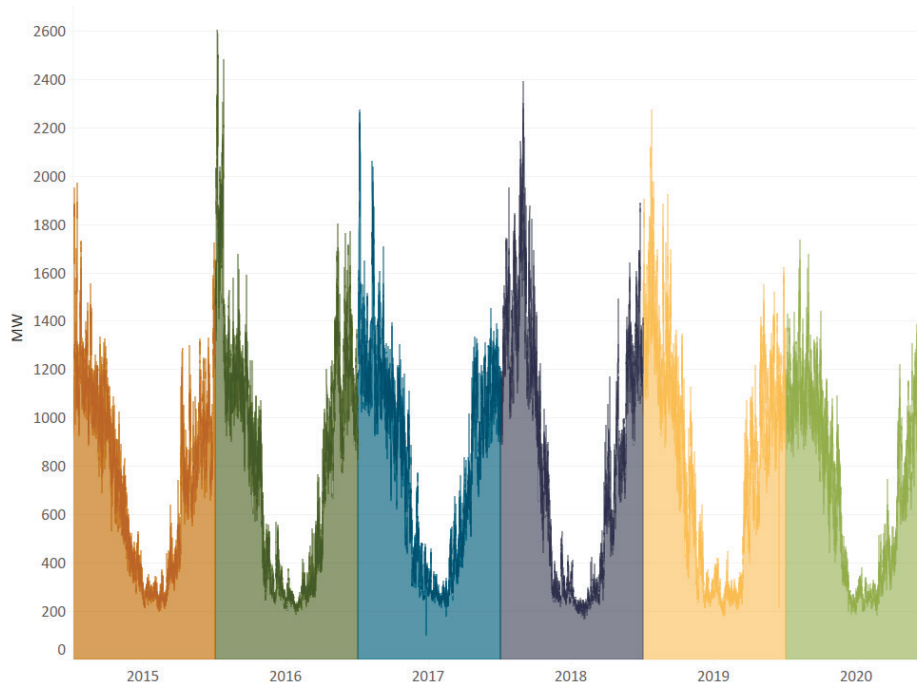


Figure 15.
District heating production 2015 to 2020, Helen Oy, Helsinki [29].

Another way to view this variability is through a load duration curve, see Figure 16. Comparing baseload and peak load shows that winter peaks can be around ten times higher than summer demand, with minimum and maximum demand for very limited durations.

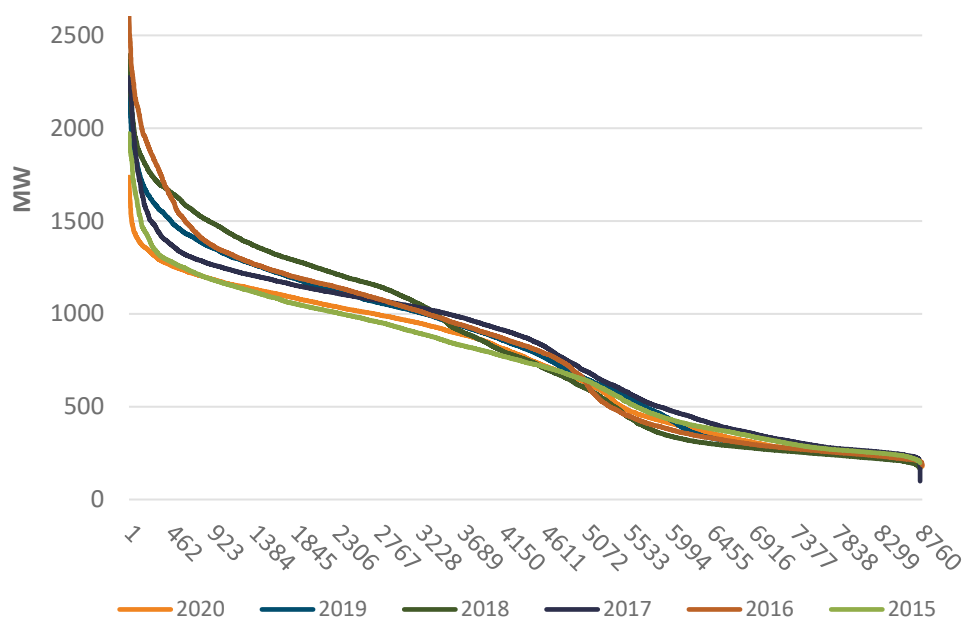


Figure 16.

Baseload vs. peak load – duration curve of district heat production from Helen Oy, Helsinki [29].

This seasonal variability is a significant barrier for a reactor, which is capital intensive and benefits from maximising the utilisation factor.

However, seasonal variability barriers could be overcome with storage. With a storage equal to approximately 25% of total demand it is possible to remove all or almost all seasonal variation. This enables even heating supply all year around while still meeting peak demand and could also assist in meeting minimum demand during maintenance outages.

The potential size of district heating markets for nuclear reactors is dependent on the number of grids or cities with sufficiently high demand for a sufficiently high number of hours. Only a few district heating grids demand 400 MWth for half of the year or more.

1.3.1 District heating transmission

It is often said that nuclear energy is not well suited for district heating as large nuclear power plants are often 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.

1.3.2 District heating cost and deployment

In terms of cost, new and advanced reactors working as combined heat and power plants providing district heating could potentially be very competitive. Estimates⁸ indicate that conventional small modular reactors could provide heat for between 20 – 25 EUR/MWh. This is significantly cheaper than alternative district heating alternatives. Heat only reactors, as developed by VTT and LUT, are also competitive with costs estimates around 30 EUR/MWh. Estimates for heat-only reactors are however very early estimates and perhaps better presented as design-to-cost targets.

With the possible near-term commercialisation of SMRs, nuclear energy offers an interesting alternative for combined heat and power plants. Countries in eastern Europe with largely fossil based district heating systems are well positioned to phase out fossil fuels in heating and dramatically decrease emissions.

However, many countries and cities in Europe lack district heating infrastructure. Switching households from gas heating, gas stoves and internal combustion engine cars to electric could potentially add multiple kW of peak demand per household. The challenge of sufficient energy production, transmission, and delivery to meet this demand poses a looming infrastructure problem.

On an aggregated basis across all of Europe, seasonal variability poses a giant decarbonisation challenge as it is almost entirely met through fossil gas supply. Gas consumption is 2.5 times higher in winter than in summer. By contrast, the seasonal variability in electricity and oil is 30% and 20% respectively. Winter variability and gas presents a unique challenge which will need to be solved.

Developing district heating networks and thermal storages could perhaps go some way towards solving it. The arguments for district heating seem as strong today as it was in the 1960s – good for the environment, flexible, convenient and with high security of supply while diversifying energy supply.

⁸ Not publicly available. A very rough estimate of the cost of heat can be achieved by simply dividing cost estimates for power production by 3, which is approximately the thermal efficiency of a nuclear power plant. More sophisticated extraction of heat could yield more heat and smaller losses in electricity production, so dividing by 5 or 8 would give the cost of heat.



1.4 DESALINATION

Securing a reliable supply of energy and freshwater is critical for the sustainable development of any society. Despite this, freshwater scarcity is a serious problem which affects approximately 4 billion people globally. Producing and delivering water requires large amounts of energy. Water in turn is used extensively in energy production, an inseparable link referred to as the energy-water nexus. Nuclear energy can be used as a low-carbon option to provide large amounts of fresh water.

Water scarcity is not a general problem in Scandinavia, although drought can result in restrictions on water use in some Scandinavian regions. Globally, 4 billion people experienced severe water scarcity for at least one month of the year in 2016 and 2.1 billion people lacked access to safe drinking water in 2015 [30], [31]. Demand for freshwater is driven by population growth, improved standards of living, changing consumption patterns, increased water use in the industrial and agricultural sectors and by climate change [32], [33]. As the availability and quality of remaining fresh water sources diminishes, the problem is exacerbated. This is the result of short-sighted policies and projects, in particular dams and irrigation for supply-side management, which initially mobilise more water but ultimately decrease freshwater availability. Fewer rivers reach the ocean and groundwater levels are dropping across many important aquifers while industrial and agricultural sectors pollute the remaining freshwater sources [34], [35].

Solving water scarcity is a difficult problem with many stakeholders. In addition to holistic water policies, seawater desalination could aid in solving the water scarcity crisis.

Seawater has two unique features as a source of water: it is drought proof, and it is practically limitless. However, desalination of seawater is very energy intensive. Today, that energy is supplied primarily from fossil fuels but with fossil fuel prices

volatility, uncertain availability, carbon taxes, and increasing environmental and geopolitical concerns, developers of desalination plants are looking to other energy sources such as renewable energy or nuclear energy. Desalination could play a vital role in securing safe, affordable, and reliable fresh water for all. Nuclear energy could play an important role.

Several countries are already looking to seawater desalination power by nuclear heat to provide freshwater.

1.4.1 Desalination processes

There are three main desalination processes used in large scale applications today: evaporative desalination through Multiple Effect Distillation (MED) or Multi-Stage Flash (MSF) distillation and membrane distillation through Reverse Osmosis (RO). Each process has advantages and disadvantages, but distillation processes are inherently energy intensive as they must all break the hydrogen bond and provide a phase change of the feedwater. This energy, called latent heat of vaporisation, is significant and contributes to a higher cost as energy is a considerable fraction of the total cost.

Table 2.
Overview of different types of desalination. Main desalination processes are marked in bold.

Type	Desalination process	Type of energy used
Phase change	Multiple-Effect Distillation (MED)	Thermal
	Multi-Stage Flash distillation (MSF)	Thermal
	Geothermal desalination	Thermal
	Solar humidification-dehumidification (HDH)	Thermal
	Multiple Effect Humidification (MEH)	Thermal
	Seawater Greenhouse	Thermal
	Vapour Compression (VC)	Mechanical/Thermal
	Freezing desalination	Electrical
No phase change	Electrodialysis Reversal (EDR)	Electrical
	Forward Osmosis (FO)	Electrical
	Ion exchange	Electrical
	Reverse Osmosis (RO)	Electrical
	Nanofiltration (NF)	Electrical
	Membrane Distillation (MD)	Thermal

Before 2000, the main desalination method was MSF, but it has since been overtaken by RO. Today, most of the desalination is performed through RO but in two or more methods are often used together in a hybrid process to provide water with the right purity and properties.

The theoretical minimum energy required for desalination is the thermodynamic minimum energy necessary to separate salt and water.

Mixing salt and water releases energy in the process. This means that the mixture of salt and water has a lower free energy than the sum of the individual components. The minimum energy required to reverse, or unmix, the saltwater is the same as the energy released in the first place.

The thermodynamic minimum energy of separation can be determined in kWh/m³ of fresh water, depending on the recovery rate and the salinity. Higher recovery and higher salinity require more energy. The thermodynamic minimum energy for water of normal seawater salinity is approximately 1 kWh/m³. Because of inefficiencies and losses, the actual Specific Energy Consumption (SEC) to produce one m³ of water is always higher than 1 kWh/m³.

Another measure, for distillation type desalination is Gain Output Ratio (GOR). This is a measure of kilograms of distilled water produced per kilogram of steam consumed. GOR does however not take consider the quality, pressure or temperature of the steam.

1.4.2 Multiple-stage flash distillation (MSF)

In MSF, the feedwater is first pre-treated. Chemical additives prevent the formation of scale on heat transfer tubes and de-aeration removes oxygen and carbon dioxide in the water to improve heat transfer.

The water is first preheated through heat recovery from the outgoing product water and brine. The feedwater is then distilled by flashing a portion of the feedwater into steam in multiple stages. A modern MSF facility may have up to 30 stages.

The resulting water is highly pure and required remineralisation before it is fit for human consumption.

MSF typically has a better GOR than MED.

1.4.3 Multiple-effect distillation (MED)

After basic screening and filtration as pre-treatment, feedwater is heated by steam in the first effect (stage), which causes some of the water to evaporate. Feedwater can either be sprayed onto heat transfer tubes carrying steams, or the opposite way around. After the first effect, vapour and brine are sent to the next one, at a lower pressure. The vapour condenses by heating and evaporating more incoming feedwater. This process is repeated for up to around 24 effects.

MED also produces highly pure water which must be remineralised.

It is slightly more complex than MSF and has a lower GOR but due to the lower brine temperature MED typically has a lower energy consumption and is less prone to scaling. This results in MED requiring less pre-treatment, if any at all, and it can also tolerate large variations in feedwater quality.

1.4.4 Reverse Osmosis (RO)

The movement of a solvent across a semi-permeable membrane to a region with a solution of higher solute concentration is called osmosis. Osmotic pressure⁹ is a measure of the tendency of a solution to take in more solvent. Osmotic equilibrium can be reached if a pressure is applied to the solution so that the flow is stopped. If the pressure on the solution is increased beyond the osmotic equilibrium pressure, reverse osmosis occurs, and pure solvent is forced through the semi-permeable membrane. This leaves solute behind in a more concentrated solution.

RO requires heavy pre-treatment of the feedwater to avoid fouling and scaling of the fine membranes. This includes screening, coagulants, air flotation and filtration through hard coal, sand, and ultra-fine filters. The feedwater is then pumped through RO membranes at somewhere between 50 – 80 bar.

After passing through the membranes, the now desalinated water still carries a significant amount of energy. This is partially recovered through Energy Recovery Devices (ERDs) which can provide around 25% in energy savings. The ERD is normally mechanically coupled to a booster pump which increases the pressure of the feedwater before the main feedwater pump. Other ERDs use different types of pressure exchanges which transfer energy hydraulically from the brine concentrate to the feedwater. This causes some mixing of brine concentrate and feedwater, which increases the salinity of the feedwater, but modern ERD devices have excellent efficiency of over 95%.

RO membranes are arranged in modules and in most plants the feedwater goes through two separate RO passes. Some post-treatment is required, including disinfection.

The RO process is much more energy efficient and uses less energy than other processes and can be built with much higher capacity per unit at a lower capital cost. It also has significant potential for improvements with future advances in membrane technology.

However, it also has several disadvantages. The quality of the product water is not as high as MSF or MED and there is poor tolerance for variations in feedwater quality. The energy consumption is approximately proportional to the feedwater salinity.

1.4.5 Energy use in desalination

Desalination is an energy intensive process. The required energy, or Specific Energy Consumption (SEC), is measured in kWh/m³. The information in Table 3 is from 2010. Newer data from large scale thermal plants confirms that RO plants use significantly less energy, with a reported SEC between 5 – 16 kWh/m³ for large scale thermal desalination plants and between 2 – 4 kWh/m³ for large scale RO plants [36].

⁹ Osmotic pressure is measured in psi and the pressure of a solution of water and sodium chloride can as a rule of thumb be estimated as 1% of the salt concentration, or 1 psi for every 100 mg/L of concentration. Multiplied by 7 000 provides a rough estimate in pascal, Pa.

Table 3.

Overview of specific energy consumption of desalination processes. Data from 2010, [37]

		MSF	MED	RO
Typical unit size	[m ³ /d]	50 000 – 70 000	5 000 – 15 000	24 000
Electrical SEC	[kW h/m ³]	4 – 6	1.5 – 2.5	3 – 5.5
Thermal SEC	[kJ/kg]	190 – 390	230 – 390	–
Gain Output Ratio		12.2 – 6	10 – 6	–
Electrical equivalent ¹ SEC	[kWh/m ³]	9.5 – 19.5	5 – 8.5	–
Total equivalent SEC	[kWh/m ³]	13.5 – 25.5	6.5 – 11	3 – 5.5

¹The electrical energy which is not generated as a result.

1.4.6 Nuclear desalination

According to the IAEA, nuclear desalination has historically contributed only around 0.1% of total desalination capacity worldwide [38]. While there used to be as many as 20 reactors providing nuclear desalination only four reactors produced desalinated water in 2020 [18]. This number excludes marine reactors that provide nuclear desalination.

The experience of running nuclear desalination facilities stems primarily from Japan, with 10 reactors providing around 150 reactor-years of experience. The BN-350, a Russian sodium-cooled fast reactor on the Caspian Sea peninsula in Kazakhstan provided 135 MW_e and 120 000 m³/d of drinking water for 27 years before it was closed in 1999.

Several countries are building or planning to build nuclear desalination facilities. In China, the Shandong Nuclear Power Company plans to use steam extracted from the Haiyang nuclear power plant to provide district heating and fresh water. South Africa and Jordan are countries that are both considering building nuclear power desalination facilities.

By providing both steam and electricity for a hybrid desalination facility, nuclear energy could make an important contribution to securing access to affordable fresh water, without carbon emissions.

An alternative possibility for nuclear desalination, which has never been demonstrated, is to power RO pumps directly with steam. Steam driven pumps is nothing new and are fairly common in nuclear power plants. With a steam driven pump, nuclear desalination could reduce energy consumption by around 10% by reducing the losses in the conversion steps from steam to powering the pump.

Whether with a novel solution or through demonstrated large scale desalination methods such as RO, MSF, and MED, nuclear energy would dramatically decrease the emissions associated with desalination.

As energy consumption is roughly proportional to feedwater salinity, the relatively low salinity of the seawater around the Nordic countries and especially the brackish water of the Baltic Sea provides another advantage for desalination in a Nordic context.

2 Direct air capture, DAC

2.1 NEGATIVE EMISSION TECHNOLOGIES

2.1.1 The need for negative emissions

There is consensus across global climate modelling efforts that Negative (CO₂) Emissions Technologies (NETs) will be needed to keep the global average temperature increase below 2°C, in line with the Paris Agreement, alongside drastic reductions and eventual elimination of greenhouse gas emissions.

Almost all pathways in the IPCC Special Report on Global Warming of 1.5 °C relies to some extent on removal of CO₂ and requires negative emissions after 2050 to reach the warming target [39]. The earlier IPCC Fifth Assessment Report also stressed the importance of NETs in the 2°C warming scenarios [40]. In the IPCC's scenario database 344 of the 400 scenarios with a 50% or better chance of achieving no more than 2°C warming assume the successful and large-scale deployment of some form of NET. The scale of such negative emissions was estimated by Smith et al. (2016) to require extraction of up to 12 Gt of CO₂ per year after 2050 to stabilise atmospheric concentrations at levels consistent with a 2 °C limitation (430–480 parts per million (ppm) CO₂-eq) [41]. Figure 17 shows a stylized view of a typical integrated assessment model (IAM) pathway that stabilizes temperatures at well below 2 °C warming by the end of the century. The yellow part is the assumed contribution to the carbon balance by NETs.

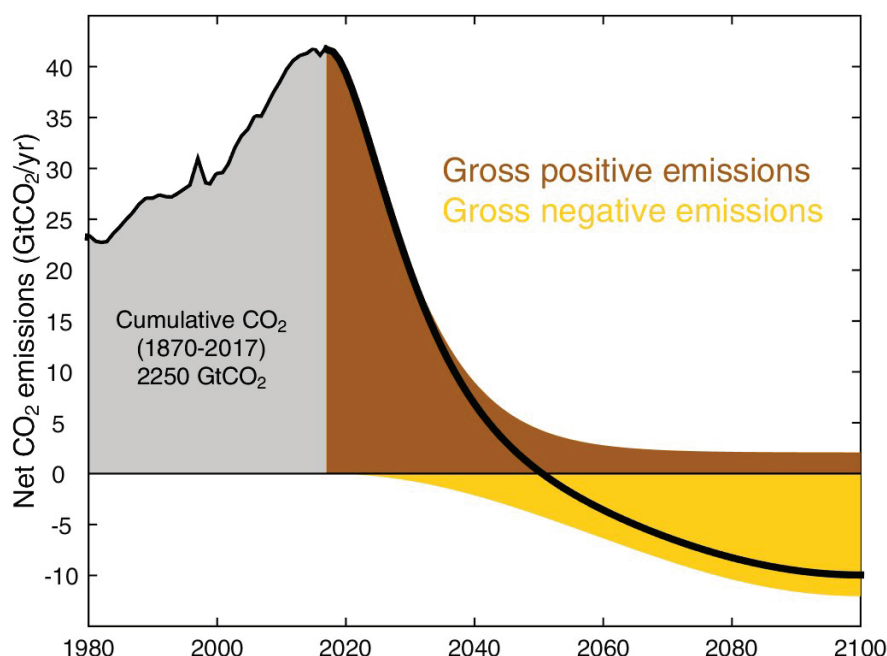


Figure 17. Stylized figure of global carbon budgets for below 2°C warming [42]

2.1.2 Negative Emissions Technology (NET) Options

At least eight general options to achieve negative emissions exist and are being explored today:

1. CO₂ extraction from sea water
2. Direct Air Capture (DAC) of CO₂ from the atmosphere
3. Carbon Capture Storage coupled with sustainably sourced biomass combustion (Bio-CCS)
4. Biochar production from sustainably sourced biomass
5. Afforestation and reforestation
6. Enhanced weathering¹⁰
7. Soil carbon sequestration¹¹
8. Iron fertilization of the ocean¹²

Out of these, options 1 and 2 are potentially compatible to be effectively coupled to and powered by a nuclear energy source. Because the ocean and the atmosphere are in a state of equilibrium, if CO₂ is taken out of the water, the ocean will then pull more from the air. The oceans have an average CO₂-concentration about 150 times the level in air. However, the technology for CO₂ extraction from sea water is at an early stage of development and has so far proven challenging to commercialize. This technology does not exist outside of lab-experiments today and is therefore not the focus of the analysis in this report.

Direct Air Capture of CO₂ (DAC) involves a system where air flows over a contactor that selectively removes the CO₂, which is then released as a concentrated CO₂ stream for disposal or use. The sorbent is regenerated, and the CO₂-depleted air is returned to the atmosphere. In principle, this type of technology is similar to “conventional” carbon capture systems that have been used commercially for many decades, with the main difference being the concentration of CO₂ in the incoming gas stream (which is far lower for DAC) and the fractional CO₂ capture requirement (which is far more relaxed for DAC). Several DAC technologies dedicated to the extraction of atmospheric CO₂ have been prototyped during the past 10 years, and dozens of smaller-scale systems by a number of vendors are currently in operation. Out of available NETs, DAC is unique in that it is nearing commercial maturity as a technology, is geographically independent (can be implemented essentially anywhere) and is not limited by for example biomass feedstock availability. DAC is also ideally suited to be powered by a nuclear energy source and is therefore the technology category choice for this chapter of the “Nuclear Beyond Electricity” report.

¹⁰ Enhanced weathering essentially means grinding selected rock materials that have the potential to sequester relevant amounts of atmospheric CO₂ into rock powder with a suitable grain size distribution to facilitate a maximum reactive surface area.

¹¹ Soil carbon sequestration (SCS) occurs when land management change increases the soil organic carbon content, resulting in a net removal of CO₂ from the atmosphere.

¹² Which boosts the growth of phytoplankton, tiny plants in the ocean.

2.2 PRINCIPLES AND CHARACTERISTICS OF DIRECT AIR CAPTURE (DAC)

2.2.1 Introduction

The ambition of a Direct Air Capture (DAC) system is to separate the CO₂ in air from its other major constituents, primarily nitrogen, oxygen, and argon. The composition of air at the Mauna Loa Observatory, Hawaii on November 24th, 2021, is shown in Figure 18, and is representative for air in general.

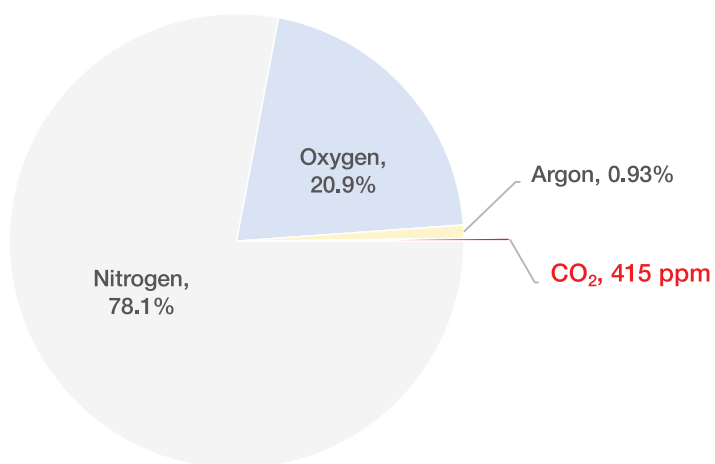


Figure 18. Composition of air by molecules (not mass), 2021/11/24.

To maximize potential use cases of the captured CO₂, or alternatively to minimize volume requirements for storage & sequestration, most DAC systems as well as conventional carbon capture systems are configured to produce a nearly pure stream of CO₂ (>99.9 vol.%). Figure 19 shows the concentration of CO₂ for DAC, conventional carbon capture at fossil-fuelled power plants (from nat. gas or coal) and the target concentration required for use in for example the beverage industry.

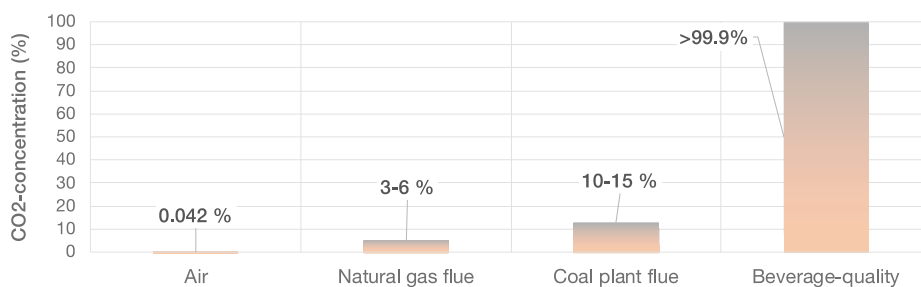


Figure 19. Typical CO₂ concentrations in different locations and use cases.

2.2.2 Size and area requirements of a DAC system

While all DAC systems are different, some general characteristics regarding their size, energy consumption and operation can be derived from first principles. One cubic meter of air contains about 0.75 grams of CO₂ today. A system designed to capture T tonnes of CO₂/year with a DAC contactor that captures X % of the CO₂ in the air that passes through it, will need to process F m³ of air per year, with F given as:

$$F \left[\frac{\text{m}^3 \text{ air}}{\text{year}} \right] = \frac{T \left[\frac{\text{tCO}_2}{\text{year}} \right]}{X [\text{Frac CO}_2 \text{ captured}] \times \frac{0.75}{1000} \left[\frac{\text{tCO}_2}{\text{m}^3 \text{ air}} \right]}$$

If $X = 50$ % (half of the CO₂ in the passing air is captured) and T is 1 ton/year, the value of F becomes:

$$F \left[\frac{\text{m}^3 \text{ air}}{\text{year}} \right] = \frac{1 \left[\frac{\text{tCO}_2}{\text{year}} \right]}{50\% [\text{Frac CO}_2 \text{ captured}] \times \frac{0.75}{10^6} \left[\frac{\text{tCO}_2}{\text{m}^3 \text{ air}} \right]} =$$

$$2666667 \left[\frac{\text{m}^3 \text{ air}}{\text{year}} / \frac{\text{tCO}_2}{\text{year}} \right] = 304 \left[\frac{\text{m}^3 \text{ air}}{\text{hour}} / \frac{\text{tCO}_2}{\text{year}} \right] = 0.085 \left[\frac{\text{m}^3 \text{ air}}{\text{second}} / \frac{\text{tCO}_2}{\text{year}} \right]$$

Therefore, 85 litres of air must flow through a system capturing 50 % of the CO₂ (42 litres at 100 %) in the stream to capture 1 tonne of CO₂ per year, regardless of the type of technology employed. The intake area (A) of the facility depends on the average air flow velocity through the system (V), as well as how much of the cycle time it spends capturing CO₂ (t_x) and the availability of the unit (C_f).

$$A [\text{m}^2] = \frac{F}{V} \times \frac{1}{C_f \times t_x}$$

With an average air flow velocity of 1 m/s and a cycle that spends 50 % of its time in capture mode (the other half for regeneration of the sorbent) and an availability of 80 %, the above expression gives:

$$A [\text{m}^2] = \frac{0.085 \left[\frac{\text{m}^3 \text{ air}}{\text{second}} / \frac{\text{tCO}_2}{\text{year}} \right]}{1 \left[\frac{\text{m}}{\text{s}} \right]} \times \frac{1}{0.8 \times 0.5} = 0.106 \left[\frac{\text{m}^2 \text{ intake}}{\text{m/s flow}} / \frac{\text{tCO}_2}{\text{year}} \right]$$

The required in-take area for letting air into the capture system is roughly 0.1 m² for every tonne of CO₂ to be captured per year, scaled linearly by the air flow velocity achieved. At 2 m/s, the requirement is down to about 0.05 m². The current per capita emissions rate in Sweden is approximately 5 tonnes of CO₂ per year ¹³. To net this out entirely, each person would need to continuously run a DAC system with an intake the size of a square with a side of 35-70 cm (for 1-4 m/s flow).

¹³ Based on official territorial emissions and population. Finland emits just under 9 tons of CO₂ per year.

How large would then a DAC system, scaled to capture 1 million tons of CO₂ per year, be? About 40 such systems would be needed to equal Swedish emissions.

At an average velocity of 4 m/s, the required intake area of the 1 Mt/y system is approximately 100,000 m². Each DAC contactor depletes the air in CO₂, which means they cannot be placed directly behind one another and operate effectively. 250 meters of downwind separation between contactors ensures sufficient air mixing. A myriad of different layouts for such a system is possible. If we assume a height of the contactor facility of 25 meters, a 1-million-tonne CO₂/year facility would fit inside a square footprint of 1000 x 1000 meters, the vast majority of which is used for spacing between contactors. The layout could be 4 rows of contactor intakes 25 meters high, 1000 meters wide and separated by 250 meters. If instead built in a single row as a wall, it would be 4 km long and take up just 0.05 km² of area, since the length of contactors behind the intakes can be limited to just a few meters even with a high fractional capture requirement.

2.2.3 Minimum thermodynamic separation energy in a DAC process

The minimum theoretical work required to separate CO₂ from a gas mixture can be calculated based on the combined first and second laws of thermodynamics. For an isothermal (constant temperature) and isobaric (constant pressure) process it is equal to the negative of the difference in Gibbs free energy of the separated final states (the captured CO₂ stream and the stream of gas depleted in CO₂) and the initial incoming gas, which in this case is outside air. This type of theoretical calculations provides no real useful engineering guidance regarding the actual absolute energy consumption of a DAC process, but it does give insight into the relative effort involved in separating out CO₂ from a stream of gas under different conditions. Real DAC systems will use approximately an order of magnitude more energy than the thermodynamic minimum, since the minimum is derived for a reversible isothermal process happening infinitely slowly.

The factors influencing the separation energy are the concentration of CO₂ in the incoming gas, the temperature, the fraction of the CO₂ in the gas stream that is to be captured, and the required CO₂-purity of the captured stream. The separation work for a hot stream of gas with high capture requirement (red line, giving maximum work required) and a cold stream with low capture requirement (black line) are shown with CO₂ concentrations from 400 ppm to 99 % in Figure 20. A typical coal power plant may emit a combustion gas stream with 12 % CO₂ concentration, which is about 300 times higher than the average concentration of CO₂ in the atmosphere. As shown in Figure 20, it takes 3.4 – 3.8 times more minimum work to achieve the same separation at the same temperature, with the same fraction of CO₂ extracted and same CO₂ purity in the separated stream from air as from a coal plant flue stack.

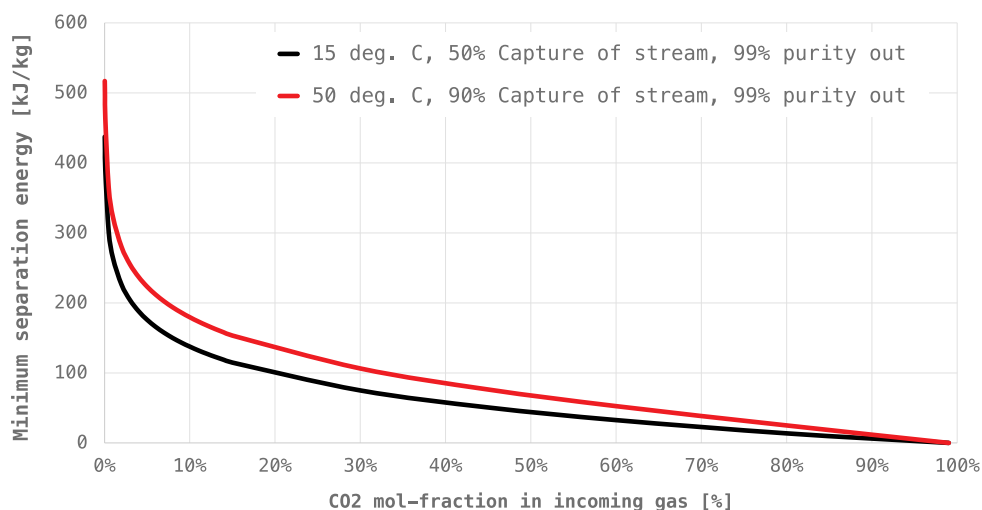


Figure 20. Minimum theoretical work required to separate out CO₂ from a stream of gas.

While there are local variations in the concentration of CO₂, it is difficult to utilize this fact to improve the economics of large-scale DAC facilities. Crowded indoor spaces such as classrooms, offices (particularly conference rooms) and dense housing units can reach 600-1200 ppm concentration but would not allow for sufficient airflow to feed anything but a tiny capture unit. Polluted city centres may reach average CO₂-concentration levels 25 % higher than the atmospheric average due to the “urban dome” effect. However, placement of larger-scale DAC systems inside crowded city centres is economically unfeasible. Placement near a point source of emissions would be difficult to motivate since, if operation of such a facility is to continue, it will always be far more cost-effective to implement conventional carbon capture integrated in the facility rather than DAC nearby. Therefore, this analysis will focus solely on DAC systems with a CO₂-concentration of 420 ppm, representing the current average atmospheric concentration. The main factors determining the minimum thermodynamic work effort required for CO₂-separation for a given incoming concentration are temperature (Figure 21), the requirement for how much of the CO₂ in the incoming stream should be captured (Figure 22) and the requirement for CO₂-purity of the captured stream (Figure 23).

From the perspective of CO₂ separation, it is more effective to place DAC facilities in colder regions, as the separation work per kg of CO₂-captured decreases significantly¹⁴. However, since the regeneration of solvents or sorbent (to remove the CO₂ and enable another cycle of capturing) typically requires heating to a certain temperature, the overall benefit to a real process is minimal. A key difference between a DAC process and a conventional flue stack carbon capture process is that the requirement for fractional capture of the CO₂ in the stream is completely relaxed in the case of DAC while typically rather strict for carbon

¹⁴ The density of air at -20 and 50 °C is 1.394 kg/m³ and 1.093 kg/m³ respectively, meaning a fan to move the air through the system would consume 27.5 % more electricity to maintain the same volumetric airflow in the colder condition. However, since the incoming air contains 27.5 % more CO₂ at the colder condition, a correspondingly lower airflow is required to maintain the same capture mass rate of CO₂.

capture (90 % or more). A system with a more relaxed requirement for fractional capture can capture a kilogram of CO₂ with a smaller thermodynamic separation energy requirement but requires a correspondingly larger mass flow of incoming gas to capture the same amount of CO₂ per unit of time. The main impact for the design of a DAC-system is to aim for a lower fractional capture target than for a conventional carbon capture system, avoiding the non-linear increase in separation work above 80-90 % of capture. Finally, an increasing requirement for purity of the captured CO₂-stream significantly increases the separation work. To be able to effectively sequester the CO₂, to sell it as an industrial gas, or for use in some further process (for example for electro-fuels), this requirement remains very high for any real DAC-process, ideally above 99 % or even 99.9 %.

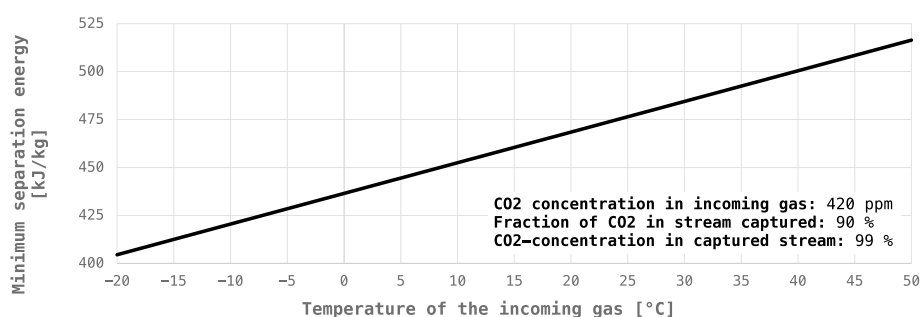


Figure 21. Influence of incoming gas temperature on CO₂ separation work.

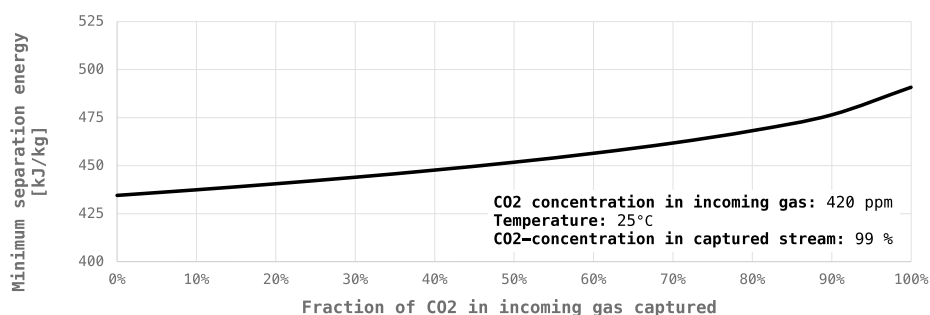


Figure 22. Influence of fractional capture requirement on CO₂ separation work.

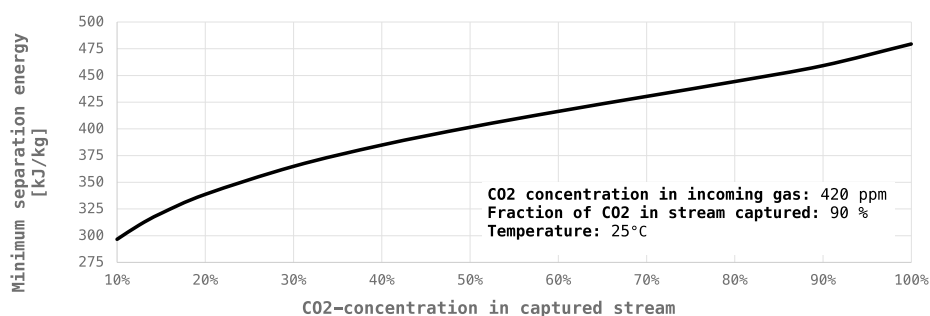


Figure 23. Influence of CO₂ purity requirement of capture stream.

The water vapor in outdoor air also has a substantial impact on system operation. In outdoor air at 25°C and 50% relative humidity, there are 40 water molecules for

every CO₂ molecule. Water vapor will compete with CO₂ for the reactive sites on sorbents, degrading capture performance. Water vapor also adds to the thermal mass of a sorption system that must be heated during regeneration, adding to operating costs.

2.3 TYPES OF DAC SYSTEMS

There are today essentially two major development pathways for DAC – systems using a solid sorbent and systems using a liquid solvent as the capture medium. Several serious vendors of DAC equipment are pursuing the former pathway, while the latter targeting a liquid solvent solution is primarily represented by the company Carbon Engineering.

Overall, the total energy demands of the solid sorbent and liquid solvent systems do not differ greatly from one another, and there is presently no clear frontrunner pathway between the two. Both the solid sorbent and liquid solvent DAC approaches require roughly a share of 80-90% thermal energy and 10-20% electricity for operation with existing proposed configurations. For the solid sorbent approach, the electricity requirements result from fans/blowers required to move air through the system and the vacuum pumps that remove air before regeneration. The liquid solvent system also requires electricity to move air, as well as for pellet reactors, steam slaker and filtration units. However, the temperature requirements of the different types of DAC processes differ greatly, which is of fundamental importance to the possibilities for effectively powering the process by a nuclear power plant. Most proposed solid sorbent systems require thermal energy on the order of 100°C–120°C for regeneration, which can be delivered highly effectively by all commercial and developing nuclear energy technologies.

Solvent-based separation of CO₂ from air requires a strong base, which in turn leads to a process that ultimately requires very high temperatures. The liquid solvent system proposed by Carbon Engineering requires heat near 900°C, which is required in the calciner step for the decomposition of CaCO₃ into CaO and CO₂. There are nuclear technologies which are designed to operate with a peak primary coolant outlet temperature of more than 900°C, but this type of operation is limited to the advanced high-temperature gas reactor (HTGR) reactor class. Both the German *Arbeitsgemeinschaft Versuchsreaktor* (AVR), in operation 1967-1988, and the Japanese *High-Temperature Test Reactor* (HTTR), in operation since 1999, have successfully achieved steady coolant outlet temperatures of 950°C¹⁵. Systems such as these can thus in theory provide all the heat required for either type of DAC process. Due to the much wider range of potential nuclear energy heat provision coupling for lower-temperature solid sorbent DAC-systems, this is the focus of this chapter, and the liquid-solvent approach is not explored further here. For readers interested in a deeper introduction to liquid-solvent DAC, there is an excellent paper by Carbon Engineering introducing the technology [43].

¹⁵ The Ultra-High Temperature Reactor Experiment (UHTREX), in operation at Los Alamos in the United States from 1959-1971, even achieved a steady-state coolant outlet temperature as high as 1316 °C.

2.4 LOW TEMPERATURE (LT) SOLID SORBENT DAC TECHNOLOGY

2.4.1 Operational principle

Technologies in this category work at ambient temperatures to chemically bind CO_2 to a filter made from a solid sorbent¹⁶, typically an amine¹⁷. This continues until the sorbent of the filter is saturated with CO_2 . In the next step, the system is emptied of gases through vacuum. The system is then heated to a certain temperature to regenerate the sorbent by releasing the CO_2 , either in a dry process or by injecting steam. The CO_2 is then transported out of the system for further purification and compression for storage or utilisation. Then system is finally cooled back down to ambient temperature before the cycle is repeated. These five stages of operation are shown in Figure 24.

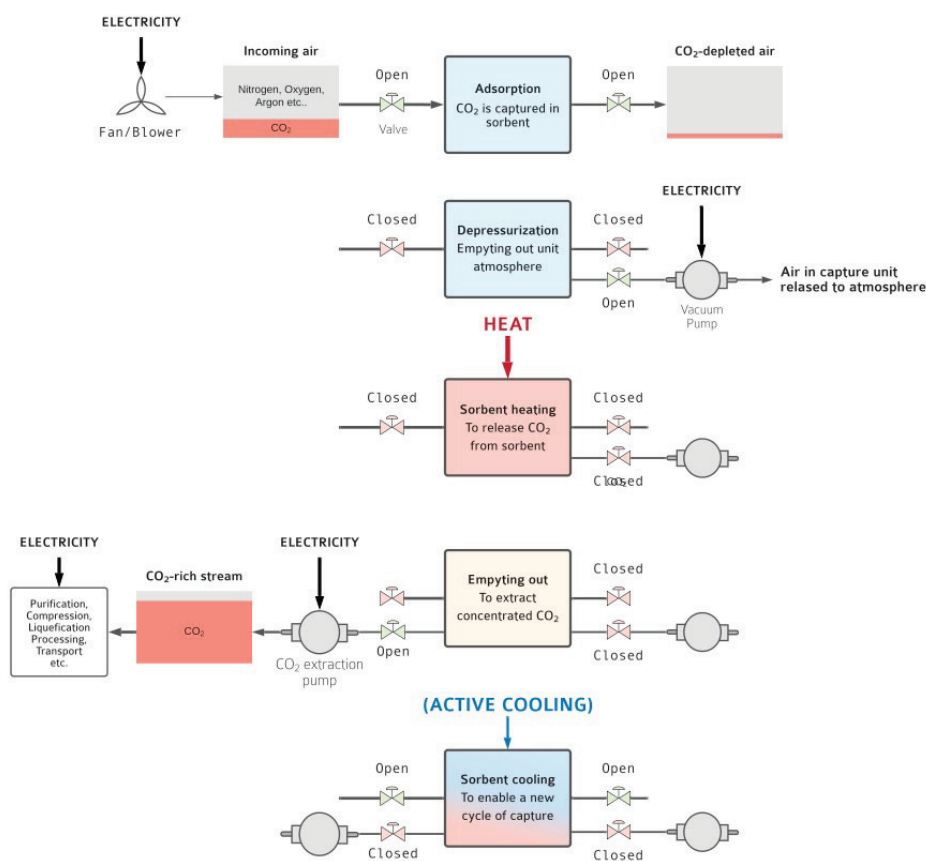


Figure 24. Combined dry temperature- and pressure-swing DAC process with solid sorbent.

¹⁶ A molecule in the fluid phase prior to adsorption is referred to as an adsorbate, once on the surface it is defined as an adsorbate, with the surface defined as the adsorbent, or more general to include both adsorption and desorption processes, sorbent.

¹⁷ Amines are compounds and functional groups that contain a basic nitrogen atom with a lone pair. Amines are formally derivatives of ammonia, wherein one or more hydrogen atoms have been replaced by a substituent such as an alkyl or aryl group.

2.4.2 Sorbent choice

To speed up the capture of CO₂, air is forced through the system with fans or blowers in all existing DAC system designs. An ideal sorbent for such a system has the following general characteristics:

- (1) High volumetric and gravimetric adsorption capacity for CO₂
- (2) Regeneration using temperature swing over a limited temperature range
- (3) Low specific heat
- (4) High reactivity towards CO₂
- (5) Mechanical and thermally stable
- (6) Low manufacturing costs
- (7) Stable performance in the presence of water

Sorbents are arranged into three categories based on the sorption mechanism:

- (1) Physisorption (or physical adsorption)
- (2) Chemisorption (or chemical adsorption)
- (3) Moisture-swing sorption

Chemisorption occurs when a chemical bond is formed, whereas physisorption relies on weaker physical interactions such as van der Waals or ion–quadrupole interactions. Hydroxides, oxides and alkaline salts can effectively scrub CO₂ from air and convert it into carbonates through chemisorption because of a high chemical binding energy. However, releasing the captured CO₂ is expensive since overcoming the binding energy and paying for the heat losses encountered during heating of the materials to very high temperatures is energy intensive.

Regeneration of materials operating through physisorption is much easier than from chemisorbed materials because of the weaker bonds. On the other hand, as the thermodynamic drivers for capture are reduced, there is a correspondingly lower uptake capacity for physisorption at atmospheric CO₂ levels. Moisture-swing sorbents change their affinity to CO₂ through interaction with water. Dry sorbents bind CO₂ and wet sorbents release CO₂. A system that uses steam condensation to regenerate the sorbent is estimated to use 1.6 tonnes of water per tonne of CO₂ captured, which can be a challenge to provide in many locations. In contrast, systems based on dry regeneration are in fact net producers of water due to the co-adsorption of water from air humidity.

The current frontrunner in terms of sorbent choice are “*amine-functionalized*” adsorbents, which comprise a support, typically porous, with weakly bonded amines or polyamines that capture the CO₂ in a combination of physisorption and chemisorption. Amine-based CO₂ adsorbents of this type have been designed with several support materials and methods of adding amines (including impregnating pre-made amines, chemically grafting on amine molecules or in situ formed amines). Most of the supports used are relatively inexpensive, e.g. silica, carbons, zeolites, and clays, as are most of the used amines, e.g. polyethylenimine (PEI).

Well-made functionalized amine-based adsorbents are reusable and can last for several thousand cycles (approx. 2-3 years), thus they have the potential to meet most, if not all, characteristics required as defined at the beginning of this chapter.

2.4.3 System energy requirements

Heat for regeneration of sorbents

For a given sorbent lifetime, the heat requirements for regeneration along with the required gas blower power for overcoming the pressure drop through a sorbent bed determine the operating and maintenance costs associated with the adsorption process for CO₂ capture. The heat required to regenerate the sorbent per tonne of CO₂ captured can be calculated as:

$$H \left[\frac{\text{kWh}}{\text{tCO}_2} \right] = \frac{\text{HeatCapacity} \left[\frac{\text{kJ}}{\text{tonne Sorbent} \times \text{K}} \right]}{\text{CO}_2 \text{Capacity} \left[\frac{\text{tCO}_2}{\text{tonne Sorbent}} \right]} \times \frac{1}{3600} \left[\frac{\text{kWh}}{\text{kJ}} \right] \times \Delta T [\text{K}]$$

The possible loading of CO₂ in a solid-supported amine system is on the order of 0.030-0.12 kg of CO₂ per kg of sorbent. Given that one wants to maintain a high rate of adsorption and not wait for full saturation in a real cycle, we will use an average of 0.03 kgCO₂/kg sorbent for this example. The specific heat capacity of amine impregnated silica lies in the range of 1.1-1.7 kJ/kgK, while metal-organic framework adsorbents such as MOF SIFSIX-3-Cu has a reported heat capacity of 0.72 kJ/kgK [44]. An average value of 2 MJ/t sorbent can be used here as an example to also account for the fact that the adsorbed CO₂ and co-adsorbed water will also need to be heated. The temperature change required for regeneration is on the order of 100K (from ambient up to around 110-120°C). The resulting minimum required regeneration energy is on the order of:

$$H = \frac{2000}{0.03} \times \frac{1}{3600} \times 100 = 1850 \left[\frac{\text{kWh}}{\text{tCO}_2} \right]$$

After regeneration, the system will need to be cooled to enable the capture cycle to restart, which opens the opportunity to use staggered operation of multiple systems, cooling one system by heating another, thereby reducing overall energy requirements. Given differences in possible system layouts, choice of sorbents and operational characteristics, the effective regeneration heat requirement of a real dry solid-sorbent system realistically lies in the range of 1-3 MWh/tCO₂ captured.

Electricity for fans/blowers

The electricity required to actively push air through the capture system using fans is given by:

$$E_{\text{fan}} \left[\frac{\text{kWh}}{\text{tCO}_2} \right] = \frac{P_{\text{drop}} [\text{Pa}]}{X [\text{Frac CO}_2 \text{ captured}] \times C \left[\frac{\text{tCO}_2}{\text{m}^3 \text{ air}} \right] \times \text{Eff} [\%]} \times \frac{1}{2.778 \times 10^7} \left[\frac{\text{J}}{\text{kWh}} \right]$$

Assuming 50 % fractional capture and 420 ppm CO₂-air with 0.75 grams CO₂/m³ and 75 % electrical efficiency of the fan, the expression simplifies to

$E_{\text{fan}} [\text{kWh}] = P_{\text{drop}} [\text{Pa}]$. The pressure drop across a capture channel in a typical optimized DAC system may lie approximately in the range of 300-400 Pa, and thus

adds an electricity consumption requirement to the system of 300-400 kWh/tCO₂ captured.

2.5 POWERING DAC WITH NUCLEAR ENERGY

2.5.1 Introduction

As described in section 2.4.3, the energy requirement for low-temperature solid sorbent DAC comes in two forms, firstly to power fans to blow air through passed the contactors (100-350 kWh per tCO₂) and secondly to regenerate the sorbents (1-3 MWh of heat at 100-120°C per tCO₂), ignoring energy needs for the handling and use of CO₂ after capture and separation. Nuclear power plants, just like most other thermal power plants, make use of steam turbines to produce electricity. The implementation of nuclear co-generation, which is defined as the supply of both electricity and heat (in the form of steam or heated water), is not directly related to the reactor system itself, but rather is something that is implemented in the steam cycle in the turbine building. This is true regardless of whether co-generation is implemented as a retrofit to an existing plant or is an integral part of the design of a new plant. A nuclear plant could quite easily and at low cost be configured to supply both the heat and electricity needs of a typical DAC system. A simplified schematic showing the main components of interest in a pressurized water reactor (PWR) plant, based on the EPR, is shown in Figure 25.

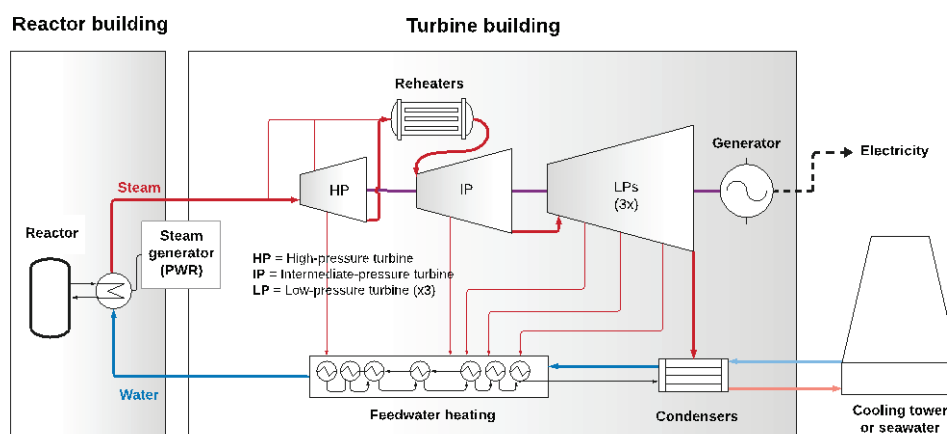


Figure 25. Basic schematic of a PWR plant focusing on the turbine building.

2.5.2 Enabling steam-extraction for DAC from an existing reactor system

To enable co-generation, a fraction of the steam produced could in principle be extracted at any point of the steam cycle and be led to an external heat exchanger¹⁸ to produce secondary steam or hot water for an external consumer such as DAC system. The fluid supplied to the user of the heat will always be kept separate from the water-steam cycle in the reactor. When there is a steam/hot-water exchange,

¹⁸ Another option is to lead the steam to a separate back-pressure turbine, which in France is referred to as "Front Heat Extraction" [16].

this equipment will resemble a conventional condenser or reheater. The extracted steam would then be returned as water at a lower temperature to an appropriate point in the cycle. A simplified view of the added equipment required to enable co-generation is given in Figure 26.

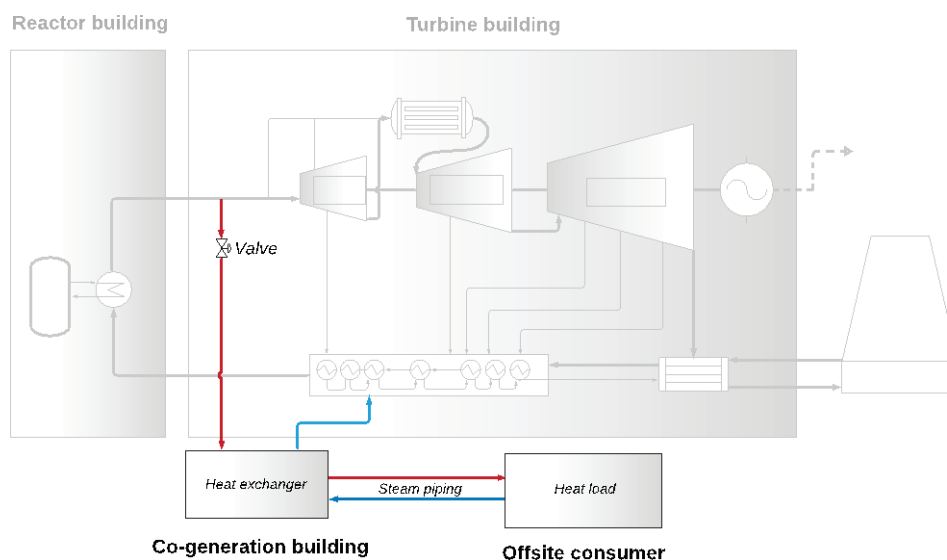


Figure 26. Example implementation co-generation in a PWR steam cycle (simplified, not to scale).

With minor modifications, these figures apply to any type of nuclear plant or indeed any thermal power plant utilizing a steam cycle. Using the steam cycle of the EPR as a general example representative of PWRs, steam could be drawn from the main steam piping at 3 different distinct conditions¹⁹ (determined by temperature, steam quality and pressure), as shown in Figure 27. At these extraction points, steam can be accessed and diverted to heat exchangers at temperatures of 292°C, 185°C and 159°C, and pressures of 7.659 MPa, 1.1 MPa and 337 kPa respectively.

¹⁹ Extraction could also be made from the main steam line *after* the Moisture Steam Separator (MSR) at point S1. Points S1 and M1 are similar enough in temperature that there is no real motivation for the more complicated extraction at S1.

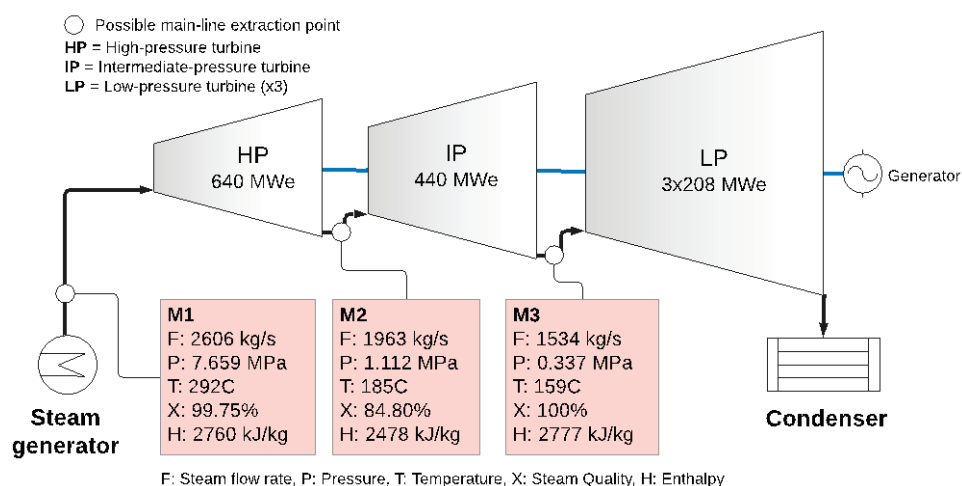


Figure 27. EPR main steam extraction points (all 4 SG lines).

As steam is diverted out of the turbine circuit, less steam is available to expand in the turbines and thus less electricity is produced. The amount of electric output lost compared to the heat output gained depends on the details on in how many stages the steam is extracted, what type of heat exchangers are employed, what the temperature drop in the secondary (customer) loop is and how the steam or condensate is returned to the plant. An approximate assessment for the loss of units of electric output per unit of thermal power (steam supply) for a single-stage extraction at 10 different points are given in Figure 28.

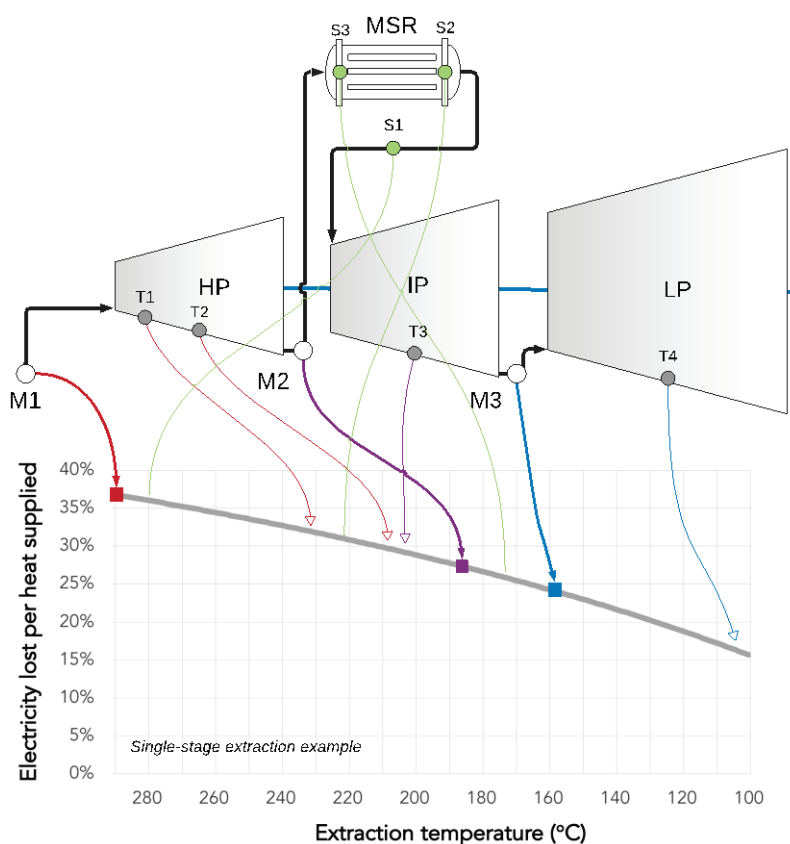


Figure 28. Approximate loss of electric output for every unit of heat co-generation supply in an LWR.

The magnitude of possible steam extraction rate of heating steam from an existing condensing cycle with existing equipment, without any major structural modifications, depends primarily on:²⁰

1. The temperature range of the heating water
2. The number of heating condensers
3. The number of low-pressure turbine flows
4. The permissible velocity of the extracted steam in the bleed pipes and orifices (limited by vibration and noise)
5. The strength of the blades preceding the bleed point concerned
6. Possibilities for arranging the piping inside and outside the LP section of the turbine.

The extraction of flow for heating beyond the normal cycle requirements changes the pressure distribution in the cycle and the turbine stage immediately preceding the extraction point is subjected to the greatest change in pressure ratio and blade loading. GE/Alstom engineers indicate that diverting 10% of thermal power is manageable with only minor changes in the steam cycle equipment, which is also confirmed by the plans for the Kaliningrad Nuclear Power Plant to use 10% of the thermal power in the reference ARABELLE™ turbine cycle for district heating [45].

²⁰ This list is based on information given by turbine experts in ref. [44].

One of the more extreme examples of an existing condensing co-generation steam turbine design for a nuclear power plant applications is that of the TurboAtom model “KT-1070-60/1500-3”. The unit, which was developed in the 1980s, allowed for the steam extraction of up to 1400 MW_{th} at 170°C, corresponding to approx. 45% of the thermal power produced in the reactor core of the VVER-1000 for which it was originally developed [46]. While no unit of that type has been put into operation, TurboAtom maintains the capability to manufacture it if the demand arises [47]. From this analysis, the following conclusions can be drawn regarding steam extraction for DAC from existing nuclear plants/designs:

- Up to 10% of thermal power could be extracted with minor modifications
- Up to 45% of thermal power could be extracted with major modifications
- Up to 66% of thermal power could be used with a back-pressure-turbine configuration
- The ideal single-stage extraction point is at the cross-over before the low-pressure turbine stage. More effective extraction can be done by also utilizing LP turbine extraction points.
- A single-stage extraction involves an opportunity cost of losing 0.25 MWh of electricity generation for each MWh of heat extracted (at ~150-160°C)
- A three-stage extraction system means losing 0.15 MWh of electricity for each MWh of heat supplied (at 120°C)

2.5.3 Optimizing a combined LT DAC nuclear system

An optimized combined nuclear DAC system would make use of multiple steam extraction points to supply 120 °C steam to the DAC units at a loss of 0.15 MWh of electricity for each MWh of heat supplied²¹. Furthermore, rather than using electricity to drive fans to push air through the system, the DAC system could be configured to effectively act as a purpose-built cooling tower for condenser cooling of the steam cycle. Natural draft cooling towers, common at inland/river-sited thermal power plants, are the locations with the highest steady and engineered flow of air on the planet. In a cooling tower, which exists in both dry and wet configurations, air flow is driven by the density difference between the ambient air and the hot air inside the cooling tower. Using the principle of natural draft cooling towers to move air through DAC systems has the very significant advantages of essentially no electricity consumption, low maintenance costs and no mechanical noise. Removing one 1 MW of heat by condensing 0.4 kg/s of 40°C steam requires approximately 67 kg/s (56 m³/s) of airflow with a temperature rise in the air of 15 °C. Thus, about 42 grams of CO₂ pass through a natural draft cooling tower per second per MW of heat that is removed. For a 1000 MW_e nuclear power plant that rejects around 1800 MW_{th} of heat from the condensers using

²¹ A combined DAC and nuclear system that is optimized from the ground up for maximum capture capacity could instead make use of a backpressure-turbine solution rather than extracting steam. This would allow for close to 2/3rds of the full thermal energy of the nuclear system to be utilized in the DAC system with a loss in electricity output (compared to a condensing turbine with no steam extraction) of 0.15-0.17 MWh per MWh of heat supplied.

cooling towers, about 2.3 million tons of CO₂ flow through these systems at a steady and controlled rate, for free, each year. Life cycle analysis of existing Nordic power plants indicate an embedded emissions rate of 3-5 gCO₂/kWh, which for a 1000 MW_e plant at 90% capacity factor translates to about 20-30 ktCO₂/year. Thus, capturing approximately 1% of the CO₂ in the air that would naturally flow through such a plants cooling towers would turn the plant in to a net-negative carbon emitter on a life-cycle basis. With a regeneration energy requirement of 2 MWh per tCO₂ captured, around 0.2 % of the thermal energy generation of the core would need to be diverted for this purpose to achieve net negative emissions. A principal schematic of how such a system would work is shown in Figure 29, with low-grade heat driving air flow through the DAC systems and higher-grade heat providing the energy for regeneration.

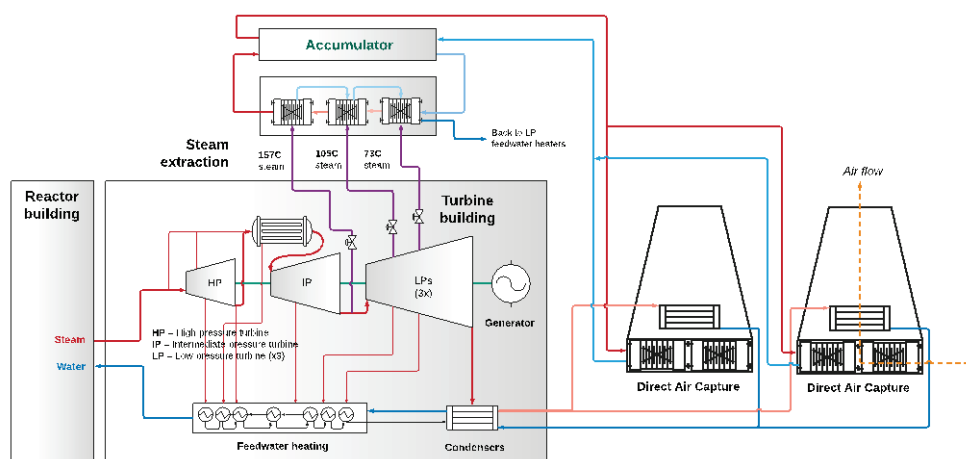


Figure 29. Nuclear heat-powered DAC system schematic.

If a total of 10 % of the thermal energy of the steam produced in the core (in boiling water reactors) or transferred in the steam generators (in all other types of reactors) is diverted for sorbent regeneration in the DAC system, the required air flow for such a system can be provided by the waste heat for condenser cooling. Above this rate of steam extraction, the air flow will need to be assisted by electrical fans. Table 4 shows the conditions for the 300 MW_e GE-Hitachi BWRX-300 reactor unit in reference condition and equipped with a DAC system.

Table 4. GE-Hitachi BWRX-300 system with/without DAC integration at 10 % extraction.

Parameter	Reference	With DAC integration
Thermal power	830 MW _{th}	830 MW _{th}
Process heat provision	0 MW _{th}	83 MW _{th}
Electricity generation	2.37 TWh/y	2.27 TWh/y
CO ₂ captured	0 tons	370,000 t/year
Net lifecycle CO ₂ emissions	9500 t/year	-360,500 t/year

Parameter	Reference	With DAC integration
CO ₂ intensity of electricity generation	4 gCO ₂ /kWh	-160 gCO ₂ /kWh
Thermal (waste) heat required to drive airflow at 50 % capture and ΔT of air of 15°C	N/A	563 MW _{th} (100 % of available)

The actual engineering implementation of a system working along these principles will differ quite substantially from that shown in Figure 29. A consortium²² consisting of Sizewell C (EDF Energy), Doosan-Babcock, Atkins, Strata Technology and Nottingham University has finished design of a prototype system following these principles that is scaled to capture 100 tons of CO₂ per year to prove the concept. The consortium has been awarded £250,000 by the UK Government for the first design phase of the project under the Net Zero Innovation Portfolio which supports the development of low-carbon technologies²³.

2.5.4 Economic analysis

The levelized cost of DAC can be divided into three components relating to the costs of DAC equipment (including sorbents) and the cost of providing the system with electricity and heat:

$$\text{LCOD} = \text{DAC Equipment} + \text{Electricity} + \text{Heat}$$

The levelized cost of the DAC equipment can be calculated as:

$$\text{DAC Equipment} = \frac{\text{CAPEX}_{\text{DAC}} \times \text{crf} + \text{OPEX}_{\text{fix}}}{\text{CF}} + \text{OPEX}_{\text{var}}$$

Where CAPEX is the total investment cost for the equipment, crf is the annuity factor, OPEX_{fix} is the fixed operational costs (which do not vary with utilization) which includes replacement costs for the sorbent, OPEX_{var} are any operational expenses that scale with the amount of CO₂ captured, and CF is the capacity factor of the equipment in operation. The annuity factor can be calculated as:

$$\text{crf} = \frac{WACC \times (1 + WACC)^N}{(1 + WACC)^N - 1}$$

Which for an expectation of 20 years of operational time (N=25) and a weighted average cost of capital of 7 % is 0.0944. Recent research indicates, by use of learning curves, that the capital cost of low-temperature solid adsorbent DAC equipment may follow the following trajectory:

²² to which the author of this chapter serves as a technical advisor.

²³ Sizewell C and partners awarded Direct Air Capture funding, <https://www.edfenergy.com/energy/nuclear-new-build-projects/sizewell-c/news-views/sizewell-c-and-partners-awarded-direct-air-capture-funding>

Table 5. LT DAC equipment and operation cost assumptions [48].

Year	2020	2030	2040	2050
CAPEX _{DAC} (€/tCO ₂ /y)	730	338	237	199
OPEX _{FIX} (€/tCO ₂ /y)	29.2	13.5	9.5	8.0
OPEX _{var} (€/tCO ₂)	3	3	3	3
CF	0.85	0.85	0.85	0.85
LCOD _{DAC} (€/tCO ₂)	111.0	53.0	38.1	32.5

The proposed solution avoids the need of fans and all the electrical installation required to power the fans in order to move air through the system, which may indicate a potential for further reduction of the CAPEX_{DAC} value. The LCOD_{DAC} capture value thus corresponds to the floor of possible levelized cost per tCO₂ captured, with zero cost assumed for any of the heat or electricity required to run the system. The electricity cost for DAC can be calculated simply as the LCOE of the dedicated electricity supply multiplied by the electricity consumption required to capture one tonne of CO₂. Small modular reactor systems are typically expected to land at an LCOE-value (with 7 % WACC) in the span of 40-60 €/MWh. We will use a reference value of 50 €/MWh for this analysis. The levelized cost of electricity value already includes full costing of a condenser cooling system, including cooling towers (or once-through ocean cooling) and associated piping and pumps. However, for the proposed implementation, a dry rather than wet cooling tower type system is envisioned in connection to the DAC contactors. This may conservatively raise the reference level of LCOE by up to 10 %, indicating a reference level of 55 €/MWh. The electricity requirements for a system where both regeneration and air flow are provided by heat is limited to the operation of valves and pumps and is dominated by the pumping power requirement to move high grade heat from the turbine island to the DAC system. The total requirement is on the order of 20 kWh/tCO₂, indicating a direct levelized electricity expense of 1 €/tCO₂.

Finally, the cost of DAC heat consumption can be estimated as:

$$\begin{aligned}
 \text{Heat Cost} = & \text{Electricity Opportunity Cost} \\
 & + \text{Terminal equipment \& Upgrades at plant} \\
 & + \text{High Temp Heat Transport Equipment Cost} \\
 & + \text{Low Temp Heat Transport Equipment Cost} \\
 & + \text{Additional operational expenses}
 \end{aligned}$$

The electricity opportunity cost is on the order of 15 % of the cost of electricity, since roughly 0.15 MWh of electricity is lost for every MWh of district heating produced, which for 55 €/MWh electricity means 8 €/MWh. The DAC system is assumed to use 2 MWh of high-grade heat per tCO₂ for regeneration, leading to a levelized cost of 16 €/tCO₂. The terminal equipment at both ends of the heat transport system includes condensing heat exchanging stations and heat exchangers between the regional and local heating systems and may account for about 5 % of the total delivered heat cost²⁴, indicating a levelized cost of 0.8 €/tCO₂ [49]–[51]. Additional operational expenses at the nuclear plant may essentially be neglected since staffing requirements are unlikely to change compared to that of an electricity-only generation plant. What remains for heat costs are the expenses related to piping the heat from the nuclear co-generation site to the DAC facility. The capital cost (\$/meter) of the main heat transport line to supply high grade heat from a nuclear power plant can be approximated as [52]:

$$P_{HTS} \left(\frac{\text{€}}{\text{m}} \right) = 3000D^2 + 4000D + 1500$$

Where D is the inner diameter of the transport pipes in meters. P_{HTS} includes the two-ways pipeline (with 200 mm insulation thickness), pumping stations and labour cost. According to Leurent et al. 2018 [53], the resulting cost values are in line with other observed costs of long distance buried pipeline systems designed for hot water transportation (see ref. [54]). Several different studies have indicated an ideal heat transport pipe diameter of 1.2 meters per GW_{th} of capacity [55], [56]. Scaling down this optimal diameter by taking in to account the cross-sectional area of the pipe yields the following simple and very approximate costing equation:

$$P_{HTS} \left(\frac{\text{€}}{\text{m}} \right) = 10 \times P \text{ [MWth]}$$

Where P is the maximum heat capacity of the transport line in MW_{th}. We add to this expression a €5 million cost to reflect a minimum project cost regardless of size and capacity of the pipeline. For the system envisioned, a high temperature heat transport line of 83 MW_{th} supports 370,000 tons of capture per year. Assuming the substation for distributing DAC heat is located 3 km away from the plant, the CAPEX of the heat distribution system (dimensioned for 100 MW_{th}) becomes €8 million. With a pipeline payback period of 20 years and a WACC of 7%, this addition is negligible compared to the total levelized cost of DAC. In total, utility supply costs to the DAC system therefore incurs an expense of approximately 17 €/tCO₂.

Table 6. LCOE of optimized nuclear-coupled DAC (55 €/MWh LCOE).

Year	2020	2030	2040	2050
LCOE _{DAC} (€/tCO ₂)	111.0	53.0	38.1	32.5

²⁴ Although technically fairly simple and straightforward, the retrofits to existing nuclear installations in order to supply off-site heat may constitute significant one-off costs due to strict licensing and documentation requirements.

Year	2020	2030	2040	2050
LCOD_{el} (€/tCO ₂)	1	1	1	1
$\text{LCOD}_{\text{heat}}$ (€/tCO ₂)	17	17	17	17
LCOD (€/tCO ₂)	129	71	56.1	50.5

2.5.5 Economic comparison

For Nordic/Swedish conditions, the most relevant comparison case is a dedicated onshore wind farm running an equivalent DAC plant, for which the same $\text{CAPEX}_{\text{DAC}}$ can be assumed. However, the capacity factor of a dedicated facility scaled to the needs of the DAC system CO₂ capture target will need to follow the generation of the wind farm(s) it is connected to. If the wind farm was grid connected, the applicable cost of electricity for the DAC system would be that of the grid market price rather than the wind farm LCOE, since the facility faces an opportunity cost in the choice of selling power to the grid rather than supplying the DAC system. A reasonable annual capacity factor expectation for this economic analysis is therefore 35 %.

Table 7. LT DAC cost in dedicated wind-powered facility.

Year	2020	2030	2040	2050
$\text{CAPEX}_{\text{DAC}}$ (€/tCO ₂ /y)	730	338	237	199
OPEX_{fix} (€/tCO ₂ /y)	29.2	13.5	9.5	8.0
OPEX_{var} (€/tCO ₂)	3	3	3	3
CF	0.35	0.35	0.35	0.35
LCOD_{DAC} (€/tCO ₂)	265.4	124.4	88.2	74.6

Another alternative is to have a grid-powered system, that can then operate at 90% capacity factor but with a cost of electricity of about 40 €/MWh, the economics of which is shown in Table 8.

Table 8. LT DAC cost in dedicated grid-powered facility.

Year	2020	2030	2040	2050
CF	0.9	0.9	0.9	0.9
LCOD_{DAC} (€/tCO₂)	105.0	50.2	36.2	30.9

A wind or grid-powered DAC plant will ideally use heat pumps for the high-grade heat provision and electrical fans to move the air. Assuming continued aggressive cost reductions to an LCOE of 25 €/MWh (at 7 % WACC) and an electricity requirement for moving air of 400 kWh/tCO₂, the levelized electricity expense for air movement is on the order of 10 €/tCO₂ for the dedicated wind-facility and 16 €/tCO₂ for the grid-powered facility. An advanced air source heat pump capable of providing 120 °C from ambient air in Swedish conditions would push the limits of available technology, as it could involve a required “lift” in temperature of over 140 K (from -20°C air temperature). This means it would need to be complemented with an electrical resistance heater to guarantee heat delivery. Optimistically, we could assume a product line (modelled after the Mayakawa Eco Sirocco product line) that could reliably upgrade ambient air in Sweden to 120°C and operate at a year-round average COP of 2.0. At a heat requirement of 2 MWh/tCO₂, this means a levelized cost of heat provision of 25 €/MWh for the wind-powered system and 40 €/MWh for the grid-powered one. The cost of advanced multistage high-temperature heat pumps for a system of the same size as for the nuclear case (2.85*83=236 MW_{th}) is on the order of €250 million²⁵, which again when levelized and normalized per tonne of CO₂ captured adds only a small cost and is therefore ignored.

Two additional options were analysed. One is to dimension an extremely large, dedicated wind facility (that presumably mainly powers other loads, conceivably electrolyzers for hydrogen production) compared to the size of the DAC plant, allowing the DAC plant to run at a higher capacity factor than the wind farm output. This option is labelled “Minimal Wind-DAC”. A final option is labelled “Conventional nuclear-DAC” which represents a DAC-system where sorbent regeneration is supplied by nuclear heat, but air flow is supplied by fans. The resulting levelized cost of DAC for all these options, given the assumptions above, is given in Figure 30.

²⁵ Energinet, Technology data - Generation of Electricity and District heating
https://ens.dk/sites/ens.dk/files/Statistik/technology_data_catalogue_for_el_and_dh_-_0009.pdf

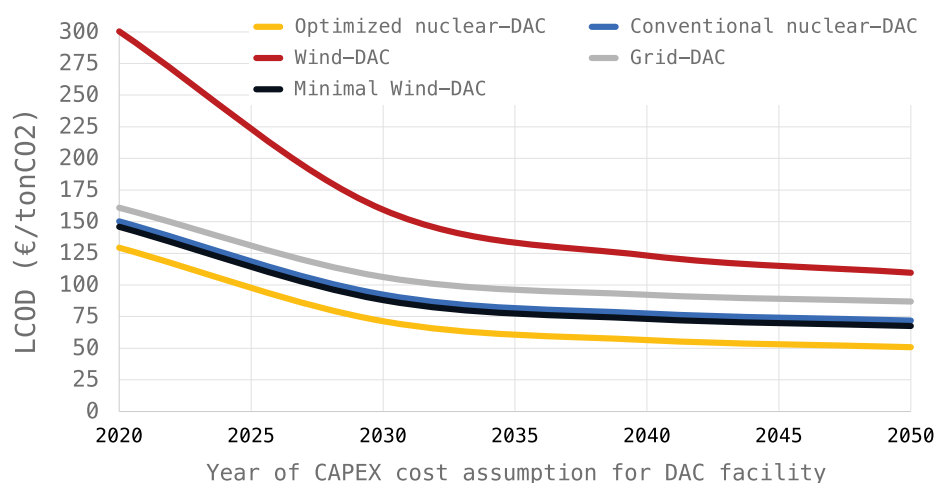
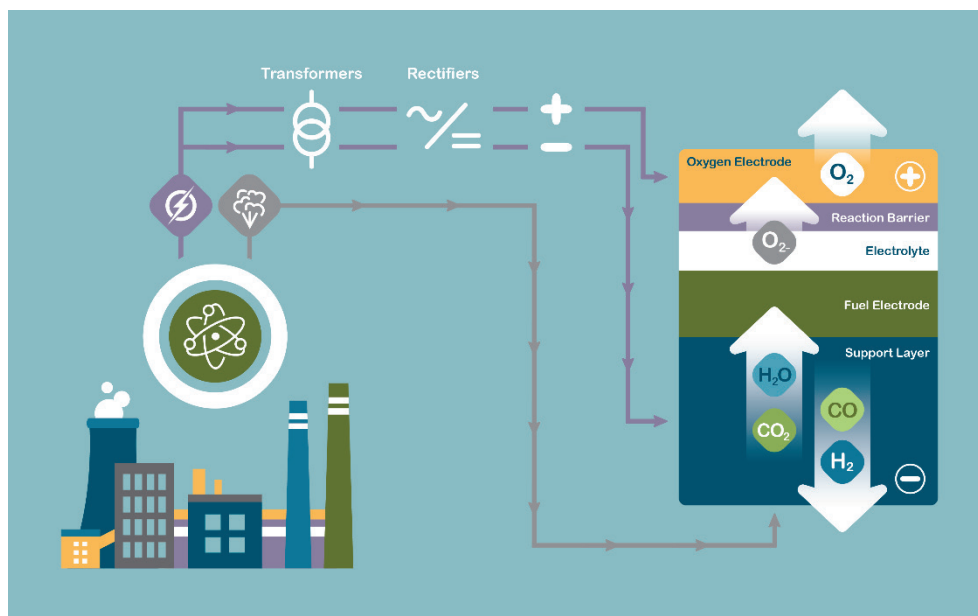


Figure 30. Approximate cost-comparison of DAC options.

2.6 SUMMARY

Nuclear energy is a thermal power source that excels at reliably making low-to-medium grade heat. Direct Air Capture (DAC) is a process primarily requiring very large amounts of heat at conditions ideal for a nuclear power plant to provide, and with a CAPEX-heavy cost structure that very strongly favours high levels of utilization. This combination means that on an economic basis, a nuclear-coupled DAC-system appears extremely attractive. In this work, we describe a way in which the electricity requirements of the DAC process can be almost entirely designed away (apart from processing of the captured CO₂, which is not included here) by making full use of what is today regarded as waste heat. With future projections for the CAPEX of DAC technology dropping toward 2040, an optimized nuclear-DAC system can capture CO₂ at a cost per tonne that is half of what a grid-connected facility would, and at a third of the cost of a dedicated wind-powered facility scaled to the requirements of the DAC system. In this example, the assumed LCOE of the nuclear facility is 1.40 times higher than the grid-power-price and 2.2 times higher than the wind-LCOE. If one includes cost improvements on the nuclear power plant side, the relative advantage in cost of captured CO₂ increases further. In optimal co-generation configuration, a nuclear plant can achieve a levelized cost of DAC of around €50/tCO₂, and would, in such a configuration, feature an effective life-cycle CO₂-emissions rate of -160 gCO₂/kWh.

3 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.

Hydrogen is the most abundant element in the universe and one of the most abundant elements on earth²⁶. Combustion of hydrogen does not produce CO₂, an attractive advantage for countries seeking to firm up their commitments to cut carbon emissions. It can also be combined with oxygen in fuel cells to produce electricity, which yields only water as a product of the reaction process. Finally, hydrogen is used extensively as an input material in the chemical and

²⁶ By atomic fraction it's one of the most abundant, but because of its slight weight only a small fraction of the mass on earth is made up of hydrogen.

manufacturing industries. The current demand for hydrogen, about 90 Mt H₂ in 2020, comes almost exclusively from the refining and industrial sectors, with industrial demand dominated by chemicals production.

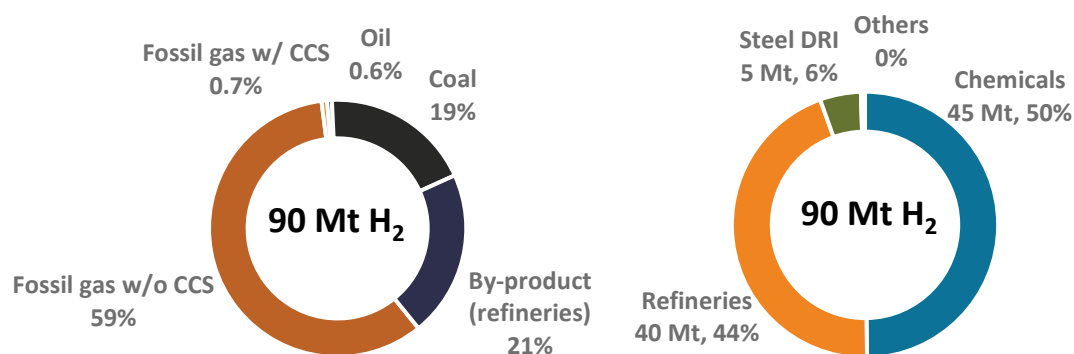


Figure 31.
Sources of hydrogen production, left, and demand, right, in 2020 [57].

Because atomic hydrogen is very reactive it will combine with most other elements to form hydrides. On earth, hydrogen is mostly found as water. Production of hydrogen therefore requires energy to separate the hydrogen from other elements, e.g. from oxygen in water, H₂O, or from carbon in methane, CH₄.

Today's production of is dominated by fossil fuel-based production methods, primarily steam reforming of fossil gas.

3.1 FOSSIL HYDROGEN PRODUCTION WITH CARBON CAPTURE

Most of the world's hydrogen is produced from steam methane reforming, which uses high temperatures and steam to separate methane into H₂ and CO₂. 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.

Producing hydrogen from fossil hydrocarbons requires capturing the emissions in order to not contribute to climate change effects. Hydrogen production today produces around 830 MtCO₂ per year.

Table 9.
Emissions of carbon dioxide associated with different fossil hydrogen production methods.

Fossil fuel	CO ₂ emissions [tCO ₂ /tH ₂]
Natural gas	10
Oil products	12
Coal gasification	19

Hydrogen can be produced from fossil fuels through steam methane reforming, partial oxidation, autothermal reforming, gas heated reformers (combined with steam methane reforming or autothermal reforming) and coal gasification.

Because carbon capture does not have a perfect capture rate, all of the above methods result in relatively significant emissions. For this reason, although there are options to implement nuclear heat in some methods, e.g. steam methane reforming, they are not considered further within the context of this report.

3.2 HYDROGEN FROM BIOMASS

Hydrogen can also be produced from biomass and several initiatives have been launched to further explore this potential, e.g. by the UK government [58].

Nuclear energy production could be integrated with production of hydrogen and other biofuels from biomass, but this is outside of the scope of this report. Additionally, biomass resources are limited and utilising biomass resources for hydrogen production may not be a wise use of resources. However, because biomass resources are limited it may also be worthwhile if nuclear energy could increase the amount and value of biofuels produced from biomass. Still, this is considered outside the scope of this report.

3.3 LOW CARBON HYDROGEN PRODUCTION

Widespread adoption of hydrogen relies on bulk production by low-carbon or zero carbon methods. There are several different methods based on electrolysis. With electrolysis, CO₂ emissions are limited to those associated with the production of the required energy in the electrolysis process. Today, electrolysis makes up a fraction of a per cent of the world's hydrogen production. Around 2% of global production is produced from chlor-alkali electrolysis as a by-product from production of chlorine and caustic soda. Efficiency of electrolyzers today typically range between 60 – 80 % [59]. Different electrolyser technologies have different efficiencies.

Production of 1 Nm³ of hydrogen requires around 0.8 litres of demineralised²⁷ water, or 9 l/kgH₂. Tap water must first be purified, which increases total water consumption to between 18 – 22 l/kg hydrogen. Electrolysis yield both hydrogen and oxygen, with 8 kgO₂/kgH₂ produced.

Access to fresh water could be a potential issue in areas affected by water scarcity. If the feedwater is salt, brins or grey water the consumption of water roughly doubles. Purifying water also increases overall costs, but only a small part of the total production cost of hydrogen.

As with desalination, see section 1.4, there is a fundamental thermodynamic minimum energy required to separate hydrogen and oxygen in a water molecule. The change in enthalpy required for the separation is constituted of both electrical

²⁷ i.e. water free from dissolved minerals, typically produced by reverse osmosis or distillation.

energy and thermal energy. The relation between total energy, electrical energy and thermal energy is given by

$$\Delta H = \Delta G + T \Delta S$$

Where ΔH is the reaction enthalpy (or total energy demand), ΔG is the Gibbs free reaction energy (electricity demand) and $T\Delta S$ is the heat demand, $\Delta Q = T\Delta S$, with T being temperature and ΔS the entropy change. This relationship is illustrated in Figure 32.

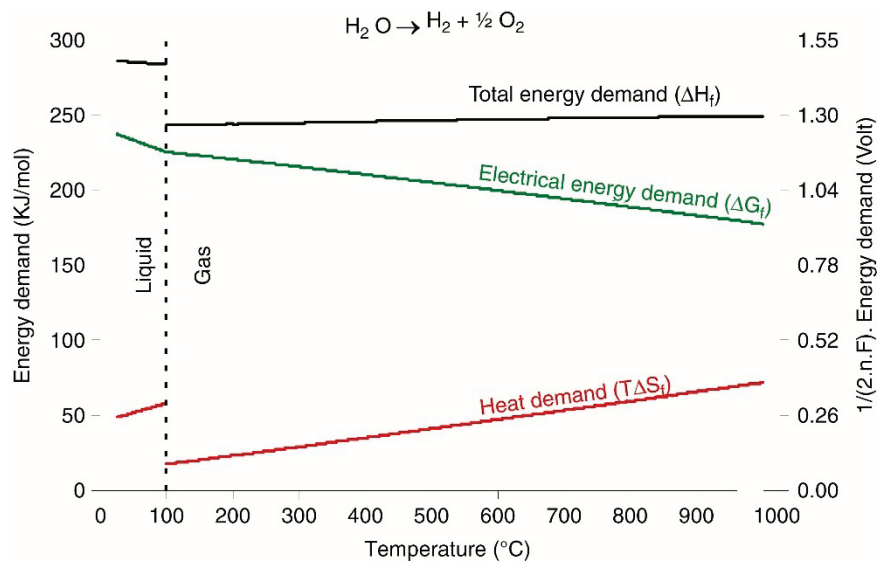


Figure 32.
Thermodynamics of H₂O electrolysis at atmospheric pressure, figure from [60].

It is shown that the relationship between electrical energy demand and heat demand is roughly linear, the more heat is used, the less electricity is required.

3.4 LOW-TEMPERATURE ELECTROLYSIS

3.4.1 Alkaline electrolysis cells (AEC)

Alkaline electrolysis has been in use for about 90 years and is a proven and mature technology used at commercial scale for production of fertiliser and chlorine. Some of the largest plants to date have been rated over 100 MW and were built to primarily produce ammonia. Heavy water was discovered as a valuable by-product. Plants in Rjukan and Glomfjord in Norway produced 60,000 Nm³/h and 30,000 Nm³/h respectively. All larger electrolysis plants were decommissioned with the arrival and expansion of steam methane reformation in the 1970s.

Alkaline electrolyzers can operate from 10 % of nominal capacity up to full capacity and can cycle between minimum and maximum load in a few minutes. No precious materials are used, which allows for low capital costs. A drawback with alkaline electrolysis is that the electrolyzers must recover and recycle the

potassium hydroxide (KOH)²⁸ electrolyte. Hydrogen is produced between 1 – 30 bar and at a temperature between 40 – 90 °C. Alkaline electrolyzers are cheap, with a capital cost around 1,200 – 1,400 \$/kW and have a comparatively long lifespan of 60,000 to 100,000 hours.

3.4.2 Proton Exchange Membrane (PEM)

Proton exchange membrane were developed to overcome some of the drawbacks of the alkaline electrolyzers. Firstly, PEM electrolyzers do not use a liquid electrolyte and consists of a solid structure which is substantially smaller. PEM electrolyzers can also produce highly compressed hydrogen with a pressure up to 85 bar in commercial units. This reduces the need for compression and thereby the overall cost. They are also more flexible than alkaline electrolyzers which allows PEM electrolyzers to operate flexibly with the grid and possibly provide ancillary services to the power grid by decreasing or increasing production. It can operate between 5 – 100 % of rated capacity.

The lifespan is shorter compared to alkaline electrolyzers, at between 30,000 to 60,000 hours. Additionally, it is more expensive at around 1,500 – 1,800 \$/kW.

3.4.3 Solid Oxide Electrolyser Cells (SOEC)

High-temperature SOEC is a comparatively immature hydrogen production technology that has not seen as widespread commercialisation as alkaline and PEM electrolyzers.

It is rather different and operates at temperatures up to 1,000 °C, but more typically between 600 – 850 °C. This means feedwater is in the form of steam at atmospheric pressure instead. As the SOEC must be operated at a voltage which generate sufficient heat to keep the electrochemical reaction going. If operated below a thermoneutral voltage, the reaction would withdraw heat from the cell components and cool the cell to the point where the reaction stops. To maintain temperature and operation, temperatures of around 850 °C must be maintained either through electrical resistance heating in the cell or from an external heat source.

The main advantage of SOEC is its considerably higher efficiency. When utilising the thermal energy, the electric efficiency can be over 100 %. Since electricity is higher quality and is more expensive than thermal energy, this is a major advantage.

SOEC uses only abundant raw materials. As a result, the risk of cost escalations or potential bottlenecks when scaling production is reduced. SOEC can also operate as a fuel cell and switch between operating as an electrolyser and a fuel cell. It can also operate in co-electrolysis mode and produce syngas from water and carbon dioxide.

However, SOEC is the least developed technology of the three electrolyser technologies. It has not been demonstrated at nearly the same scale as PEM or

²⁸ Or sodium hydroxide (NaOH).

alkaline electrolyzers and suffers from a short lifespan of around 10,000 to 30,000 hours due to the high operating temperatures. Varying the load is possible but can lead to significant thermal stresses. Additionally, SOEC has the highest capital cost of around 2,400 \$/kW.

3.4.4 Copper Chlorine cycle (Cu-Cl cycle) and Sulphur-Iodine cycle (S-I cycle)

The Cu-Cl cycle and S-I cycle are two advanced thermochemical cycles for hydrogen production.

The Cu-Cl cycle works at about 500 °C which is relatively low compared to the 830 °C of the S-I cycle. Both are cycles, meaning compounds are recovered and reused, and both are thermochemical processes researched for use with so called Generation IV reactors. In Japan, the S-I cycle has been run successfully in experiments at the HTTR reactor.

The advantage of the two cycles is the ability to use heat as a large share of the energy input but both processes have a low overall efficiency. In addition to this, both processes work at high temperatures with corrosive materials which places high demands on the equipment used.

Both cycles have low technological readiness and are not considered further in this study.

3.5 COMPARISON OF HYDROGEN PRODUCTION TECHNOLOGIES

There are several estimates for future electrolyser performance. Table 10 and Table 11 shows two estimates, the first based on various sources with different estimates and the second based on IEA estimates [59].

Table 10.

Comparison of techno-economic parameters, based on various sources.

Production method	Stack electricity consumption [kWh/m ³]	Electric efficiency	Lifespan [thousand hours]	Capital cost [\$/kW]
AEC	4.5 – 7.5	80 – 85 %	60 – 90 (90 – 100)	1,200 – 1,400 (900 – 1,000)
PEM	4.2 – 7.5	50 – 84 %	30 – 60 (60 – 90)	1,500 – 1,800 (480 – 1,200)
SOEC	3.1 ¹	>95 %	10 – 30 (40 – 90)	2,400 (1,200)

¹Varies depending on heat input and other factors.

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, SOEC is indeed a very attractive alternative.

Table 11.
Comparison of techno-economic parameters, source IEA [59].

	AEC			PEM			SOEC ²⁹		
	2020	2030	Long term	2020	2030	Long term	2020	2030	Long term
Electrical efficiency [%, LHV]	63 – 70	65 – 71	70 – 80	56 – 70	63 – 68	67 – 73	74 – 81	77 – 84	77 – 90
Operating pressure [bar]	1 – 30	–	–	30 – 80	–	–	1	–	–
Operating temperature [°C]	60 – 80	–	–	50 – 80	–	–	650 – 1,000	–	–
Stack lifetime [thousand hours]	60	90	100	30	60	100	10	40	75
	–	–	–	–	–	–	–	–	–
	90	100	150	90	90	150	30	60	100
Load range [% nominal load]	10 – 110	–	–	0 – 160	–	–	20 – 100	–	–
CAPEX³⁰ [\$/kW_e]	500	400	200	1,100	650	200	2,800	800	500
	–	–	–	–	–	–	–	–	–
	1,400	850	700	1,800	1,500	900	5,600	2,800	1 000

Many comparisons of SOEC with other technologies don't credit the benefit of reducing electricity intensity through increased efficiency and replacement with heat energy. As an indicative estimate, the direct reduction of 25 million tonnes of iron ore would require approximately 60 TWh of electricity, assuming 50 kWh per kg of H₂.

A reduction to 35 – 40 kWh³¹ per kg H₂ would mean that only between 42 – 48 TWh would be required, providing significant savings of electricity.

The final generation capacity necessary to generate the electricity is directly proportional to the reduction in electricity intensity of the hydrogen production. The generation required to provide 60 TWh per year is about 7 GW, almost half of Sweden's total demand in summer. Producing only when prices are low, perhaps 25 % of all hours, means a generation capacity four times larger is necessary – almost 30 GW. This power must not only be generated but also transferred through the transmission system to the consumption.

This poses a significant challenge.

Finally, the direct reduction of steel is not the only sector which depends on hydrogen to decarbonise. Other sectors such as the chemical industry will also need to generate large amounts of hydrogen.

²⁹ Electrical efficiency for SOE does not include energy for steam generation.

³⁰ CAPEX includes power electronics, gas conditioning and balance of plant. The ranges reflect different system sizes and uncertainties in future estimates.

³¹ Approximately 3.1 and 3.6 kWh/Nm³ respectively.

Table 12.

Illustration of reduced strain on the power grid from reducing electricity intensity of hydrogen production. Assumptions which are equal for all are in italics. This does not include heat required for SOEC in the two lower cases.

kWh_e per kg H₂	50	40	35
<i>kgH₂ per tDRI</i>	<i>50</i>	<i>50</i>	<i>50</i>
MWh _e per tDRI	2.5	2.0	1.75
<i>Million tDRI per year</i>	<i>25</i>	<i>25</i>	<i>25</i>
TWh _e per year	62.5	50	43.75
Full load MW _e of 24/7 power production (8760 h)	7,150	5,700	5,000

[illegible]

The iron and steel industry is responsible for over 7 % of global carbon emission. It is more than aviation and shipping combined, or almost as much as the emissions from road transport.

Iron ore is found and mined in the form of Hematite (Fe_2O_3) and Magnetite (Fe_3O_4). Note the different oxidation states³². This ore must be processed and reduced, meaning the oxygen is removed, to metallic iron.

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Today, ore is processed and shipped as pellets which are fired in blast furnaces with coking coal for reduction. This blast furnace route emits between 1.6 and 1.8 tonnes of CO₂ per tonne of steel produced.

Hydrogen can be used instead of fossil carbon as a reductant. This reduces iron ore to Direct Reduced Iron, DRI, or sponge iron. Using hydrogen rather than a fossil source of carbon eliminates CO₂ emissions as long as the H₂ is made from electrolysis of water and powered by zero carbon electricity.

The reduction of hematite requires 54.14 kg of H₂ per tonne of iron. As there are some impurities of gangue minerals and the DRI is closer to 95 % metallic iron, the actual hydrogen required is approximately 50 kg of H₂ per tonne of DRI.

Approximately 50 kWh of electricity is required to produce one kg of hydrogen, depending on the type of electrolyser. Further equipment such as compressors, heating and ancillary loads add losses and additional loads.

With 50 kgH₂/tDRI and 50 kWh/kgH₂ it takes 2.5 MWh/tDRI. Table 13 shows the approximate requirements to reduce 25 million tonnes of DRI per year, with different assumption for the amount of electricity required per kgH₂.

Table 13.

Illustration of reduced strain on the power grid from reducing electricity intensity of hydrogen production. Assumptions which are equal for all are in italics. This does not include heat required for SOEC in the two lower cases.

kWh_e per kg H₂	50	40	35
<i>kgH₂ per tDRI</i>	<i>50</i>	<i>50</i>	<i>50</i>
MWh _e per tDRI	2.5	2.0	1.75
<i>Million tDRI per year</i>	<i>25</i>	<i>25</i>	<i>25</i>
TWh _e per year	62.5	50	43.75
Full load MW _e of 24/7 power production (8760 h)	7,150	5,700	5,000

Approximately 1.5 % of global iron is mined in Sweden. All iron ore must eventually be reduced without producing greenhouse gas emission. A rough estimate of the hydrogen required to reduce all of the world's iron ore is approximately 80 million tons per year. Producing this amount of hydrogen would consume 4 000 TWh per year to power 5 000 GW of continuously running electrolyzers. The amount of electricity equals 16 % of global electricity production.

The production of such enormous amounts of hydrogen comes with some unique features. It is an extremely capital intensive process which benefits from high

utilisation. A relatively risk-free assumption is that the DRI furnace will run as a static base load.

The reduction process with coal is exothermic, but with hydrogen it is an endothermic process with significant heat losses. Hydrogen needs to be heated to 900 °C or more before entering the reduction reactor. Electric heating throughout the process is another significant base load. Several other processes also have base load heat and electricity requirements.

To turn the metallic iron into steel required carbon, but without carbon emissions. Adding such “zero-carbon-carbon” poses a challenge.

A mining operation also requires a significant amount of energy for other purposes such as powering operations, buildings, offices, processes as well as providing heating for all of these facilities.

4.1.2 A concept to integrate nuclear energy

A nuclear combined heat and power plant, providing electricity and heat for integration into hydrogen and steel production could offer several synergies.

An advanced reactor with 200 MWth output based on the Xe-100 is chosen for integration. The reactor is capable of outputting heat at 750 °C. This in turn provides steam with a temperature of 670 °C. Operating steam turbines above 605 °C requires novel and expensive alloys, therefore a spray coolers cooler cools the steam to a suitable temperature before entering the steam turbines.

The 670 °C steam enters the SOEC stack where extra electricity supplied to the stack heats the steam to between 850 and 900 °C. Carbon dioxide is also supplied to the SOEC cell for co-electrolysis. Carbon monoxide, CO, and hydrogen exit the SOEC stack at a temperature of 900 °C.

To reduce one tonne of iron requires 54.14 kg of H₂ on a purely stoichiometric basis. But because the reduction process is strongly endothermic and because not all hydrogen reacts with iron it is necessary to supply several times more hydrogen than actually reacts with hydrogen. This is called the λ -factor and is recommended to be around three times the amount that is required stoichiometrically. Thus, every tonne of iron pellets requires feeding approximately 150 kgH₂ into the reduction reactor. The remaining hydrogen and carbon monoxide exists the top of the reduction reactor as top gas along with carbon dioxide and steam. The gases are separated from each other and heat recovered in heat exchangers. Purified hydrogen is thus recirculated and not consumed. Before entering the reactor, this hydrogen must again be heated to around 900 °C.

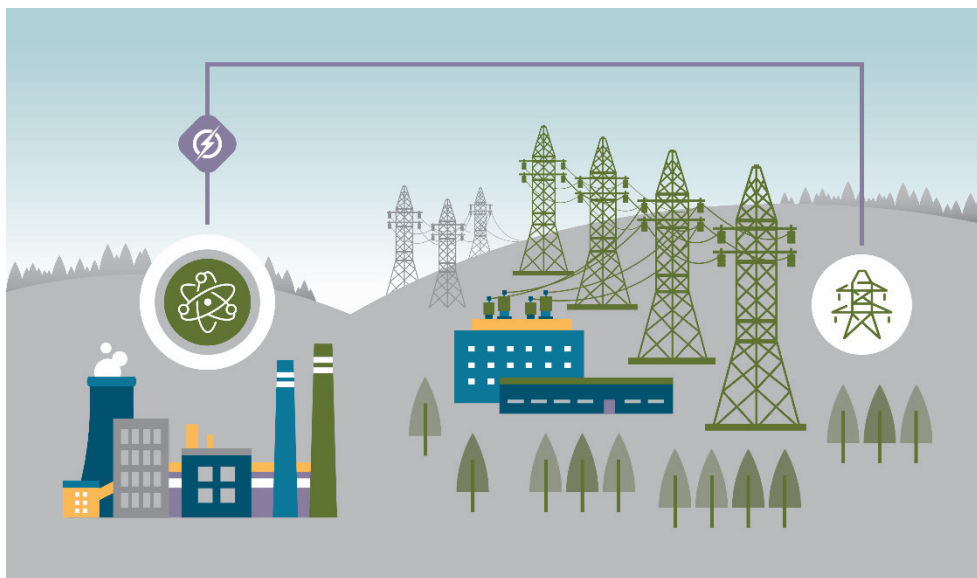
In addition to uncertainties about the amount of hydrogen consumed in the reduction process and the heat balance of the reduction process there are several technical and practical questions which need to be investigated. E.g. it possible to heat such significant amounts of hydrogen continuously? How much carbon should be added to the sponge iron, if any at all? The customer receiving the iron may also want to add carbon themselves. The practical layout of the process to

maximise the heat recovery throughout the process, including the pelletisation plant is also important.

Several practical questions relating to a safety case for the placement of a nuclear reactors must also be answered to ensure safe operations and adequate access to cooling.

Several studies were useful in the preparation of this work [61]–[70]. To properly assess the potential of nuclear energy integration in steel production requires a dedicated, focused effort.

5 Uses for existing nuclear power plants



New and advanced reactors offer more market opportunities, thanks to higher temperatures and the ability to integrate design considerations already in early design stages. However, existing reactors also offer opportunities beyond electricity production, e.g. industrial electricity applications such as datacentres, ancillary services to the power grid or low grade heat for agricultural purposes.

In Switzerland the situation is the opposite, and all operating reactors also provide heat. While none of the Nordic nuclear reactors provide heat in any applications, there have been plans for almost all reactors to provide district heating.

One example from Switzerland is the THERMOCUTLA project, where the 1190 MW_e Leibstadt BWR provides residual heat to the Leuenberger garden centre.

Section 1.2.2 Steam extraction describes three ways in which it is possible to extract steam from existing nuclear power plants with varying degrees of actions.

Except for residual low-grade heat, any use for nuclear heat will require some type of design modifications. However, providing electricity to a collocated industrial application, e.g. a data centre, would be possible. Industrial electricity applications which require a stable grid connection and security could be one potential avenue to explore for existing nuclear plants. Indeed, Oskarshamn nuclear power plant has developed a data centre company called Vaultige.

5.1 ANCILLARY SERVICES

The past year has seen balancing costs, price differences and congestion incomes for the Swedish TSO, Svenska Kraftnät, rise dramatically and set new records. Svenska Kraftnät has collected approximately 30 billion SEK in congestion income in 2020 and 2021.

Despite the commissioning of the new transmission line Sydvästlänken, transmission constraints are also at an unprecedented high.

The large price difference has, together with significant volatility in power prices, led to the rise of spectacular profile and balancing costs.

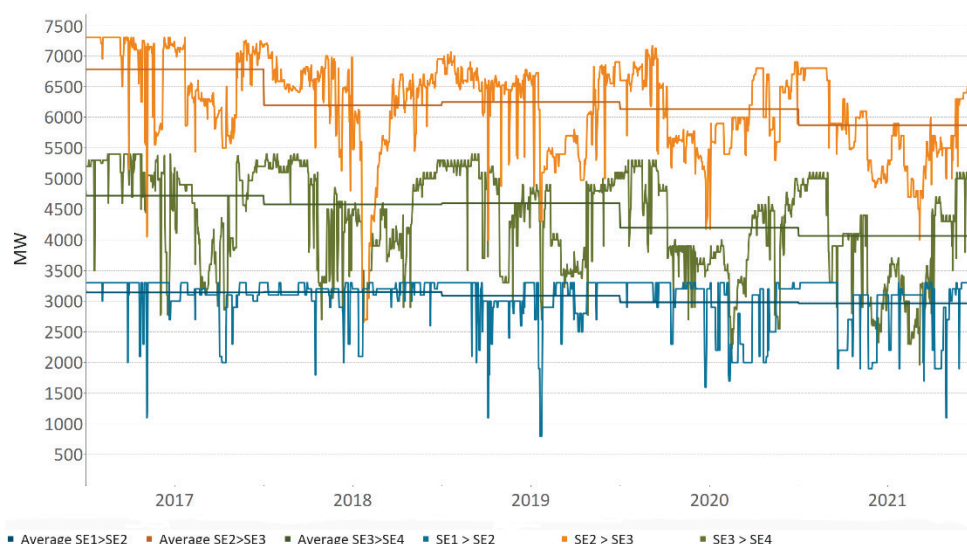


Figure 33.

Transmission capacity allocated to the day ahead market has been dropping since 2016/17.

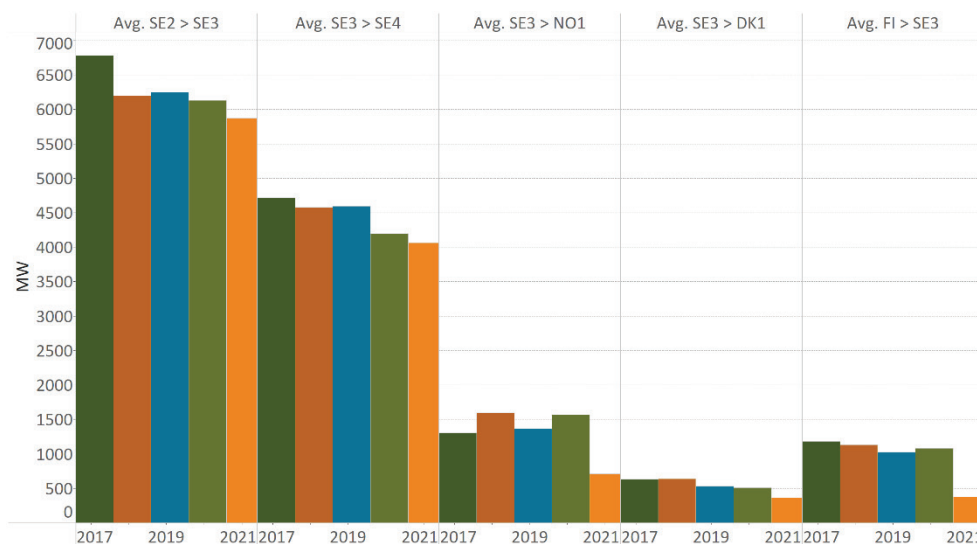


Figure 34.

Average transmission capacities between some Nordic price areas.

Restrictions in transmission capacity are increasingly correlated with reactor outages as the power system has become more sensitive to different disturbances.

This development clearly demonstrates the importance of ancillary services to provide frequency stability, voltage stability and rotor angle stability. However,

while spending on balancing and other measures increases there have not been any actions taken to compensate nuclear power plants for the services they provide.

Existing nuclear power plants could theoretically greatly expand the amount of services they provide within energy storage, grid services and operational flexibility. But most, if not all, actions require some investment while lowering the capacity factors. Without any way to be compensated, such investments are impossible to motivate for plant owners.

Examples of services nuclear plants could provide, with varying degrees of investment and interventions, include:

- Nuclear operational flexibility
 - Shallow flexible operations
 - Deep flexible operations
 - Extended Low Power Operations (ELPO)
 - Seasonal Shutdown
- Grid services
 - Voltage support and reactive power, Var
 - Inertia
 - Primary frequency control
 - Secondary frequency control
 - Ramp products
 - Capacity market
- Energy storage
 - Thermal energy storage
 - Battery energy storage

Some of the above services now have developed markets and compensation mechanism but most services are still not valued.

6 Conclusions and future work

Decarbonisation of energy will require a broad approach to tackle hard to abate sectors, not least sectors beyond electricity. With the appropriate incentives and measures, nuclear could play an important part on the decarbonisation journey. There is now an almost overwhelming amount of information about nuclear energy. In the past year, the interest in nuclear beyond electricity applications has risen dramatically with a large number of reports published. Funding for nuclear energy projects beyond electricity is also picking up, although there is still a lack of concrete projects and research focused on detailed implementation. If enabled, nuclear energy can contribute to ensuring security of supply, competitiveness and sustainability targets are met.

This report has reviewed several applications and possibilities for nuclear beyond electricity. Most, if not all, are well suited applications for nuclear energy, although many challenges remain to be addressed. For some applications, e.g desalination and ancillary services, it is important that the value provided is compensated fairly. Without compensation mechanisms, there is no incentive. A lot of attention is focused on flexible operations and hydrogen production, but other strategies and applications are also worth pursuing.

Other applications like integration of SMRs in steel production seem to hold great potential, but require focused and dedicated efforts to tease out complicated (and sometimes confidential) technical details.

A nuclear-coupled Direct Air Capture system (DAC) was also analysed. Such a system could potentially achieve a levelized cost of DAC around €50/tCO₂ which looks very competitive, especially when taking into account the current emission price of CO₂ (around or above €80/tCO₂ in the EU). Work on demonstration projects is ongoing, but more research is needed to make nuclear-coupled DAC systems a reality.

Several applications were left outside of the scope intentionally but deserve their own review as well. Two such examples are nuclear energy integration in production of biofuels and in shipping.

With adequate support and incentives, nuclear energy could play an important role 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. 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.

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