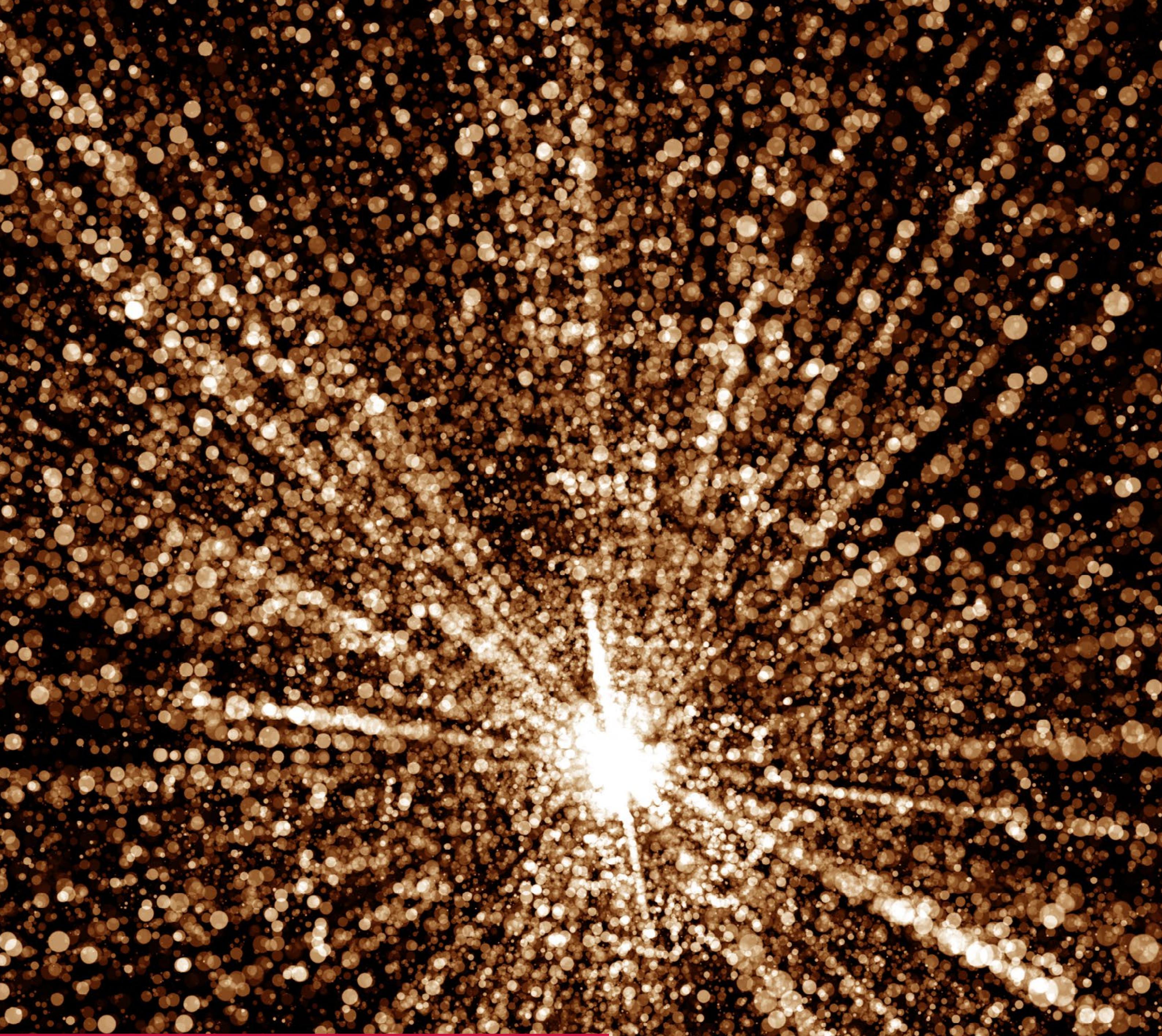

Nuclear cogeneration: civil nuclear energy in a low-carbon future

POLICY BRIEFING

THE ROYAL SOCIETY

Policy briefing
Politics and science frequently move on vastly different timescales. A policymaker seeking evidence on a new policy will often need the answer in weeks or months, while it takes years to design and undertake the research to rigorously address a new policy question. The value of an extended investigation into a topic cannot be understated, but when this is not possible good evidence is better than none.

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Nuclear cogeneration: civil nuclear energy in a low-carbon future policy briefing
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Contents

EXECUTIVE SUMMARY

Executive summary

Nuclear power has provided low-carbon electricity for 60 years and today contributes 17% of the UK's total consumption on an annual basis. It could provide more. There are two key issues that impact on the utility of current nuclear: it is most economic when run at high output, and 65% of the energy generated is lost as waste heat.

Future nuclear power must work with a generating system dominated by intermittent renewable energy. The gap between intermittent generation and electricity demand is currently accommodated using gas fired generation which produces carbon dioxide. The introduction of more intermittent renewable generation coupled with the need to reduce gas fired generation demands greater flexibility from nuclear generation if it is to remain an important part of our energy mix.

This briefing examines how the use of nuclear power could be expanded to improve the overall efficiency and energy system resilience to meet the net-zero 2050 goal. It achieves this by considering cogeneration, where the heat generated by a nuclear power station is used not only to generate electricity, but to address some of the 'difficult to decarbonise' energy demands.

A range of options for cogeneration exist, using either low or high temperature heat. For low temperature heat, space heating notably via district heating, holds potential. Desalination of water is also of interest, though not currently in great demand in the UK. High temperature heat from advanced reactors would introduce an interesting set of decarbonising strategies, not least in the production of low-carbon hydrogen. Whilst this would represent an untested approach to hydrogen production, the practicality, synergy and costs appear to be attractive.

For example, hydrogen could be produced at times when electricity demand is low. This would likely be associated with new builds, and users of the high temperature heat would have to be co-located with the power plant.

Other cogeneration interests that should be considered range from the manufacture of synthetic fuels and ammonia to medical isotopes. The development of a cogeneration capability that includes isotope production represents a commercial opportunity due to a global shortage of key radioisotopes. Further, there is potential to use nuclear to power direct air capture of carbon dioxide.

Small modular reactors (SMR[1]) present a particularly interesting proposition for cogeneration. Their design can be either current type 'Generation III' low-temperature reactors or future design 'Generation IV' high-temperature reactors (known as advanced modular reactors, AMR, in the UK). SMR designs would enable the thermal output from the reactor to be matched to the thermal/electrical requirements of a single or cluster of industrial processes.

The building of nuclear reactors closer to industrial clusters or areas of the population to utilise the heat available would require support from the public and attention to regulations and licensing.

A few nuclear cogeneration facilities already exist in several countries. Whilst the economic case to adapt the UK's existing reactor fleet for cogeneration would be challenging, both planned and future UK nuclear reactors could accommodate cogeneration applications. This would help the UK increase the flexibility of its electricity system to support a higher proportion of renewable generation and allow deep decarbonisation of otherwise challenging energy-intensive processes. It also offers the opportunity to create a new industry with export potential.

1. SMR is used internationally to describe a variety of commercial nuclear reactors under 300 MW electrical output. The UK Government makes a distinction between small generation III reactors (termed SMRs) and generation IV reactors (termed AMRs). The term SMR is used in this document to refer to both UK defined reactor types.

Introduction

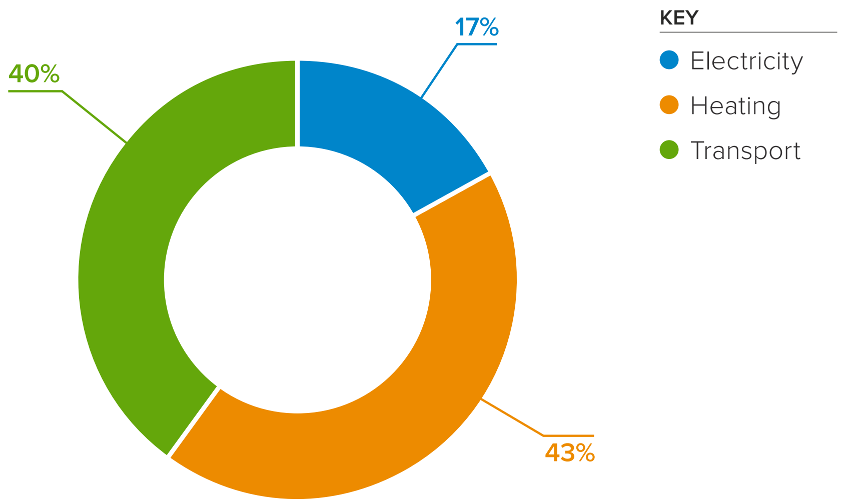
Potential role of nuclear and nuclear cogeneration in helping deliver net-zero by 2050

A major expansion in low-carbon power will be required to meet the 2050 net-zero carbon emissions target. Substantial progress in decarbonising the current level of electricity generation has been made but that will only tackle 17% of the UK's current total energy consumption.

Heating and transport are the largest energy users (Figure 1); process and space heating, as well as 'difficult to reach' transport sectors (aviation, heavy-duty vehicles, and shipping) will be particularly challenging to decarbonise using electricity.

FIGURE 1

UK energy consumption in 2018[2].



This policy briefing sets out to explore the additional uses of nuclear energy beyond electricity, such as using high temperature heat to fuel processes directly (e.g. chemical synthesis), or low temperature heat for district heating (Figure 2). The briefing also considers how a nuclear plant can be used flexibly, switching from the production of electricity when needed to another application when electricity demand is low. This would allow nuclear energy to sit more comfortably within an energy supply dominated by intermittent renewable generation.

The principle focus of this report is heat. Nuclear reactors produce heat on a vast scale. A typical nuclear power station produces around 3.4 GW of heat (~100,000 domestic gas boilers), which is used to generate around 1.2 GW of electricity. Currently, around 65% of the energy is lost in the conversion as waste heat.

Current status of nuclear electricity generation in the UK

There are 15 operational commercial nuclear reactors located at eight different sites in the UK (Table 1). Of these, only Sizewell B is planned to still be in operation in 12 years' time.

In 2019, around a third of the UK's low-carbon energy came from nuclear power. New nuclear station plants are planned but of these, construction has only started on Hinkley Point C, a Generation III twin European Pressurised Reactor station with a total generating capacity of 3.26 GW (Figure 3).

2. Department for Business, Energy & Industry Strategy. 2019 Energy Consumption in the UK (ECUK) 1970 to 2018. See https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/820843/Energy_Consumption_in_the_UK__ECUK__MASTER_COPY.pdf (accessed 15 October 2019).

FIGURE 2

Potential nuclear cogeneration options for nuclear reactors.

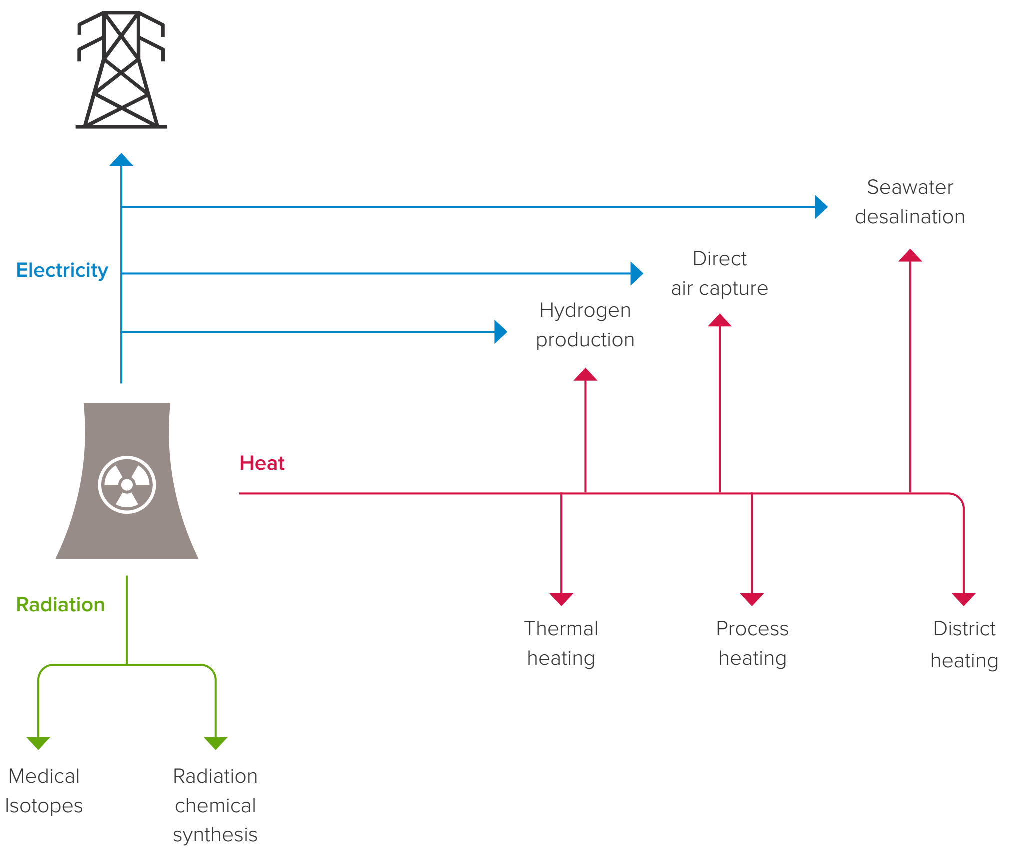


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TABLE 1

Nuclear power stations in the UK (April 2020).

Number of reactor sites	Reactor type	Total electrical generation capacity (GWe)	Reactor output temperature (°C)	Thermal efficiency (%)	Total waste heat (GWth)
7	Advanced gas-cooled (two reactors per unit)	~1.2	640	42	~1.6
1	Pressurised water (Sizewell B)	~1.2	<300	34	2.3
Total UK generation		~9.6			~13.5

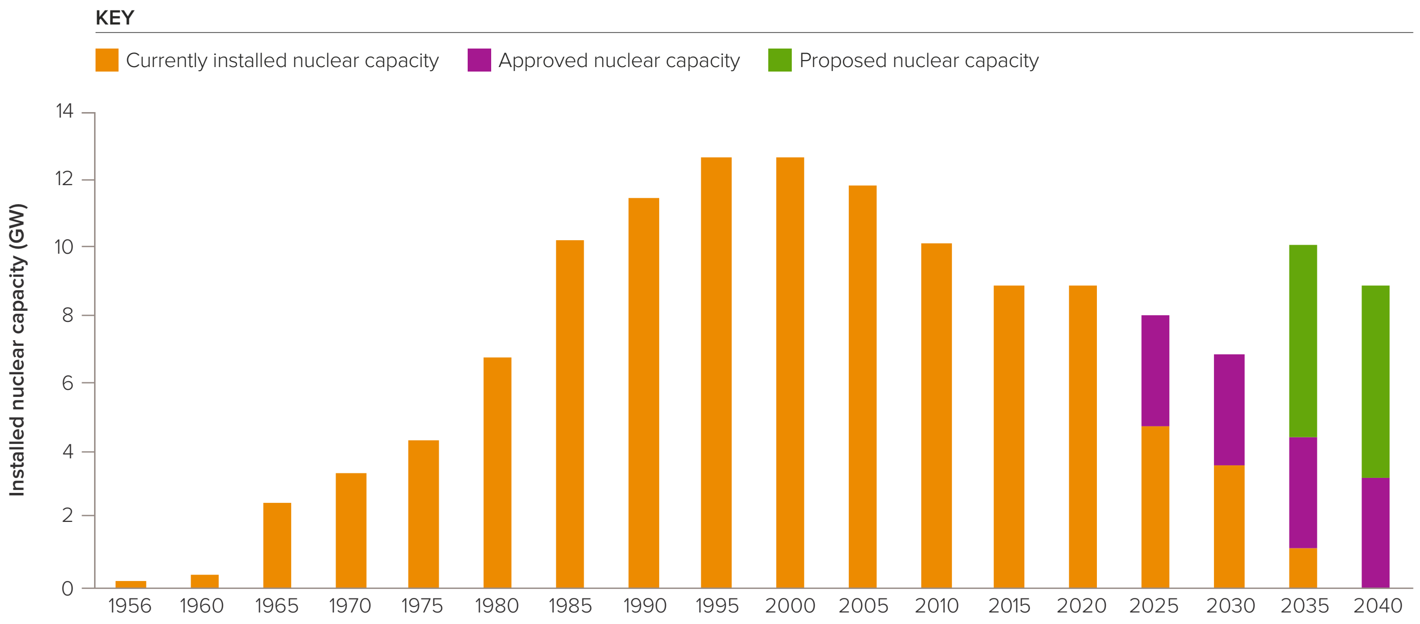
The current generation of UK nuclear power plants produce large amounts (GWs) of electricity, but operate at a constant output and have, to date, provided only baseload electricity. This was not a problem when electricity demand fluctuations could be met by switching on and off gas-powered stations. However with increasing proportions of generating capacity delivered by intermittent renewable energy coupled with the need to reduce gas fired generation, greater flexibility from nuclear generation will be required if it is to remain an important part of our energy mix. Unfortunately, if many current nuclear reactors attempt to meet these grid demand fluctuations, known as load following, the changes to the reactor environment, such as temperature fluctuations are detrimental to the lifespan of the reactor components and its fuel. Light Water Reactors can change their output by some percent and therefore have some load following capability however, large transients will impact reactor operation and lifetime, resulting in an economic penalty.

The role for nuclear energy generation is changing and will have to adapt to this new environment. Developing cogeneration technologies is one way to improve the flexibility, competitiveness and utilisation of the energy generated by nuclear reactors and improve the productivity of this primary source of low-carbon energy.

Limited nuclear cogeneration is already practised elsewhere in the world. Whilst there are no facilities in the UK, systems have been run in the past (see Case study 1). As we move away from using carbon emitting generation to address the difference in supply by low-carbon generation and demand, now is the right time to consider how nuclear can play its part in the UK energy mix.

FIGURE 3

UK installed nuclear capacity: operating, approved for construction and planned plants as of 2020[3].



Note: Approved for construction (Hinkley Point C) and planned plants (Sizewell C and Bradwell B), as of August 2020.

3. Department for Business, Energy & Industry Strategy. 2019 Special feature - Nuclear electricity in the UK. See https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/789655/Nuclear_electricity_in_the_UK.pdf (accessed 23 October 2019).

INTRODUCTION

CASE STUDY 1

Calder Hall Cogeneration

The world's first nuclear power station operating on a truly commercial scale was Calder Hall in Cumbria. While Calder Hall's original purpose was to generate plutonium for Britain's nuclear deterrent programme, it had the capacity for significant electricity generation (196 MWe), provided process heat for the Sellafield site and generated isotopes for industrial, medical and research purposes. A large portion of the station's output was reserved for the Sellafield site which required a significant and reliable power supply.

The Calder Works were comprised of four reactors, arranged in pairs (Calder Hall A and B), these were served by two turbine halls and cooled by four cooling towers (image below). Construction of Calder Hall began in 1953 with all four reactors connected to the grid by 1956. The Calder Hall reactors were originally designed for a 20-year life, but they operated for 47 years, closing in 2003.

Calder Hall produced low- and high-pressure steam for process use within reprocessing and other industrial processes, and for building heat at Sellafield and in Calder Hall itself (i.e. stairwells, control room, etc.)[4,5].

Calder Hall also produced radioisotopes for medical, industrial and research applications including cobalt-60. Cobalt-60 has several uses such as in radiotherapy for cancer treatment, agriculture (pest sterilisation), industrial thickness gauges, weld inspection (industrial radiography) and sterilisation of medical equipment and other materials.

Reprocessing plants at Sellafield were built to allow specific isotopes of elements, such as plutonium and uranium, to be separated from irradiated material[6].

Plutonium-238 generates significant amounts of heat during radioactive decay, radioisotope thermoelectric generators (RTGs) can use this heat to make electricity, providing a very long-lived power source, as employed in deep space probes such as Voyager 1&2 and Cassini[7, 8, 9, 10]. This isotope was used in heart-pacemakers and ocean navigational buoys[11, 12].

Another important isotope was carbon-14, which was produced by irradiating cartridges of aluminium nitride[13]. This was sent to the Radiochemical Centre in Amersham for incorporation into radioactively labelled organic compounds for tracer studies in medical and biological experiments[14].

Image
Calder Hall reactor suite.

4. Nuclear Decommissioning Authority. 2007 Calder Hall Nuclear Power Station Feasibility Study. See (https://tools.nda.gov.uk/publication/nda-calder-hall-nuclear-power-station-feasibility-study-2007/ (accessed 23 October 2019).
5. International Atomic Energy Agency. 1998 Nuclear Heat Applications: Design Aspects and Operating Experience. See https://www.iaea.org/publications/5353/nuclear-heat-applications-design-aspects-and-operating-experience (accessed 23 October 2019).
6. United Kingdom Atomic Energy Authority. 1961 British Experience in the Technical Development of Nuclear Power Reactors. See https://www.osti.gov/servlets/purl/4060892 (accessed 23 October 2019).
7. Lange RG, Carroll WP. 2008 Review of recent advances of radioisotope power systems. Energy Conversion and Management, 49, 293-401. (doi: 10.1016/j.enconman.2007.10.028).
8. Champier D. 2017 Thermoelectric generators: A review of applications. Energy Conversion and Management, 140, 167-181. (doi: 10.1016/j.enconman.2017.02.070).
9. He J, Tritt TM. 2017 Advances in thermoelectric materials research: Looking back and moving forward. Science, 357, eaak9997. (doi: 10.1126/science.aak9997).
10. American Institute of Aeronautics and Astronautics. 2006 Mission of Daring: The General-Purpose Heat Source Radioisotope Thermoelectric Generator. See https://fas.org/nuke/space/gphs.pdf (accessed 13 May 2020).
11. Nuclear Decommissioning Authority. 2015 Insight into Nuclear Decommissioning Issue 19. See https://www.gov.uk/government/publications/insight-into-nuclear-decommissioning-edition-19 (accessed 23 October 2019).
12. Flowers BH. 1976 Sixth Report of The Royal Commission on Environmental Pollution: Nuclear Power and the Environment. Technology & Engineering.
13. Hastings C et al. 2016 Preparation of Waste Fingerprints for the Miscellaneous Beta Gamma Waste Feeds to the Box Encapsulation Plant at Sellafield. WM2016 Conference, 16080.
14. United Kingdom Atomic Energy Authority. 1961 British Experience in the Technical Development of Nuclear Power Reactors. See https://www.osti.gov/servlets/purl/4060892 (accessed 23 October 2019).

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Applications for nuclear cogeneration

The heat generated by civil nuclear reactors can be extracted at two points (Figure 4):

- **Higher temperature heat** can be accessed before the turbine generator in the secondary cooling circuit
- **Lower temperature 'waste' heat** can be extracted from the steam turbine exhaust

With nuclear cogeneration, high-temperature heat can be used to drive a turbine generator to create electricity, supply heat to industry or be stored for later use. Low-temperature heat can be used by industry or used to heat homes (Figure 5).

In both situations, the reactor can be used to generate electricity and supply heat, or to switch between electricity and heat.

It is possible that existing power plants could be retrofitted to accommodate heat extraction at both points. However, given the inherent difficulties in evaluating the whole installation and impact on electrical output of a plant, it is considered that in general, retrofitting is unlikely to give as great an economic return as an integrated optimised design in a new build.

FIGURE 4

Simplified schematic of a PWR nuclear power plant showing cogeneration extraction and return points. The primary circuit cools the reactor core. The secondary circuit extracts heat for use in the steam turbine. The two circuits are separated within the heat exchanger.

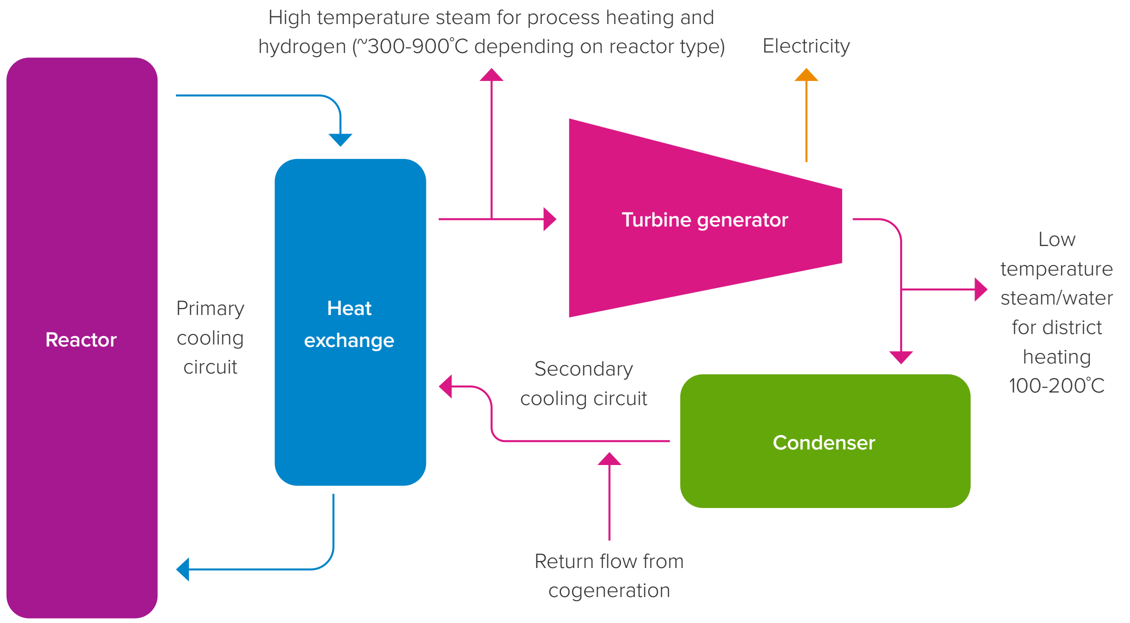
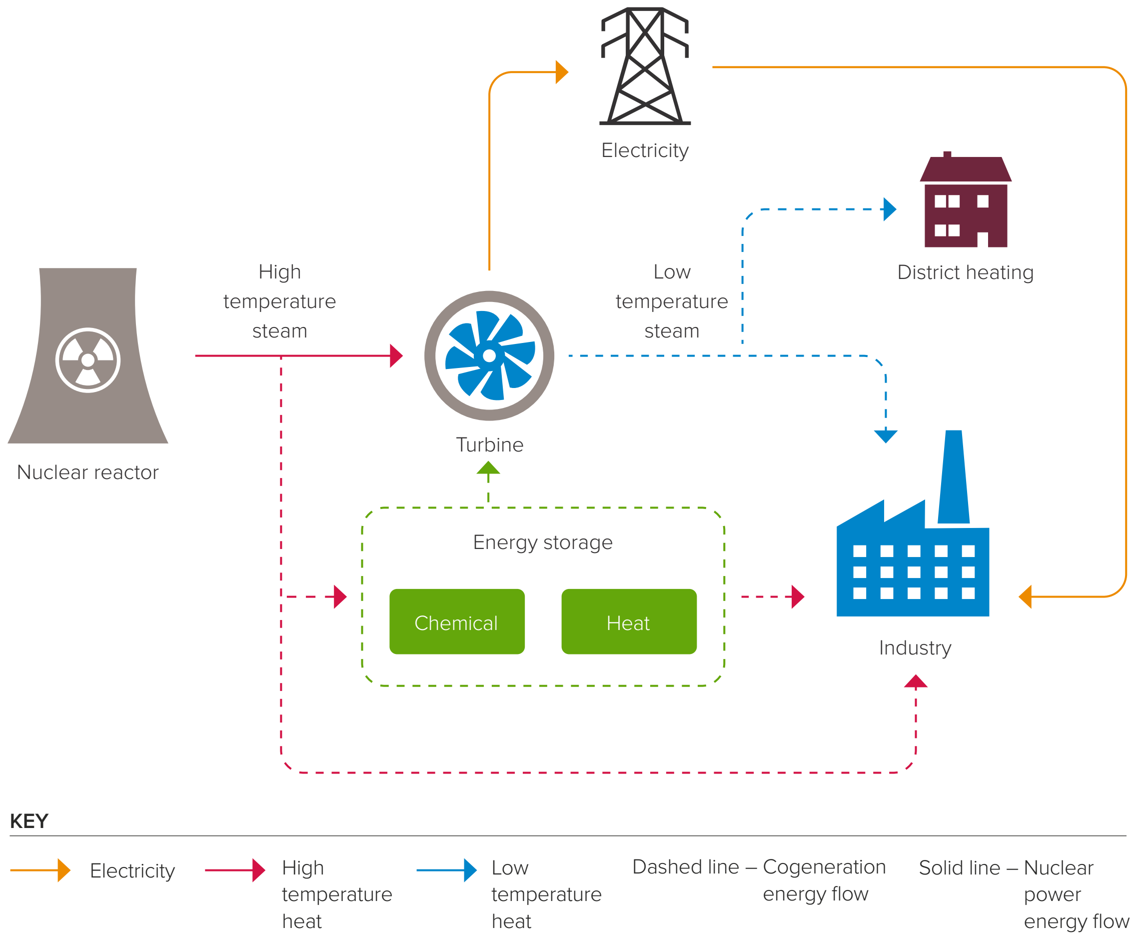


FIGURE 5

Heat use in nuclear cogeneration.



1.1 An overview of cogeneration and reactor type

The two principal factors that influence the application of nuclear energy to heat cogeneration are:

a. The nuclear power plant design and operating temperature (Figure 6)

b. The reactor power output

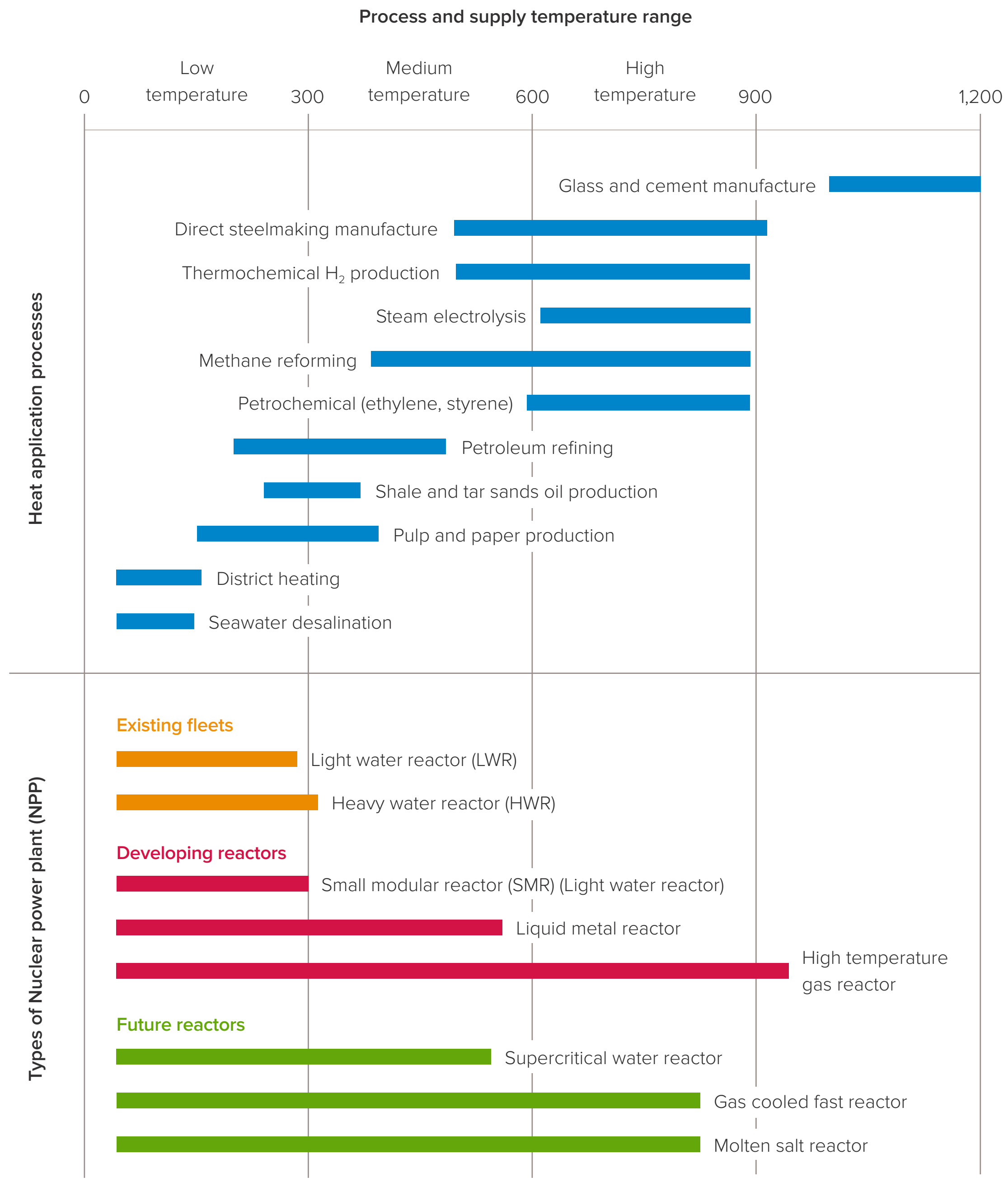
All reactor types (Generation II, III, IV, and Fusion – see Annex B for detail) can provide relatively low-temperature post turbine steam for applications such as district heating and desalination. These plants can operate a considerable distance away from the application as the steam/heat transmission losses are relatively small. In this regard, the size of the reactor is of minor importance, and the suitability is governed by the usual economic, political and regulatory considerations.

For cogeneration applications requiring higher temperature steam (e.g. for hydrogen production), certain Generation IV reactors (e.g. Liquid Metal Cooled Reactor, Very-High Temperature Reactor, High Temperature Gas-Cooled Reactor (HTGR), etc.) could, in principle, be better suited as they are designed to operate at considerably higher temperatures (above 600°C). However, a challenge for such applications is the practical need for proximity to the process plant due to high steam/heat transmission losses. The deployment for such plant for commercial use will take time and developmental funding.

Cogeneration applications using low-temperature and high-temperature heat differ in many aspects of operation, as highlighted in the following sections.

FIGURE 6

Temperature ranges of heat application processes and types of nuclear power plant[15]



15. International Atomic Energy Agency. 2017 Opportunities for Cogeneration with Nuclear Energy. See https://www.iaea.org/publications/10877/opportunities-for-cogeneration-with-nuclear-energy (accessed 31 October 2019).

1.2 Low-temperature cogeneration

1.2.1 District heating

The heating of homes and offices is a major contributor to carbon dioxide emissions. In the UK, most homes are heated using natural gas (Figure 7). In 2018, this resulted in the emission of 65.9MtCO_2, accounting for 18% of all UK carbon dioxide emissions.

District heating offers one solution to reducing carbon emissions by providing space and water heating for a group or district of buildings from a large central heating source. Typically, district heating uses a fossil fuelled or household waste incineration combined heat and power plant. Heat is distributed to buildings using insulated pipes. Important aspects of district heating systems are:

- the scale, density, and phasing of the heating demand
- backup systems in case of failure
- the installation cost of the distribution network

In the UK, conventional district heat networks provide only 2% of the overall heat demand across residential, public, commercial and industrial sectors; 17,000 networks that supply 500,000 consumers[16]. Recently, the UK Government announced a £320 million Heat Networks Investment Project which aims to increase this coverage to 18% of UK heat demand by 2050[17]. Currently, none of these proposed UK district heating projects involve nuclear cogeneration.

From the early deployment of civil reactors, heat from the reactor has been used in several countries to power district heating networks. To date, there have been around 500 reactor-years of experience including:

- The Ågesta reactor, south of Stockholm, produced 10MW of electricity to the grid and between 50-70MW of heat to the suburb 'Farsta' in Stockholm between 1964 and 1974.
- In China, the low-temperature Yanlong reactor, which was completed in 2017, produces 400MW of heat exclusively for district heating. China has now also built a pilot nuclear reactor to provide heat to towns and cities in the colder northern regions (see Case Study 2).

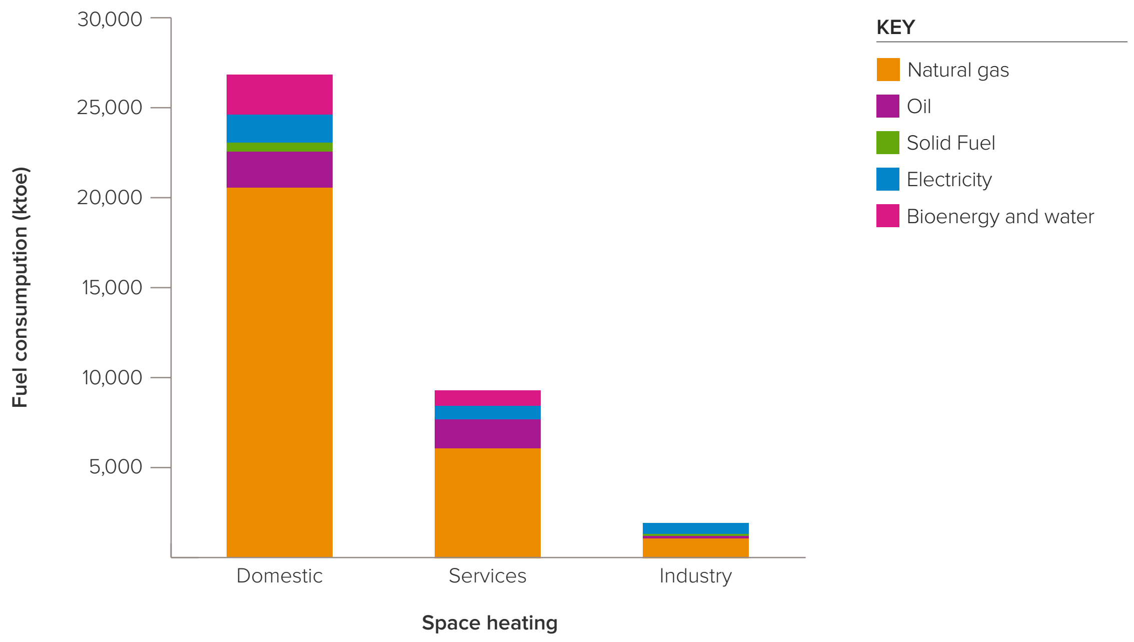
16. The Association for Decentralised Energy. 2018 Market Report: Heat Networks in the UK. See https://www.theade.co.uk/assets/docs/resources/Heat%20Networks%20in%20the%20UK_v5%20web%20single%20pages.pdf (accessed 23 October 2019).
17. Heat Networks Investment Project. 2018 Delivering Financial Support for Heat Networks – England & Wales. See https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/748477/hnip-launch.pdf (accessed 16 October 2019).

Most of the nuclear district heating has been developed within northern European or former Soviet states as cold climate and long heating periods create favourable conditions for district heating and cogeneration development. Water at around 100˚C at low pressure is required and is readily available from Generation II, III and III+ reactors.

A district heating system utilising the waste energy from a typical light water reactor increases the overall efficiency of the power station, depending on heat demand (e.g. season) to over 80%[18].

FIGURE 7

UK heat consumption for space heating by sector and fuel (2018)[19].



Note: Services include community facilities, schools, emergency services, health services, military, offices, retail, and storage. Kilo tonnes of oil equivalent (ktoe) is a large-scale measure of energy.

18. Partanen R. 2017 Decarbonizing cities: Helsinki metropolitan area. See http://energyforhumanity.org/resources/downloads-en/decarbonising-cities-helsinki-metropolitan-area/ (accessed 05 December 2019).
19. Department for Business, Energy & Industrial Strategy. 2019 Energy Consumption in the UK. See https://www.gov.uk/government/statistics/energy-consumption-in-the-uk (accessed 05 December 2019).

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1.2.1.1 Costs

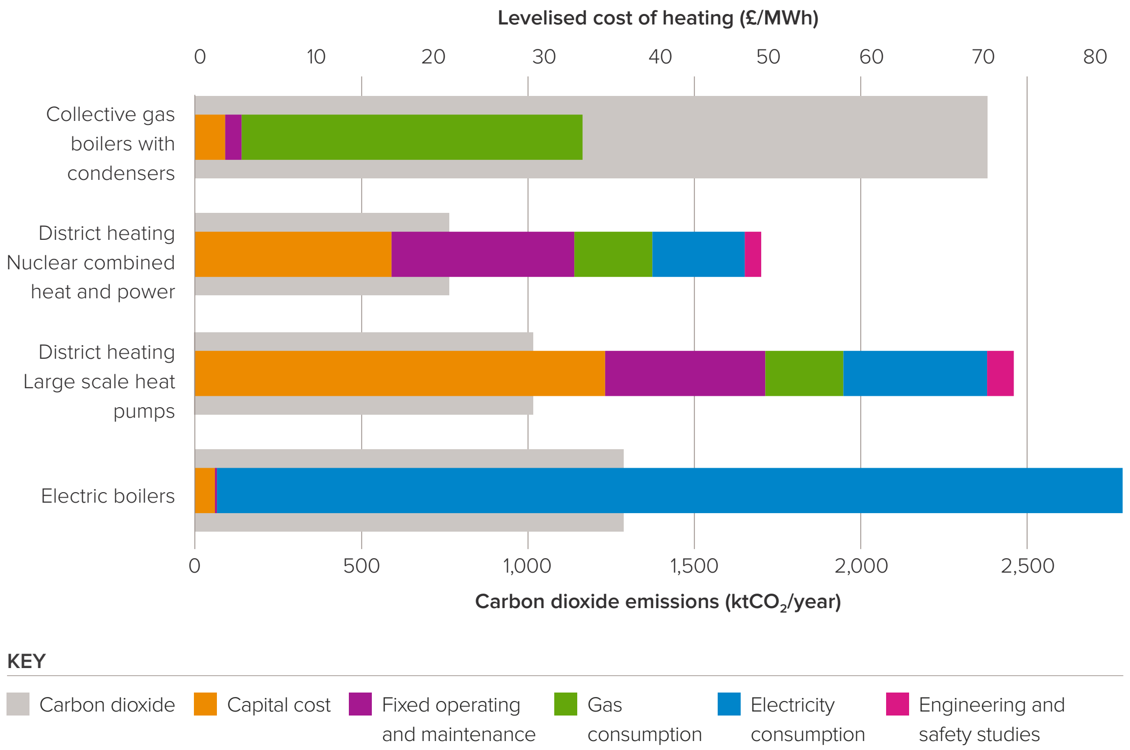
Costs arise from three factors:

- The most significant is the investment in the heat transmission network. In certain locations existing heating networks may mitigate this cost, however construction costs are lower when part of new housing or commercial development.
- If part of the heat from the secondary system is used for heating, then the thermal efficiency (electricity generation) will decrease and hence cause an associated loss of production.
- The modification of the nuclear power plant itself.

In one example, cost scenarios for nuclear district heating in Lyon, France, were explored to breakdown the levelised cost of the heat to supply an extensive network covering 103km^2 (1,122,000 inhabitants) (Figure 8). According to these scenarios, the annual energy bill of gas boilers and electric boilers were 111% and 135% higher respectively than nuclear district heating (based on 2015 energy prices). Nuclear district heating only becomes more expensive when the electricity prices were 3.5 times higher than natural gas prices. However, the initial investment is significantly higher.

FIGURE 8

Cost breakdown scenario of heating options for Lyon, France[20]



Note: Levelised cost of heating: cost of generating heat for a specific system at a specific temperature of the working fluid. In this scenario, gas boilers are used in Nuclear District Heating during peak demand. GHG emission of electricity varies with generation mix.

20. Leurent M et al. 2018 Cost and climate savings through nuclear district heating in a French urban area. Energy Policy, 115, 616-630. (doi: 10.1016/j.enpol.2018.01.043).

1.2.1.2 Infrastructure requirements

Transmission losses are generally small and nuclear power plants can be sited up to 100km from the demand[21], well within the distance between, for example Hinkley Point (Somerset) and Bristol. The capital cost of heat extraction technology in the nuclear power plant is considered negligible compared to the whole if incorporated in the build phase. Safety concerns relate to reactivity feedback mechanisms, although no instances have been reported.

There is a broad consensus that the required modifications to nuclear power plants for cogeneration represent no specific technical difficulties[22]. In practice, to produce heat as well as electricity, the reactor will need to run at a near-constant rate (maintaining a relatively stable core power) whilst throttling heat production up and down to meet demand. There are a variety of technical solutions to achieve this, but to date they have not been greatly considered by vendors.

1.2.1.3 Research and development

Recent UK focused studies have considered the potential for district heating in a scenario involving Small Modular Reactors (SMR, see Annex B: Definitions)[23].

An analysis of heat demand data suggests there are around 50 conurbations in the UK potentially suitable for hosting SMR-powered district heating networks. The theoretical SMR capacity needed to energise all these networks would be 22 GWe.

One UK study identified Hartlepool as a new-build facility with a particularly strong potential for nuclear district heating; using a 7.5km radius, the network potential could include Stockton-on-Tees, Middlesbrough and Hartlepool[24]. Scenarios have considered the use of the Westinghouse AP-1000 and Areva Evolutionary Pressurised Reactor. Focus group analysis in Teesside identified that cost, reliability, performance and design, and ownership and contract length were the main concerns.

The UK government has identified heat networks (district heating) as an important part of their plan to reduce carbon and cut heating costs. It is seen as one of the most cost-effective ways of reducing carbon emissions from heating, providing a unique opportunity to exploit larger scale recovered heat sources. Nuclear power stations offer one of the largest reliable sources of low-carbon heat. The key is to determine the economic case for exploiting this resource through comprehensive system modelling.

21. International Atomic Energy Agency. 2017 Opportunities for Cogeneration with Nuclear Energy. See https://www.iaea.org/publications/10877/opportunities-for-cogeneration-with-nuclear-energy (accessed 31 October 2019).

22. Jasserand F, de Lavergne JGD. 2016 Initial economic appraisal of nuclear district heating in France. EPJ Nuclear Sciences & Technologies, 2, 39. (doi: 10.1051/epjn/2016028).

23. Mott MacDonald. 2015 Project Summary Report - System Requirements for Alternative Nuclear Technologies. See https://www.eti.co.uk/library/alternative-nuclear-technologies-summary-report-and-peer-review-letters (accessed 16 October 2019).

24. Jones C. 2013 Utilising Nuclear Energy for Low Carbon Heating Services in the UK. See https://www.research.manchester.ac.uk/portal/files/54537956/FULL_TEXT.PDF (accessed 05 December 2019).

Image
Haiyang nuclear power plant. Photo credit: State Power Investment Corporation.

CASE STUDY 2

Nuclear district heating in China

The Haiyang nuclear power plant in Shandong province is China's first commercial nuclear heating project[25]. The plant is run by Shandong Nuclear Power Company (a subsidiary of the State Power Investment Corporation). The site houses two Westinghouse AP-1000 units (pressurised water reactors with a capacity of 1126MW each). Construction of the first unit began in September 2009 and following a trial period, the district heating system is now in operation. Plans are to eventually house six or eight units; preliminary works for units 3 and 4 have been approved. These future units will be CAP-1000 units, which are a local standardised design.

Non-radioactive steam from the secondary circuit of both units is fed through an onsite multi-stage heat exchanger, before going offsite to a heat exchange station run by a local thermal company. The heated water then flows through municipal heating pipes to consumers. This system started delivering heat to 700,000 square metres of housing in the winter of 2019/2020 and by 2021 is planned to heat all of Haiyang city (population >300,000) following completion of subsequent units. Both units will also provide 20TWh of electricity to the grid annually (around one third of the domestic demand of Shandong province). Plans will also include a large-scale desalination project to provide water for residents and industries.

At the current scale, the Haiyang nuclear district heating system is expected to replace the burning of 23,200 tonnes of coal/annum.

1.2.2 Seawater desalination

Saltwater desalination is used around the world to produce drinking water; however, the process is energy-intensive (between 3 and 25 kWh per cubic metre of water)[26]. Whilst not all parts of the UK currently require desalination, plants have been built, for example, the Thames Water Beckton desalination plant can produce 150 million litres of water daily (enough to supply around 400,000 households). The need to desalinate seawater for drinking water is expected to increase as a result of climate change.

Seawater desalination has been a feature of nuclear power plants in Japan, Pakistan, and Kazakhstan. These have operated successfully for many years with no recorded reactor anomalies or leakage of radioactive substances into the desalinated water. The International Atomic Energy Agency (IAEA) have evaluated the wider potential for nuclear power desalination in Argentina, Canada, China, Egypt, EU, India, South-East Asia, Russia, and Africa[27, 28]. Access to clean water is one of the UN Sustainable Development Goals: 6 Clean Water (& Sanitation), and recent deployment of nuclear power plants

25. Shandong Nuclear Power Company Ltd. 2019 Shandong Haiyang Nuclear Power Heating Project goes online. See http://www.sdnpc.com/news/companynews/2019/1119/16501.html (accessed 29 November 2019).
26. Encyclopaedia of Desalination and Water Resources (DESWARE). Energy Requirements of Desalination Processes. Seehttp://www.desware.net/Energy-Requirements-Desalination-Processes.aspx (accessed 23 October 2019).
27. International Atomic Energy Agency. 2002 Design Concepts of Nuclear Desalination Plants. See https://www.iaea.org/publications/6368/design-concepts-of-nuclear-desalination-plants (accessed 23 October 2019).
28. Paillère H. 2013 Joint NEA/IAEA Expert Workshop on the Technical and Economic Assessment of Non-Electric Applications of Nuclear Energy. See https://www.oecd-nea.org/ndd/workshops/nucogen/ (accessed 23 October 2019).

in the Middle East have clear potential for the effective incorporation of seawater desalination technologies.

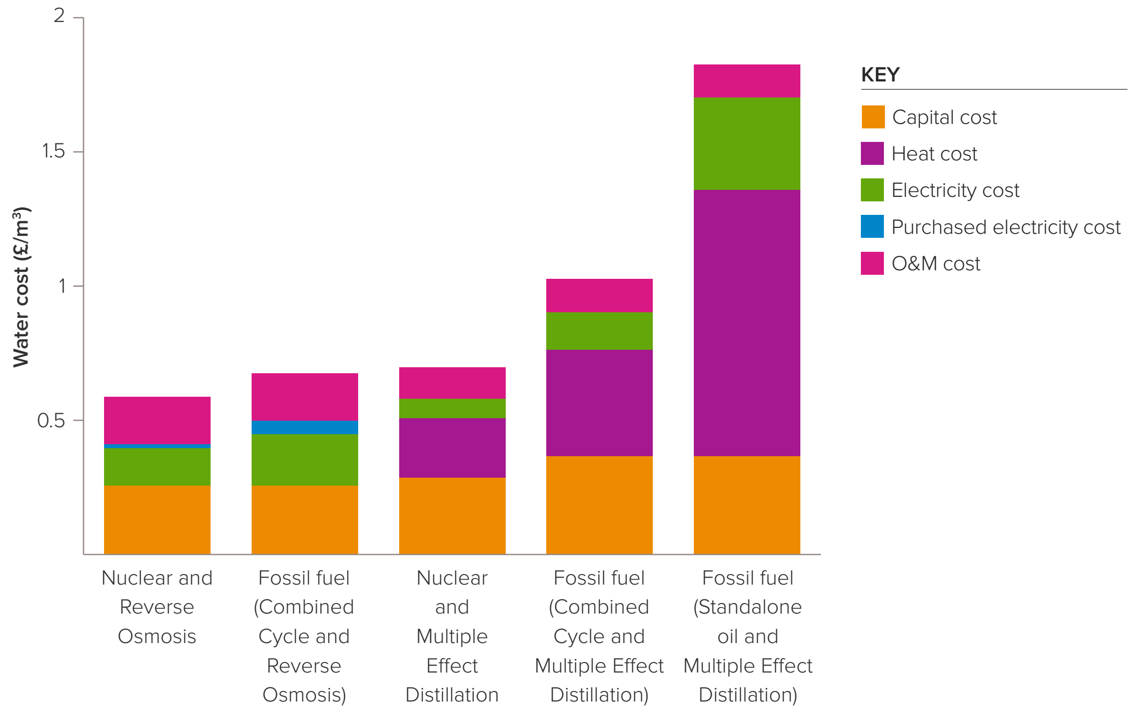
There are three different nuclear desalination technologies; Multi-Stage Flash Distillation, Multiple Effect Distillation, and Reverse Osmosis. These technologies differ in many parameters including energy requirements, pre-treatment, capital cost, and product purity. Overall, desalination processes require relatively low-temperature steam/heat (<200°C) and there is little impact on the thermodynamic efficiency of the nuclear power plant by extracting this heat. Potential carbon savings, by replacing fossil fuel sources, are in direct proportion to the volume of desalination.

1.2.2.1 Costs

Cost estimations depend on several parameters including site characteristics, plant capacity, and feed-water quality. The cost of water produced through nuclear desalination is less volatile than fossil fuel production as most of the cost is capital investment rather than dependent on fuel costs. Using lifetime levelised unit costs to compare combinations of energy source and type of desalination plant, nuclear energy with Reverse Osmosis technology is the cheapest option (Figure 9)[29]. However, the purity of the water produced is not as high as with other distillation techniques and the cost-effectiveness of Reverse Osmosis depends highly on the chemical pre-treatment of the feedwater.

FIGURE 9

Cost of desalinated water by fuel and process[30].



29. International Atomic Energy Authority. 2013 Overview of nuclear desalination technologies & costs. See https://www.oecd-nea.org/ndd/workshops/nucogen/presentations/8_Khamis_Overview-nuclear-desalination.pdf (accessed 16 October 2019).
30. International Atomic Energy Authority. 2013 Overview of nuclear desalination technologies & costs. See https://www.oecd-nea.org/ndd/workshops/nucogen/presentations/8_Khamis_Overview-nuclear-desalination.pdf (accessed 16 October 2019).

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1.3 High-temperature cogeneration

1.3.1 Decarbonising industry through nuclear process heating

In the EU, 26% of total industrial heat demand is for high-temperature heat (>400°C), with the majority generated by burning of fossil fuels[31].

In the UK, iron and steel, mineral products, and food and drink are the most energy-intensive sectors, between them accounting for over 50% of total final industrial process heat consumption (Figure 10)[32]. Heat applications in industrial processes contribute 14% of all UK carbon dioxide emissions[33].

High temperature heat from nuclear power plants offer the potential to remove those carbon emissions. Nevertheless to date, international experience in the use of nuclear energy for process heat is limited to a handful of low temperature cases, for example:

- Process heat from a pressurised water reactor at Gösgen in Switzerland is fed downstream for cardboard production.
- Process heat from a CANDU (Canada Deuterium Uranium) reactor at Bruce in Canada, was used for heavy water production.
- Process heat from a pressurised water reactor at Stade in Germany was used in a salt refinery.

The most economically attractive opportunities for the provision of industrial process heat are to energy-intensive industries that provide a geographically concentrated demand. Typically, these sectors demand higher process temperatures (>400°C). A review of cogeneration in Poland identified that the 13 largest Polish industrial heat recipients in the 250-550°C range have nearly 6,500 MW in installed steam boilers that are potential users of nuclear cogeneration based upon current nuclear technology[34]. This is approximately 6% of Poland's annual carbon dioxide emissions.

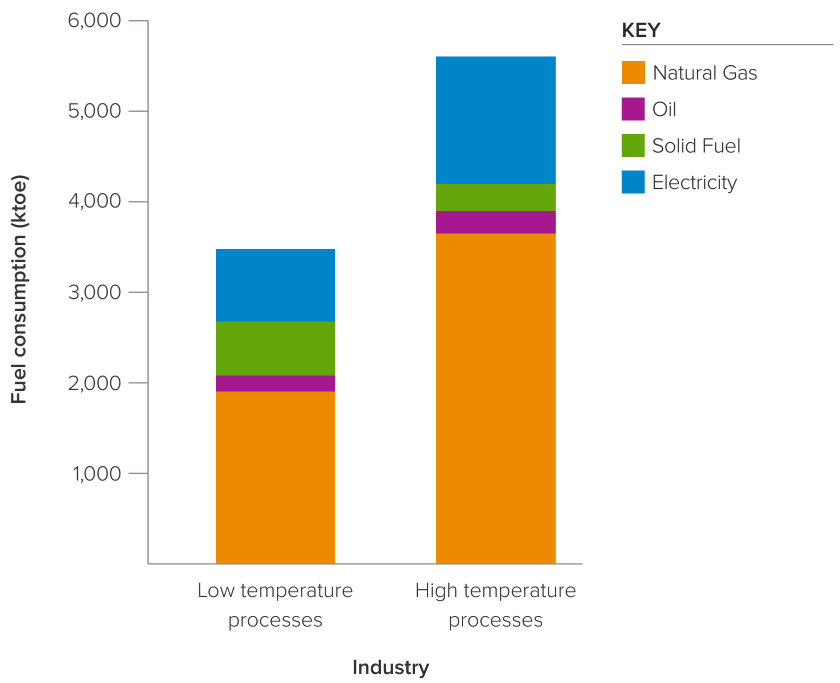
Meeting the high-temperature requirement could only be better satisfied by the deployment of 'next generation' high-temperature technologies. One particular design is the High Temperature Gas-Cooled Reactor (HTGRs) that can produce heat at temperatures >600°C (Figure 6).

In theory, these reactor designs have several characteristics that make them suitable for cogeneration, including a small unit size that can be optimised to meet the industrial requirement. Clusters of industries could be built around such reactors. The Sodium Fast Reactor and Molten Salt Reactor Generation IV designs also offer such options.

Cogeneration with HTGRs is attracting significant international interest, being a focus of the European Sustainable Nuclear Energy Technology Platform (SNETP). The Nuclear Cogeneration Industry Initiative[35] is part of an international cogeneration consortium with the American Next Generation Nuclear Plant (NGNP) known as the GEMINI initiative[36].

FIGURE 10

UK industry process heat consumption by fuel (2018)[37].



Note: Ktoe is unit of energy equivalent to the energy in one thousand tonnes of oil[38].

31. International Atomic Energy Authority. 2017 Industrial Applications of Nuclear Energy. See https://www.iaea.org/publications/10979/industrial-applications-of-nuclear-energy (accessed 23 October 2019).
32. Department for Business, Energy & Industrial Strategy. 2019 Energy Consumption in the UK. See https://www.gov.uk/government/statistics/energy-consumption-in-the-uk (accessed 05 December 2019).
33. Department for Business, Energy & Industrial Strategy. 2018 Clean Growth – Transforming Heating. See https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/766109/decarbonising-heating.pdf (accessed 05 December 2019).
34. Polish Ministry of Energy. 2017 Possibilities for deployment of high-temperature nuclear reactors in Poland. See http://www.snetp.eu/wp-content/uploads/2018/06/HTR-Report-Ministry-of-Energy-Poland.pdf (accessed 13 May 2020).
35. Sustainable Nuclear Energy Technology Platform. The European Nuclear Cogeneration Industrial Initiative http://www.snetp.eu/nc2i/ (accessed 13 May 2020).
36. GEMINI. GEMINI+ project. See http://www.gemini-initiative.com/ (accessed 13 May 2020).
37. Department for Business, Energy & Industrial Strategy. 2019 Energy Consumption in the UK. See https://www.gov.uk/government/statistics/energy-consumption-in-the-uk (accessed 05 December 2019).
38. Note high-temperature processes apply to the iron & steel, non-ferrous metal, bricks, cement, glass and potteries industries (including coke ovens, blast and other furnaces, kilns and glass tanks). Low-temperature processes apply to the food, drink, tobacco industry (including heating & distillation in the chemicals sector, baking, separation, pressing, drying, washing, etc.)

1.3.1.1 Costs

The cost of thermal energy from nuclear reactors can be estimated from the levelised cost of nuclear power. If a pressurised water reactor produces electricity for 78–120 $/MWh (59-91 £/MWh) at an efficiency of 34%, then assuming the electricity cost covers all inputs and outputs, the cost of the thermal energy will be 7.42–11.42 $/GJ[39] (5.64-8.68 £/GJ). This can be compared to the cost of natural gas of around 3.5 - 8 $/GJ (2.66-6.09 £/GJ).

1.2.1.2 Barriers to deployment

Several interesting lessons can be learnt from the history of the industrial use of nuclear power in the UK (see Annex A) including:

- The need for some form of control or ownership of the nuclear reactor by the industrial process owner.
- Industry requires proven nuclear technologies to make informed investment decisions. A well-proven reactor would help assess the technology risk associated in developing and integrating nuclear heat into their process.
- The need for a sound, long term investment case.

Conventional gigawatt scale light water reactors have not been more widely deployed in cogeneration or process heat applications for several reasons:

1. Reactors are normally sited in remote locations, away from centres of population and industry; the hazard that any adjacent industrial facility might pose to the nuclear reactor also has to be addressed in the site nuclear safety case, though this is generally a less significant issue.
2. The steam turbine inlet temperatures of water reactors (i.e. most power reactors worldwide) are typically less than 300°C, which is not hot enough for some energy intensive industrial process heat applications. However, there are still a significant proportion of industrial process heating plants that do operate at low temperatures (below 300°C), these are less energy intensive and tend not to be geographically clustered.
3. More generally, it requires a good understanding of, and confidence in, the technology from both the nuclear and the industrial sides, when typically, these industries have very different cultures, as well as investor confidence from both sides.
4. Most UK companies that use industrial process heat do not have any experience or expertise in nuclear operations and the challenges such as the potential public relations implications create an understandable barrier.

39. Friedmann J, Fan Z, Tang K. 2019 Low-Carbon Heat Solutions for Heavy Industry: Sources, Options, and Costs Today. See https://energypolicy.columbia.edu/sites/default/files/file-uploads/LowCarbonHeat-CGEP_Report_100219-2_0.pdf (accessed 4 November 2019).

1.2.1.3 Research and development

High-Temperature Gas-Cooled reactors (HTGRs) provide the most promising technology options for the provision of very high-temperature process heat (800-1000°C+). However, there are no commercial HTGRs currently operating, although a commercial unit HTR-PM is under construction in China and is expected to be the first operational Generation IV reactor[40].

Other development work is being carried out under several programmes in Europe, USA, China, Japan, Saudi Arabia, and South Korea.

The UK has significant historical expertise and current experience in HTGRs, including the OECD Dragon reactor project at Winfrith in Dorset, the current support of EDF's fleet of Advanced Gas-cooled Reactors (AGR), and UK companies' experience in the design of at least two of the Government's Advanced Modular Reactor candidate systems.

Research is required to better establish the performance of materials, that are used for the construction and operation, at the high temperatures experienced in Generation IV reactor designs.

With enough support, small modular HTGR providing process heat temperatures could be available for deployment by around 2035.

1.3.2 Hydrogen production for a hydrogen-based economy

Hydrogen is produced as an industrial gas for use in a variety of sectors and end-use applications including agriculture, chemical manufacture, and heat production. Current production methods via steam methane reforming produce large quantities of carbon dioxide.

The UK government believes that hydrogen, produced using low-carbon methods, could play an important role in decarbonising industry, power, heat and transport. However, for a market to grow, low-carbon hydrogen will have to be produced at scale and at a competitive price. The UK government have instigated a £33m low-carbon hydrogen supply competition to achieve this[41].

A promising low-carbon method for hydrogen production is the electrolysis of water using renewable electricity. This would consume large amounts of renewable energy[42].

40. Zhang Z et al. 2016 The Shandong Shidao Bay 200 MW e High-Temperature Gas-Cooled Reactor Pebble-Bed Module (HTR-PM) Demonstration Power Plant: An Engineering and Technological Innovation. Engineering, 2, 112–118. (doi:10.1016/J.ENG.2016.01.020).
41. Department for Business, Energy & Industrial Strategy. Low Carbon Hydrogen Supply Competition. See https://www.gov.uk/government/publications/hydrogen-supply-competition#history (accessed 24 April 2020).
42. The Royal Society. 2018 Options for producing low-carbon hydrogen at scale: Policy Briefing. See https://royalsociety.org/~/media/policy/projects/hydrogen-production/energy-briefing-green-hydrogen.pdf (accessed 18 October 2019).

There are four pathways that hydrogen can be produced using nuclear power[43]:

1. **Water electrolysis – only using nuclear electricity.** Water electrolysis uses electricity from any source, with production costs directly related to the cost of electricity.
2. **Steam electrolysis – using nuclear heat and nuclear electricity (cogeneration)** High-temperature steam electrolysis (600-1000°C) promises higher thermal efficiency and potentially lower production cost than conventional water electrolysis, as it requires about 35% less electricity with an overall thermal efficiency of around 50%[44].
3. **Thermochemical processes – using nuclear heat and a small amount of nuclear electricity (cogeneration).** Several thermochemical processes are being considered including sulphur-iodine cycle, hybrid sulphur cycle, and copper chlorine cycle. All these processes use chemical cycles to split water molecules into hydrogen and oxygen. These processes operate at around 600°C to 900°C, with estimated efficiencies of 40-55%. Heat from some Generation IV designs could offer direct access to these processes.
4. **Reforming fossil fuels – using nuclear heat.** The steam reforming process to produce hydrogen from methane operates at a high temperature (700 – 1100°C). The thermal energy for this could be provided by a nuclear reactor rather than from fossil fuels, however, the process produces carbon dioxide as a by-product, which must be captured and stored.

1.3.2.1 Costs

The cost of hydrogen produced by steam methane reforming is closely related to the cost of methane. The cost of hydrogen produced using low-carbon processes is currently higher than that of steam methane reforming but is expected to fall to between £0.02 to £0.09/kWh depending on the process used[45].

No large-scale hydrogen production facility using nuclear energy has been built. The IAEA's Hydrogen Economic Evaluation Program (HEEP) software estimates hydrogen production costs to range between 1.58 and 3.66$/kg (£0.04 to £0.09/kWh) using nuclear energy in four nuclear reactor/hydrogen concepts[46]:

1. A Canadian Generation III, heavy water-cooled, and moderated reactor coupled with Copper–Chlorine (Cu–Cl) hybrid cycle.
2. A Chinese pebble-bed modular high-temperature gas-cooled reactor coupled with a Sulphur–Iodine (S–I) thermochemical cycle.
3. A German SMR high-temperature gas-cooled pebble bed reactor coupled with steam methane reforming
4. A Japanese very high-temperature reactor coupled with Sulphur–Iodine (S–I) thermochemical cycle.

43. International Atomic Energy Authority. 2018 Examining the Technoeconomics of Nuclear Hydrogen Production and Benchmark Analysis of the IAEA HEEP Software. See https://www.iaea.org/publications/13393/examining-the-technoeconomics-of-nuclear-hydrogen-production-and-benchmark-analysis-of-the-iaea-heep-software (accessed 05 December 2019).
44. Partanen R. 2017 Decarbonizing cities: Helsinki metropolitan area. See http://energyforhumanity.org/resources/downloads-en/decarbonising-cities-helsinki-metropolitan-area/ (accessed 05 December 2019).
45. The Royal Society. 2018 Options for producing low-carbon hydrogen at scale: Policy Briefing. See https://royalsociety.org/~/media/policy/projects/hydrogen-production/energy-briefing-green-hydrogen.pdf (accessed 18 October 2019).
46. International Atomic Energy Authority. 2018 Examining the Techno-economics of Nuclear Hydrogen Production and Benchmark Analysis of the IAEA HEEP Software. See https://www.iaea.org/publications/13393/examining-the-technoeconomics-of-nuclear-hydrogen-production-and-benchmark-analysis-of-the-iaea-heep-software

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1.3.2.2 Research and development

The requirement for high-temperature materials performance research and development has already been highlighted. Here an additional challenge comes from the chemically aggressive environments in the hydrogen production process plant. However, recent research offers the potential to reduce the temperature required for high-efficiency steam electrolysis to less than 600°C[47]; within the proven temperature range for current HTGRs.

The Japan Atomic Energy Agency (JAEA) operates the High Temperature engineering Test Reactor (HTTR) investigating both Generation IV operation and hydrogen cogeneration capability. The HTTR is a helium cooled graphite core reactor with a maximum outlet temperature of 950°C. JAEA has research and development plans to demonstrate the production of hydrogen via the sulphur-iodine cycle utilising the high temperature output of the HTTR[48]. The HTTR recently gained basic approval from the Nuclear Regulation Authority in Japan to restart operations from early 2021.

The US Department of Energy recently announced up to $3.5 million (~£2.6 million) for nuclear compatible hydrogen research and development[49], including the Joint Use Modular Plant (JUMP) based at the Idaho National Laboratory Site which is being jointly developed by the U.S. Energy Department and partner companies[50].

1.3.3 Sustainable synthetic fuel production

The availability of high-temperature process heat can be used to facilitate the production of other chemicals. These include single molecule feedstocks such as ammonia, and more complex molecules, for example synthetic fuels.

- The production of ammonia requires the reaction of hydrogen with nitrogen using the Haber Bosch process at high temperatures (350 - 500°C) and pressures[51]. Nuclear cogeneration offers the possibility of using nuclear heat and nuclear power to drive both the production of hydrogen from steam and the Haber Bosch process to produce zero-carbon (green) ammonia.
- The production of synthetic fuels via Fischer Tropsch synthesis requires the reaction of hydrogen with carbon monoxide at up to 300°C to produce a range of hydrocarbons[52]. Again, nuclear heat and power could be used to power the production of hydrogen from steam electrolysis, power the capture of carbon dioxide from the air for conversion to carbon monoxide, and power the Fischer Tropsch synthesis.

47. Wu W et al. 2018 3D Self-Architectured Steam Electrode Enabled Efficient and Durable Hydrogen Production in a Proton-Conducting Solid Oxide Electrolysis Cell at Temperatures Lower Than 600°C. Advanced Science, 5, 1800360. (doi:10.1002/advs.201800360).
48. Japan Atomic Energy Agency. High temperature engineering Test Reactor. See https://httr.jaea.go.jp/eng/index.html (accessed 13 May 2020).
49. US Department of Energy. 2018 Energy Department Announces up to $3.5M for Nuclear-Compatible Hydrogen Production. See https://www.energy.gov/eere/articles/energy-department-announces-35m-nuclear-compatible-hydrogen-production (accessed 03 December 2019).
50. Idaho National Laboratory. 2019 JUMP presents big opportunity for nuclear scientists, industry. See https://inl.gov/article/advanced-reactors/ (accessed 04 December 2019).
51. The Royal Society. 2020 Ammonia: zero carbon fertiliser, fuel and energy store. See https://royalsociety.org/topics-policy/projects/low-carbon-energy-programme/green-ammonia/ (accessed 25 February 2020).
52. The Royal Society. 2019 Sustainable synthetic carbon based fuels for transport. See https://royalsociety.org/topics-policy/projects/low-carbon-energy-programme/sustainable-synthetic-carbon-based-fuels-for-transport/ (accessed 25 February 2020).

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In this way, nuclear energy could be used to produce ammonia and synthetic fuels to store energy for later use and to decarbonise difficult to electrify transport modes, such as shipping, aircraft, and heavy goods vehicles.

The shipping sector alone accounts for 2.2% of global greenhouse gas emissions and this is projected to increase. The International Maritime Organisation have set the target to reduce this by 50% by 2050 (compared to 2008 levels)[53]. Lloyd's Register (based in the UK) is taking the lead for the global shipping sector on how this can be achieved from a techno-economic and regulatory standpoint. Both hydrogen and ammonia are possible zero-carbon fuel types for ship propulsion, replacing liquid natural gas and heavy fuel oil.

1.3.4 Direct air capture (DAC) of carbon dioxide

There are two main methods in development to capture carbon dioxide from air: chemical liquid solvent and chemical solid sorbent technologies. Both are energy-intensive requiring at a thermodynamic minimum of around 20kJ/mole of carbon dioxide captured, in an approximate 80% thermal:20% electrical energy split[54]. Heat application is required to release the captured carbon dioxide from the capture media and regenerate the solvent or solid sorbent. The liquid solvent approach requires temperatures up to 900°C, whereas the solid sorbent method requires significantly lower temperatures (around 100°C)[55].

Both low and high-temperature steam from a nuclear reactor could be used to supply the thermal energy required for DAC, improving the net removal of captured carbon dioxide compared to the current fossil fuelled systems. For example based on a recent scenario analysis, a near-sited sorbent DAC plant could utilise a 5% slipstream of steam from a nuclear plant to satisfy 80% of sorbent DAC thermal requirements and reduce the DAC emissions footprint to 0.29 tCO_2 per tCO_2 captured compared to 0.65 tCO_2 per tCO_2 captured from a DAC system supplied by steam from natural gas (without point source capture and storage, CCS)[56, 57].

The captured high purity carbon dioxide could then be sequestrated or utilised in several industrial processes, for example, manufacturing chemical feedstocks for polymers or the Mond process to extract and purify nickel.

1.3.5 Thermal energy storage

The thermal energy from a nuclear reactor could be stored for later use or to provide a buffer to cogeneration applications. Thermal energy storage systems can be highly efficient (greater than 90%) when coupled to a thermal power generator. For example, the heat from the nuclear reactor could be applied directly to a reactor coolant that also acts as the storage medium or via a heat exchanger to the storage medium.

53. International Maritime Organisation. Greenhouse Gas Emissions. See http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Pages/GHG-Emissions.aspx (accessed 04 August 2020).
54. House KZ et al. 2011 Economic and energetic analysis of capturing CO2 from ambient air. Proceedings of the National Academy of Sciences, 108, 20428-20433. (doi: 10.1073/pnas.1012253108).
55. The National Academies of Sciences, Engineering and Medicine. 2019 Negative Emissions Technologies and Reliable Sequestration: A Research Agenda. The National Academies Press. (doi: 10.17226/25259).
56. McQueen N et al. 2020 Cost Analysis of Direct Air Capture and Sequestration Coupled to Low-Carbon Thermal Energy in the United States. Environ Sci Technology, 54, 7542 – 7551. (doi: 10.1021/acs.est.0c00476).
57. N.B. All carbon dioxide emissions associated with the DAC process, compression and transportation are included however the base scenario using natural gas without CCS does not include the emissions associated with upstream natural gas leakage.

This technology is already deployed worldwide alongside concentrated solar power stations (where direct sunlight is focused to produce superheated steam). There are several potential storage media including molten salts, phase-change materials, graphite, hot water and clay-based refractory bricks[58]. The choice of medium depends on the operating temperature of the thermal power plant and the scale of storage required.

Thermal storage can be used with conventional light water reactors that operate at low temperatures (~300°C), however, the higher operating temperatures of future nuclear plants offer greater thermal storage potential[59]. Research is needed to assess this potential and to demonstrate that nuclear power plants can be operated safely in the thermal storage mode.

2.4 Medical isotope production

Radioactive isotopes are used in medicine to image and treat a range of medical conditions. Nuclear power stations have been used to make radioactive isotopes, for example the Darlington CANDU reactors in Canada have been used to make medical isotopes. Over the years, the number of countries producing radioisotopes has diminished due to ageing research reactors, and as a result there is a global shortage of key radioisotopes[60]. The new isotope-producing reactors and alternative production technologies currently under construction or planned are likely to address the global shortage. Possible UK solutions include the development of an isotope-producing research reactor or a multi-purpose reactor with cogeneration capability that includes isotope production (see Case study 1).

58. C Forsberg. 2015 Strategies for a Low-carbon Electricity Grid with Full Use of Nuclear, Wind and Solar Capacity to Minimize Total Costs. See http://energy.mit.edu/publication/strategies-for-a-low-carbon-electricity-grid-with-full-use-of-nuclear-wind-and-solar-capacity-to-minimize-total-costs/ (accessed 05 December 2019).
59. Denholm P, King JC, Kutcher CF, Wilson PPH. 2012 Decarbonizing the electric sector: Combining renewable and nuclear energy using thermal storage. Energy Policy, 44, 301-311. (doi:10.1016/j.enpol.2012.01.055).
60. Lee WE. 2014 Securing a Sustainable Supply of Medical Isotopes for the UK. Nuclear Innovation and Research Advisory Board.

Challenges of cogeneration systems

2.1 Safety and security

Different reactor types pose different safety and security challenges, and these will impact the siting, footprint and security requirements for cogeneration installations. For example, proposed Small Modular Reactors (SMRs, see Annex B: Definitions) enhance safety through the simplification of engineering systems (e.g. elimination of pipes) or designed-in passive safety features that allow natural convection and radiation to remove decay heat during an emergency. In combination with their smaller scale, this reduces the hazard and the demands for evacuation in the event of an accident scenario. Consequently, SMRs facilitate the kind of proximity desirable for economic and engineering reasons, between a heat source and heat applications[61].

The production of hydrogen is a strong use case for cogeneration using high-temperature reactors (e.g. Generation IV) but would necessitate the co-siting of the nuclear power plant and the hydrogen production facility. The potential for a non-nuclear accident at the hydrogen plant to compromise the nuclear power plant would need to be addressed in any risk assessment. Regulatory licensing of a nuclear cogeneration system coupled to any industrial facility is a challenge for both end user and public acceptance.

2.2 Regulation

Regulation will need to be modified to ensure it is fit for cogeneration. As with conventional reactor designs, a Generic Design Assessment (GDA) will be considered but remains costly and typically takes around five years. Cogeneration options would need to be included in the GDA process.

In Chapter 1, it was postulated that SMR designs might be useful for cogeneration. While an SMR has not been built in the UK for civil purposes, the regulator has started considering how it would approach a GDA for an SMR.

One of the benefits of SMRs is that the same design can be used, leading to a steady pipeline of demand, which will reduce unit production costs. Cogeneration options would need to be built into the SMR generic design assessment.

2.3 Waste reuse, recycle and disposal

The application of cogeneration to a reactor does not in itself increase the amount of spent nuclear fuel produced by a reactor. An increase in the number of reactors will increase the amount of spent fuel that will require disposal. All current international waste management programmes plan to either directly dispose of spent fuel or reprocess and dispose of high-level waste in glass. Disposal of high-level waste glass and spent fuel is planned to be permanent and aimed at emplacement in deep geological repositories[62].

Generation IV reactors are intended to generate less waste per MW of energy than older designs[63] while some new reactors (e.g. Hitachi's resource-renewable boiling water reactor) are being designed to burn long-lived isotopes in waste and so reducing the perceived burden on future generations.

61. International Atomic Energy Agency. 2017 Opportunities for Cogeneration with Nuclear Energy. See https://www.iaea.org/publications/10877/opportunities-for-cogeneration-with-nuclear-energy (accessed 31 October 2019).
62. Lee WE, Ojovan MI, Jantzen CM. 2013 Radioactive Waste Management and Contaminated Site Clean-up: Processes, Technologies and International Experience. Processes, Technologies and International Experience, 879. (IBSN: 978-0-85709-435-3).
63. Ojovan MI, Lee WE, Kalmykov SN. 2019 An Introduction to Nuclear Waste Immobilisation. Elsevier, 400. (ISBN: 978-0-08102-702-8)

2.4 Public attitudes

Attitudes to nuclear so far have not been a barrier to new nuclear construction in the UK, but that is partly because construction has been limited to sites of existing nuclear stations, where local support is high. It is less clear how the public would view the building of new nuclear stations in new areas, especially closer to urban areas. Research into public acceptance of such developments is needed.

2.5 Future research and development

There is currently no UK co-ordinated research and development into nuclear cogeneration. However, there is expertise in conventional industrial combined heat and power, and district heating in various places around the region. The UK also has expertise in the hydrogen economy. The options for cogeneration could be evaluated if nuclear technologists are brought together with those involved in demand evaluation (e.g. energy-intensive industries). An ambition would be to facilitate a demonstration project of a nuclear reactor with cogeneration capability. Further, behavioural science research would be useful to:

- to understand what consumers would want from cogeneration, how it could be financed, and how it fits into the wider net-zero energy system.
- to gather public attitudes regarding the use of high-temperature applications and the safety, security, and regulation of joint high-risk installations, such as for nuclear-powered hydrogen, ammonia, and synthetic fuel production facilities.

2.6 Economics

It is common to discuss the relative merits of different energy generation methods by comparing their generation cost. One problem with this approach is that the amount the market will return for energy supplied fluctuates greatly and on an hourly basis. Energy generation processes that can closely match demand (e.g. gas) can command much greater revenues per kilowatt supplied. However, as mentioned previously, current nuclear is best suited to supply energy at a constant rate and there is a similar lack of flexibility with intermittent renewable energy. One solution is to store low-carbon energy until it is demanded but storage comes at a cost. If nuclear energy can be diverted rather than stored this could engender an economic improvement for nuclear generation.

The economic benefits of nuclear cogeneration are not easy to quantify. It depends upon the mix and value of the alternative nuclear power derived products compared to the lost value of electricity that could have been produced. These in turn depend upon the whole energy system design and constraints, for example, the demand for hydrogen or its products, the cost of carbon and the value of dependable power, especially in a system dominated by renewable generation. This is beyond the current report. An economic analysis will be necessary to determine how much cost difference cogeneration might make, in a range of possible systems; possible headline costs have been included here. If the construction cost reductions for SMRs can be realised and the regulation and licencing costs streamlined, then the additional revenue benefits of cogeneration could be material for SMRs and for the future of nuclear generation in the UK.

CONCLUSIONS

Conclusions

- Nuclear energy has the potential to help the UK to achieve net-zero carbon emissions by 2050, not only through the generation of low-carbon electricity but by more fully utilising the generated heat. This could support the UK taking a 'whole systems' view of future energy production and use by addressing difficult to decarbonise energy demands.
- UK nuclear energy is currently only used to generate baseload electricity. Nuclear reactors work best if operated continuously at a constant full capacity. To support the integration of increased renewable energy penetrating the grid coupled with the need to reduce gas fired generation, greater flexibility will be required to offset the intermittency. Cogeneration could facilitate this by enabling switching between electricity generation and cogeneration applications.
- Nuclear cogeneration could help decarbonise heat. Cogenerating reactors can provide a dedicated constant output of heat, or constant heat plus electricity supply.
- There are no existing nuclear cogeneration installations in the UK, and it would be economically challenging to convert current nuclear power plants to support cogeneration.
- Current planned new build nuclear power plants are designed primarily for the generation of electricity; however, the designs could be modified to make use of the various benefits of cogeneration. In the case of Sizewell C, the potential for cogeneration is already under consideration (see Case study 3).
- Generation IV reactor designs offer higher temperature opportunities for industrial process heat, including production of hydrogen, industrial chemicals, and heavy industrial processes. While no design is currently in commercial operation, China and Japan are progressing with development of High Temperature Gas-Cooled Reactor (HTGRs).
- The economic benefits of nuclear cogeneration depend upon the whole energy system design and its constraints e.g. the demand for hydrogen or its products, the cost of carbon and the value of dependable power.
- Small Modular Reactors (SMRs) can offer greater flexibility and better co-location opportunities for many power and cogeneration applications.
- If the construction cost reductions for SMRs can be realised and the regulation and licencing processes streamlined, then the additional revenue benefits of cogeneration could be material for SMRs and for the future of nuclear generation in the UK.
- Regulation to enable cogeneration would need to be established.
- Public opinion and acceptance of nuclear reactors supplying domestic heating and being sited closer to population centres would need to be examined.

Image
Proposed Sizewell C nuclear power station.
image credit: EDF Energy.

CASE STUDY 3

Sizewell C, Suffolk

The proposed new Sizewell C nuclear power station would produce enough electricity to meet 7% of the UK's electricity demand. The Sizewell C project is also investigating using some of the heat for district heating networks, process heat demands within industrial applications or agriculture, and to increase the efficiency of low-carbon fuel production. In particular, the possibility of making hydrogen using nuclear energy is being explored. Beyond water electrolysis, steam for heat-assisted electrolysis, which is currently being commercialised, could be supplied from Sizewell C. EDF is seeking to establish a pilot electrolyser project at the existing power station (Sizewell B) in the short-term. The hydrogen produced would meet the station's internal demand (for example, in certain cooling mechanisms), power elements of the construction of Sizewell C (for example buses, excavators and forklifts), and feed into several other applications in the local area. Ultimately, if successful, a large-scale, high efficiency steam electrolyser could be constructed at Sizewell C, as part of a regional Energy Hub.

Annex A: Historical industrial uses of nuclear power in the UK

Image
Anglesey Aluminium smelter plant prior to closure.
© Crown Copyright: Royal Commission on the Ancient and Historical Monuments of Wales.
© Hawlfraint y Goron: Comisiwn Brenhinol Henebion Cymru.

Aluminium smelters and nuclear power

The aluminium smelters established during the late 1960s on Anglesey and Invergordon (Figure 11), provide a historical example of the use of nuclear energy to power an industrial process. The extraction of aluminium from its ore, Bauxite, is an energy-intensive process (58GJ/tonne aluminium).

Not only must the electricity supply be cheap, but it must also be uninterrupted: an extended power-cut can be catastrophic for the plant[64]. For these reasons, smelters had often been associated with large hydropower schemes for the reliable supply of cheap and plentiful electricity.

In response to a commercial plan to build nuclear power stations to power aluminium smelting operations, the UK Government agreed to provide financial support for construction and the price of electricity. Smelters were established at Anglesey Aluminium in North Wales (image below) and the British Aluminium plant at Invergordon in the Scottish Highlands. Each would produce over 100,000 tons of aluminium a year (starting operation in 1971). At their height, each employed over 900 people. The initial plan was to power both smelters using two new AGR reactors, Dungeness B and Hunterston B.

A third smelter was also established at Lynemouth close to the coalfields in the northeast of England (Figure 11). Unlike Anglesey and Invergordon this was powered by a privately-owned coal power station. Starting from 1974 these new plants increased overall UK aluminium production from around 38,000 tons to over 350,000 tons/annum.

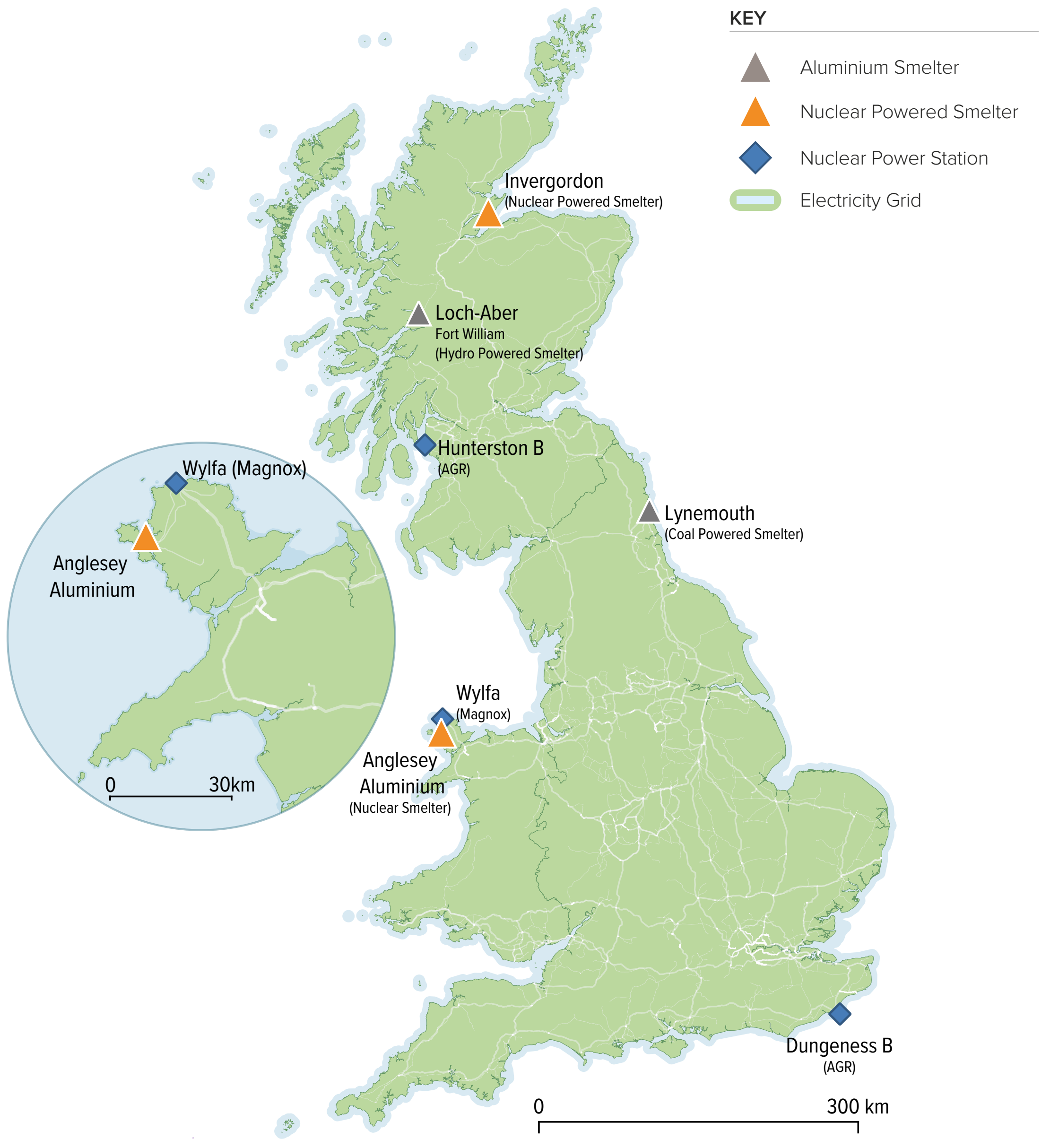
The construction of the AGR stations over-ran and in the end, Anglesey Aluminium received its electricity primarily from the Wylfa Magnox station and problems with Hunterston B led to significant pressures on the Invergordon smelter.

Operational experience on Anglesey demonstrated a benefit in the geographical co-location of a nuclear power plant (Wylfa) with its associated industry in the event of a grid failure.

64. Tabereaux A, Lindsay S. 2019 Lengthy Power Interruptions and Pot Line Shutdowns. Light Metals, 108. (doi:10.1007/978-3-030-05864-7-108).

FIGURE 11

Map of the UK showing the locations of the aluminium smelters and relevant nuclear power stations.



For example, typically during a grid outage, a nuclear power station would have to shut-down and so a five-hour interruption would lead to a three-day loss of revenue. Instead, Anglesey Aluminium was able to provide a large continuous load, allowing Wylfa to avoid shutting down.

In 2009, Anglesey Aluminium announced that they had been unable to re-negotiate their power contract[65]. At this time, the Nuclear Decommissioning Authority (NDA) operated the Wylfa Magnox station and as a non-departmental arm of UK Government, were unable to supply electricity at reduced rates. Consequently, without cheap electricity, Anglesey Aluminium's smelting operation closed in September 2009 with the loss of 400 jobs.

The Invergordon smelter closed after only ten years of operation in late 1981. This was due to several factors, including the high price of electricity[66]. Invergordon's supply contract through the South of Scotland Electricity Board (SSEB) provided energy at 1.7 p/unit whilst Anglesey paid 1.3 p/unit. This highlights the need for not only reliable but also cheap energy for competitive aluminium production.

Lessons learned

- Power-Station Ownership Model: Both atomic aluminium smelters made capital contributions to the construction of two nuclear power stations. However, this investment did not result in a physical asset which the aluminium producers could control; a factor leading to their closure. For example, at Lynemouth, Alcan was able to build their own 420 MW coal power station dedicated to smelting which ultimately outlasted both Invergordon and Anglesey.

- Industry require established nuclear technologies to make informed investment decisions. The Anglesey and Invergordon smelters were linked to the development of AGR reactor technology. At the time of planning, no commercial AGR had been built and operated. As a result, much of the technology risk associated with AGRs was imposed on the aluminium smelter projects too. Had the projects been associated with a well-developed reactor system many of these issues might have been avoided.

While not completely successful, this historical case study highlights the need for the main stakeholders to establish a clear business and operation plan from the outset.

65. Robertson D, Mortished C. 2009 The end for UK's biggest energy user as Rio shuts Anglesey aluminium smelter. See https://www.thetimes.co.uk/article/the-end-for-uks-biggest-energy-user-as-rio-tinto-shuts-anglesey-aluminium-smelter-n79trcknz97 (accessed 04 December 2019).
66. MacKenzie N. 2012 Be careful what you wish for: comparative advantage and the Wilson smelters project, 1967-82. See https://pureportal.strath.ac.uk/en/publications/be-careful-what-you-wish-for-comparative-advantage-and-the-wilson (accessed 04 December 2019).

Nuclear Steelmaking

Steel production has very high energy requirements, and nuclear heat and electricity have been considered for this purpose. Using conventional methods, the core process of producing liquid metal consumes between 1.6 - 10.4 GJ/tonne[67]. Including additional contributions from transport, mining, transmission losses and secondary forming operations, manufacturing one tonne of steel consumed 20.3 GJ in 2016[68]. In 2017, 1689 million tonnes of crude steel were produced, accounting for 17% of industrial and 4.9% of total primary worldwide energy production[69, 70]. Energy represents a significant portion of production costs ranging between 20% and 40%[71, 72]. Due to the scale of production, even marginal decreases in energy costs can yield considerable economic benefit.

Currently, 75% of steel production is via the Blast Furnace-Basic Oxygen Furnace (BF-BOF) route, with electric arc-furnaces (EAF) providing the rest[73]. During the BF-BOF route, coal is converted to coke in high-temperature ovens and finely ground iron ore is combined with powdered coke, limestone, and other additives before being pressed and sintered into pellets. These are then added to the blast furnace with more coke. Here the coke has two functions: it acts as a reducing agent reacting with the oxygen in the pelletised iron oxide ore, and secondly, it is the fuel providing the heat required by this reaction. Coke is a form of carbon and when it combusts and reacts with the iron oxide it emits large amounts of carbon dioxide. The product of the blast furnace is molten pig-iron which is rich in carbon. This is poured into a basic oxygen furnace (BOF) where pure oxygen gas is injected, at supersonic speed, into the liquid metal. The carbon in the pig-iron reacts with the oxygen and leaves the melt as carbon dioxide, dropping the carbon content sufficiently for the iron-carbon alloy to be classed as steel.

Production routes using electric arc furnaces are growing in popularity for steel production. Production via this method is expected to grow to 50% of the output by 2050. Arc-furnaces are loaded with various combinations of scrap metal, blast furnace steel or directly reduced iron, which are then melted by application of a large electric current. Directly reduced iron has been a focus of nuclear steelmaking research. In this route, reducing gases (typically hydrogen and carbon monoxide) are passed through a bed of pelletised iron-ore at high temperature 800 – 1200°C, and the oxygen is removed from the ore to leave pig-iron, carbon dioxide, and water.

Image
Hot steel pouring.
© photllurg

67. Fruehan RJ, Fortini O, Paxton HW, Brindle R. 2000 Theoretical minimum energies to produce steel for selected conditions. See https://www.energy.gov/sites/prod/files/2013/11/f4/theoretical_minimum_energies.pdf (accessed 16 October 2019).
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ANNEX

Direct reduction does not produce liquid metal, instead, the pellets are converted into a very porous metallic sponge, which has few engineering applications but is an ideal feedstock for an arc furnace where it is melted before forming into mill-products.

Currently, 89% of the energy input into the BF-BOF route comes from coal, 7% from electricity, 3% natural gas and 1% from other gases. Half of the energy for the arc furnace route is from electricity, 11% from coal, 38% natural gas and 1% from other sources.

The electricity for electric arc furnaces could be supplied by existing commercial nuclear reactor technology. A large electric arc furnace consumes up to 175 MW and typically there are two furnaces on a single site[74]. The electricity demand of 350 MW for both furnaces is well within the capabilities of most existing reactor systems and could also suit some SMR designs. However, electric arc melting is a batch process: furnaces typically operate for 45 minutes at a time and current nuclear power reactors tend to favour continuous operation at full power. Careful scheduling of electric arc furnace deployment, therefore, offers an excellent opportunity to utilise nuclear electricity during times when grid demand is low.

During the 1970s, concerns regarding the rising cost and scarcity of coking coal and fossil fuels led to nuclear steelmaking being given serious consideration. The European Nuclear Steelmaking Club (ENSEC) was founded in September 1973[75] and included major European steelmakers from Belgium, France, Germany, Great Britain, Italy, Luxembourg and the Netherlands. Similar initiatives were established in the USA (Task Force on Nuclear Energy in Steelmaking – 1973), Japan (Research Association for Nuclear Steelmaking Engineering – 1974) and Germany. This period also corresponds with a time of great development in high-temperature gas reactors. By 1973, the OECD's Dragon reactor (located at Winfrith, Dorset) had been successfully operating for eight years with an outlet temperature of 750°C[76, 77] and in Germany, the AVR pebble bed reactor first went critical in 1966 with outlet temperatures in the range 650-850°C which were increased to 950°C in early 1974[78, 79]. With these experimental reactors, it was thought that by the mid-1990s high-temperature gas reactor technology would have been harnessed for use in steelmaking.

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The primary thrust of the 1970s nuclear steelmaking research considered a direct reduction route producing sponge for electric arc melting[80], like the direct reduction route described above. The heat required would be provided by a high-temperature reactor, reducing fossil fuel consumption. Also, the nuclear reactor would provide heat to convert natural gas into the required reducing gases by steam reforming. The natural gas is used as a chemical agent rather than as fuel, reducing fossil fuel consumption considerably (and avoiding the need for coke and coal). Consequently, the nuclear route would only account for 10% of the total cost of steel production and would help insulate steelmaking from the volatility of fossil fuel markets. Using direct reduction with nuclear process heat, it was estimated that a reactor producing 3 GW heat would be required for a large steelwork producing 7 million tonnes a year[81]. On this basis, 92 such reactors would have been required to satisfy world steel demand in 1975.

Lessons learnt

Why did nuclear steelmaking not take off in the way predicted in the 1970s? Fundamentally there were two causes:

- Fossil fuel prices remained relatively low meaning nuclear steelmaking costs more than conventional methods.
- Despite early success with experimental reactors, progress in commercialising gas-cooled high-temperature reactors was slow. Without a well-proven reactor, it was unlikely that the steel industry would accept the technology risk associated with developing and integrating nuclear heat into the steel making process.

Steelmaking remains a carbon-intensive process due to the reliance on coal and natural gas as heat sources and carbon monoxide as a reducing agent. Despite the carbon savings, the nuclear steelmaking method proposed in the 1970s still relied on natural gas. However, current research has been ongoing to use hydrogen in steelmaking instead, which would help to further reduce carbon dioxide emissions. As discussed elsewhere in this report, nuclear technology is suitable for producing hydrogen gas, and if coupled with nuclear electricity and process heat, could provide a modern low-carbon route to producing steel.

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81. Kenward M. 1974 Energy File: Steel club disintegration. New Scientist, 64, 662.

Annex B: Definitions

	Description	Examples
Generation I	Early prototype reactors.	Calder Hall-1, Shippingport, Dresden-1.
Generation II	Commercial power reactors designed for a typical lifetime of 40 years. Comprised the majority of the world's commercial PWRs and BWRs (over 400) – typically referred to as light water reactors (LWRs).	Pressurised water reactors (PWR), CANada Deuterium Uranium reactors (CANDU), boiling water reactors (BWR), advanced gas-cooled reactors (AGR).
Generation III	Evolved Gen II designs. Improvements include fuel technology, thermal efficiency, modularised construction, safety systems, and standardised design. Planned lifespan of 60 years.	Advanced boiling water reactors (ABWRs), Westinghouse 600MW advanced PWR (AP-600), Enhanced CANDU 6.
Generation III+	Improved Gen III designs, mainly regarding safety. Gen III+ reactors incorporate passive safety features that do not require active controls. Further improvements to fuel efficiency and waste production.	Advanced CANDU reactor (ACR-1000), AP-1000, Economic simplified boiling water reactor (ESBWR), European pressurised water reactor (EPR e.g. Hinkley C).
Generation IV	Currently in R&D phase. Mainly comprised of small modular reactor (SMRs) or advanced modular reactors (AMRs), designs. The advantages of Gen IV reactors include high temperatures, less waste per generated output, use of waste and increased variety of viable fuels.	Gas-cooled Fast Reactor (GFR), Lead-cooled Fast Reactor (LFR), Molten Salt Reactor (MSR), Supercritical Water-cooled Reactor (SCWR), High-temperature or Very High-temperature Reactor (HTR/VHTR).

ANNEX

	Description	Examples
Small Modular Reactor (SMR)	Small modular reactors are nuclear fission reactors producing up to 300MW of electrical power. They can be largely built in factories as modules to minimise costly on-site construction. Their designs can be based on Generation III or Generation IV reactor designs. The term is used by the UK Government to refer to small Generation III reactor designs.	
Advanced Modular Reactor (AMR)	The term used by the UK Government to describe small modular reactors based on new Generation IV designs.	
Fusion reactor	All Generation I to IV reactors are fission reactors that produce energy from splitting atoms. A fusion reactor produces energy from combining atoms.	Research is ongoing around the world to develop fusion reactors e.g. ITER.

Currency exchange used (as of 5 August 2020)	
1USD	0.761GBP
1EUR	0.906GBP

Annex C: Acknowledgments

This policy briefing is based on Steering group discussion meetings, from a workshop held at the Royal Society on 25 September 2019 and subsequent input. The Royal Society would like to acknowledge the contributions from the Steering group, workshop attendees, and those people who helped draft and review the policy briefing.

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