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The Role of Nuclear Power in Meeting Current and Future Industrial Process Heat Demands

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Received: 23 July 2019; Accepted: 17 September 2019; Published: 25 September 2019



Abstract: There is growing interest in the use of advanced reactor systems for powering industrial processes which could significantly help to reduce CO_2 emissions in the global energy system. However, there has been limited consideration into the role nuclear power would play in meeting current and future industry heat demand, especially with respect to the advantages and disadvantages nuclear power offers relative to other competing low-carbon technologies, such as Carbon Capture and Storage (CCS). In this study, the current market needs for high temperature heat are considered based on UK industry requirements and work carried out in other studies regarding how industrial demand could change in the future. How these heat demands could be met via different nuclear reactor systems is also presented. Using this information, it was found that the industrial heat demands for temperature in the range of 500 °C to 1000 °C are relatively low. Whilst High Temperature Gas-cooled Reactors (HTGRs), Very High Temperature Reactors (VHTRs), Gas-cooled Fast Reactors (GFRs) and Molten Salt Reactors (MSRs) have an advantage in terms of capability to achieve higher temperatures (>500 °C), their relative benefit over Liquid Metal-cooled Fast Reactors (LMFRs) and Light Water Reactors (LWRs) is actually smaller than previous studies indicate. This is because, as is shown here, major parts of the heat demand could be served by almost all reactor types. Alternative (non-nuclear) means to meet industrial heat demands and the indirect application of nuclear power, in particular via producing hydrogen, are also considered. As hydrogen is a relatively poor energy carrier, current trends indicate that the use of low-carbon derived hydrogen is likely to be limited to certain applications and there is a focus in this study on the emerging demands for hydrogen.

Keywords: process heat; industry; generation-IV; hydrogen; SMR; nuclear reactors

1. Introduction

There is increasing interest in deployment of reactor systems beyond their conventional use of large, centralised plants producing electricity, with some advanced reactor systems, primarily Generation-IV systems and High Temperature Gas-cooled Reactors (HTGRs), identified as being more suitable than Light Water Reactor (LWR) systems for process heat applications [1]. In general, there is a long history of interest in using nuclear reactor systems for heat applications, in particular HTGRs, with a number of HTGRs operating in the 1970s [2]. This historic approach has mainly been technologically driven, based on the question of what the reactor can provide. However, from a more demand driven view, ultimately the relative importance of the process heat attribute will be governed by the demand for heat at specific temperature levels that a particular reactor technology can offer.

This study aims to quantify how present and potential future industrial process heat demand could be met by nuclear reactor systems and the often under-looked aspect regarding whether they would complement or compete with other low-carbon technologies that are under development. There has

also been historic and continuing interest in using hydrogen to provide a substantial proportion of future energy demand (sometimes referred to as the hydrogen economy) [3]. However, as will be outlined, hydrogen is a relatively poor energy carrier, current trends indicate that the use of low-carbon derived hydrogen is likely to be limited to certain applications. These applications relate to overcoming current challenges in the areas of: energy storage; industrial demand (both as a feedstock and as a heat source); and meeting residential and commercial heat demands.

With the above in mind, a detailed breakdown of current industrial heat demand, using the UK as a case study, is presented and is followed by a discussion of the role different nuclear reactor systems could play and consideration for alternative low-carbon means to meet industrial heat demand. Furthermore, consideration is given to how future industrial heat demand could change in a world with stringent limits on greenhouse gas emissions across many economic sectors. Besides heat demand at specific temperature levels, there would also be a need to consider other technical specifications such as pressure demands; however, the focus in this study is on heat demand by temperature level to act as a starting point to determine the potential role different reactor systems could play in meeting industrial heat demand.

2. Industrial Heat Demand and Reactor Technologies

UK industry consumes around 400 TWh per year in energy [4], of which around 300 TWh is used for industrial heat application [5]. Some of this 300 TWh heat demand is met via electricity (as will be highlighted in this section). By assessing heat demand by temperature levels and energy demand per site, it is possible to see what role different nuclear reactor systems can play. The literature on industrial heat demand [5,6] tends to group industrial heat demand into the following categories:

- Heat demand <300 °C,
- Heat demand between 300–500 °C,
- Heat demand between 500–1000 °C,
- Heat demand >1000 °C.

These categories are in broad alignment with the output of current reactor systems and the more advanced Generation-IV systems, namely:

- Current generation LWR systems (Boiling Water Reactors (BWRs) and Pressurised Water Reactors (PWRs)) with outlet temperatures of approximately 300 °C [7].
- Generation-IV Liquid Metal-cooled Fast Reactors (LMFRs), with international experience focusing on lead and sodium coolants. Most international experience is with sodium-cooled fast reactors (SFRs) [8], but there is some limited experience with lead-cooled fast reactors (LFRs) in naval systems. Both SFRs and LFRs are envisaged at operating at similar outlet temperatures around 550 °C in the case of SFRs [9] and around 500 °C in the case of LFRs. Note that in principle LFRs could operate at much higher outlet temperatures, but such reactor concepts are at relatively low technology readiness levels [10]. The relative benefits of LFRs vs. SFRs for heat applications are discussed further in Section 2.1.
- High temperature Gas-cooled Reactors (HTGRs), which have previously demonstrated routine operation at around 800 °C, with some limited operation experience around 950 °C (see Section 2.2). The Generation-IV variant of HTGRs is the Very High Temperature Reactor (VHTR) which currently targets outlet temperatures of 1000 °C [11].
- Molten salt reactors (MSRs) with fast and thermal variants under development, with most interest in the Generation-IV fast spectrum variant [12]. There is some experience with thermal spectrum MSRs due to the operation of the Molten Salt Reactor Experiment at Oak Ridge National Laboratory [13]; however, no experience with the operation of fast spectrum MSRs. Both thermal and fast spectrum MSRs are envisaged to have similar outlet temperatures of around 700 °C [14–16].

- Supercritical Water Reactors (SCWRs) with fast and thermal variants under development and both fall within the Generation-IV category. Unlike the preceding four reactor systems, there is no operational experience at the prototype or demonstration level with SCWRs. SCWRs are envisaged to operate with outlet temperatures of around 500 °C [17].
- Generation-IV Gas-cooled Fast Reactors (GFRs) with outlet temperatures up to around 800 °C considered [18]. Similar to SCWRs, there is no operational experience at the prototype or demonstration level with GFRs.

2.1. LFR vs. SFR for Heat Applications

There is no consensus on the relative benefits of LFRs versus SFRs for heat applications. The technical maturity of SFRs is a clear advantage relative to LFR systems. In addition, the chemistry control and corrosion challenges associated with lead create large uncertainties on the ability to deploy the technology in the near-term. However, for a reactor system designed for heat applications, LFR systems do have the following potential benefits relative to SFR systems:

- The neutron leakage penalty is much smaller.
- There is the ability to employ natural convection cooling.
- It may be possible to eliminate the need for an intermediate circuit on the assumption that water ingress into the primary circuit can be adequately mitigated against.

With respect to the final point, there is a lot of uncertainty regarding the possibility of eliminating the intermediate coolant circuit in LFRs, with some designs proposing to remove them [19]; however, some studies say the risk of water ingress into the reactor vessel is difficult to mitigate against [20]. Nevertheless, a large cost penalty associated with SFR technology is the need for an intermediate loop [21]. For a small LMFR, the leakage penalty can be significant and impair the ability to achieve a high conversion ratio (>1.00). However, a low conversion ratio (resulting in open-cycle operation) may be acceptable, particularly when the relative benefits associated with operating a fuel re-processing facility and low uranium prices are accounted for.

2.2. Operational Experience with HTGRs

A number of HTGRs have operated as summarised in Table 1. Whilst operation experience is significant (decades of experience), it is much less than with LWR systems (hundreds of reactors, each operating for many decades) and SFR systems [8]. Furthermore, much of the operation experience is with outlet temperatures of around 800 °C, with relatively short periods of operation at temperatures above 900 °C [22–24]. In addition, many of the systems operate with relatively low thermal power outputs (around 30 MWth). However, as will be shown, these relatively low thermal outputs may be suitable for a number of industrial heat applications, assuming the economic penalty associated with deploying such small reactors is not unduly burdensome, noting that historically there has been a strong focus on increasing the reactor power output to improve economic performance [25].

Table 1. High Temperature Gas-cooled Reactors (HTGRs) that have been built and operated along with key parameters.

Reactor Name	Operation Dates	Power	Outlet Temperature	Reference(s)
Dragon	1964–1975	20 MWth	750 °C	[22]
Peach Bottom 1	1966–1974	115 MWth/40 MWe	700 °C	[22]
AVR	1967–1988	46 MWth/15 MWe	850–950 °C	[23,26]
Fort St. Vrain	1976–1989	842 MWth/330 MWe	800 °C	[22]
THTR	1985–1989	750 MWth/300 MWe	750 °C	[22]
HTTR	1998–present	30 MWth	850–950 °C	[22,24]
HTR-10	2000–present	10 MWth	750–950 °C	[22]

2.3. Reactor Systems by Operating Temperature

Table 2 provides a summary of the reactor systems capable of operating in a particular temperature range, with the temperature range mapping to those highlighted earlier in the industrial heat demand literature. Note that this investigation has not considered the role heat pumps could play in artificially raising the outlet temperature from reactor systems since: (1) this adds complexity to the heat supply system and (2) creates extra demand for electricity. It is also important to first gain an understanding of the direct role (i.e., without artificially raising outlet temperatures) nuclear produced industrial process heat could play before considering the complexity of technologies to boost reactor temperatures.

Table 2. Industrial heat demand temperature ranges from the literature and reactor systems capable of operating in the associated temperature ranges.

Temperature Range	LWRs	LMFRs	HTGRs	VHTRs	MSRs	SCWRs	GFRs
<300 °C	✓	✓	✓	✓	✓	✓	✓
300–500 °C	x	✓	✓	✓	✓	✓	✓
500–1000 °C	x	x	✓ [1]	✓ [2]	✓ [1]	x	✓ [1]
>1000 °C	x	x	x	x	x	x	x

[1] These systems are capable of operating over only a portion of the prescribed temperature range; [2] VHTRs currently target temperatures of 1000 °C.

3. Industrial Sectors

Heat is used in industry in a variety of applications which can be grouped into seven main categories [5]:

1. Basic metals, with this category dominated by iron and steel manufacturing;
2. The manufacture of chemicals and chemical related products including basic pharmaceutical products and pharmaceutical preparations;
3. Coke and refined petroleum products;
4. Food and beverages;
5. Non-metallic minerals, which this category dominated by glass, cement and ceramics;
6. Pulp and paper; and
7. Wider industry, which explicitly refers to industries not included in the first six categories and encompasses many industries including vehicle manufacturing, construction and textiles.

A key part of this study is to understand how the seven industry sectors relate to the nuclear reactor systems in Table 2. Figure 1 shows total heat demand for these seven industrial sectors per year, in addition to the proportion of heat for each sector already generated by electricity. Note that no information was found on the proportion of heat from electricity for wider industry but, given that the literature indicates wider industry is dominated by electricity, heat in the range 300–500 °C and heat <300 °C [6]; it has been assumed that, in the wider industry sector, heat demand consists of up of 33% electrically generated heat, 33% heat at temperatures below 300 °C, and the remaining 33% at temperatures in the range 300 to 500 °C. The uncertainty on this estimate is illustrated by the error bars under the wider industry category, see Figure 1. Please note that the error bars are illustrative and relate to industrial sectors where there is a lack of data relating to heat demand met by a particular fuel type (e.g., heat demand met by electricity) and/or heat supplied at a particular temperature range are uncertain. The aim of the error bars is to highlight data gaps remaining for UK industrial heat demand.

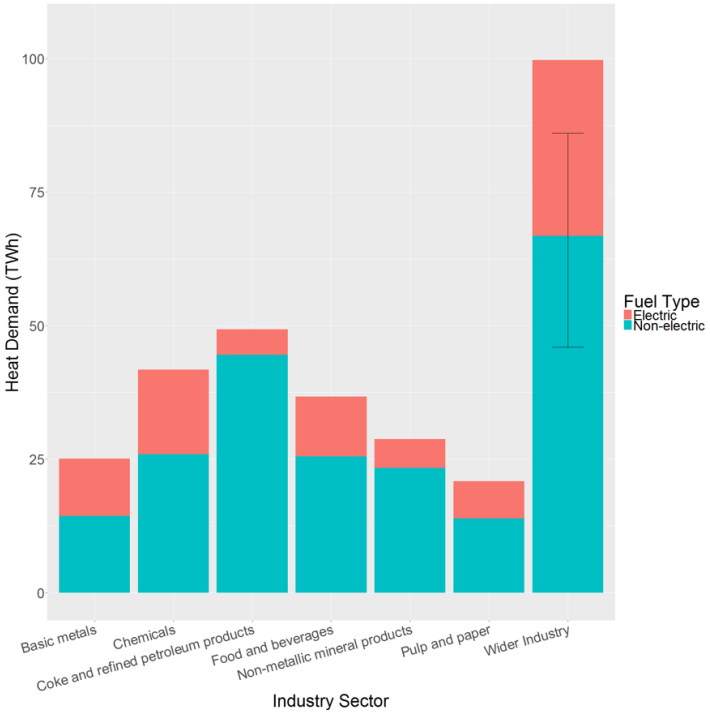

Figure 1. UK industrial heat demand per year by sector [5].

3.1. Basic Metals

Basic metals covers the production of iron and steel, through blast furnaces and electric arc furnaces, as well as electrolytic production of aluminium and copper [27]. For basic metal production, heat demand is primarily met via a mixture of electricity, solid fuels and gas providing heat at temperatures above 1000 °C [28]. Therefore, based on the information in Table 2, the use of direct process heat (i.e., not electrical heat demand) from a nuclear plant is considered very unlikely.

3.2. Chemicals

The chemicals sector covers a highly diverse range of products from industrial gases, fertilisers, plastics, paints, pharmaceuticals and detergents [27]. There are some inconsistencies in the work published previously; reference [27] states that the majority of processes are between 100 and 500 °C, whereas [28] indicates that the bulk of heat demand is between 500 and 1000 °C. Reference [6] gives a breakdown of temperatures >500 °C, between 100 and 500 °C and below 100 °C. The data from reference [6] appears to be in broad agreement with [28], but the boundaries are not consistent with those outlined in this investigation. Therefore, combining the data in [6,28], the following heat breakdown was obtained:

- The proportion of heat <300 °C is 5%.
- The proportion of heat between 300–500 °C is 20%.
- The proportion of heat between 500–1000 °C is 55%.
- The proportion of heat >1000 °C is 20%.

As highlighted in [29], the chemical sector consists of many diverse and interacting sub-sectors covering a wide range of feedstocks, processes and products. In addition, as the industry is also highly focused on private R&D and protective of information, the availability of data in the public domain is very poor [29]. This is underscored by the lack of data within [28] on the number of sites and the large number of businesses operating in this area (of the order 1000). Reference [28] does indicate that a small number of sites operate to produce a large proportion of bulk chemical products, but no data are presented on what proportion of industrial heat is used at these facilities. Therefore, it is not possible to

derive an estimate for the average heat demand per site; furthermore, in the authors' opinion, such an average will likely be of limited value since it is likely that a small number of sites consume large proportions of heat to generate bulk chemicals such as ammonia, nitric acid and hydrogen, for use in upstream chemical processes carried out by different manufacturers at different sites.

3.3. Coke and Refined Petroleum

Within this sector, the dominant source of emissions and heat demand are oil refineries, operating at temperatures in the range 300 to 750 °C and according to [28] have the highest heat demand per site. On average, the amount of heat demand is around 500 MWth per site [28]. This analysis does not include electricity demand at refineries for non-heat purposes. Electricity demand for heat applications is relatively small in this sector [5]. Reference [30] indicates that overall electricity demand is low compared to other industrial sectors. Oil refineries at first appear well-suited for industrial heat applications with much of their heat consumption in the range suitable for LMFRs; however, it is important to note that much of the energy demand at oil refineries is supplied (relatively cheaply) by the materials consumed in the process or via by-products (for example refinery natural gas) [28], resulting in significant quantities of CO_2 release. The low cost associated with meeting current heat demand in at refineries (namely using by-products produced during operation) creates a high-barrier for nuclear power to compete, unless there is a strong legal requirement limiting emission reductions and/or a high carbon price [31].

3.4. Food and Beverages

The food and drink sector makes use of hot water and steam for the production, processing, drying and separation of food and drink products [27]. The heat demands in this sector are principally supplied via natural gas. There are no data available on the number of sites, but around 5800 businesses operate in this area [28]. On the assumption that many businesses are grouped together on the same site, then, supposing there are around 1000 sites, the heat consumption per site (averaging across the year) is ∼0.03 TWh/yr or ∼3 MWth. Given the relatively low power demand (<10 MWth), in the authors' opinion, it seems unlikely (unless there are far fewer sites than 1000) that nuclear power would play a direct role in supplying heat. Furthermore, there are considerable uncertainties regarding the public acceptability of using heat supplied directly from nuclear power in food and beverage production.

3.5. Non-Metallic Minerals

Non-metallic minerals includes the production of glass, ceramics, bricks, lime and concrete, all using a high proportion of gas but also solid fuels within high temperature kilns and furnaces [27]. This sector is dominated with processes having heat demands >1000 °C [28]. Therefore, it is likely that only a very limited role would be played via nuclear power in this sector.

3.6. Pulp and Paper

The pulp and paper sector operates with large amounts of hot water and steam used for the production and evaporation of pulp and drying of the paper product [27]. The process heat temperatures are below 300 °C and currently the heat is provided via natural gas. It has an annual heat consumption of around 14 TWh and operates over 51 sites [28], thus consuming around 30 MWth of process heat per site. The process heat demand is well suited to LWRs (noting in particular experience using nuclear derived heat to power paper mills, with the historic operation of the Halden Research Reactor [32]). Heat demand for this sector could potentially be supplied from large or small LWRs, and the demand is perhaps sufficient to warrant the deployment of a dedicated Small Modular Reactor (SMR) concept.

SMRs, with power outputs of less than 300 MWe, have gained attention in recent years with many SMR concepts being LWR type systems [33,34]. Apart from being ideally suited to customers with

smaller power requirements, the benefits SMRs may offer are: increased flexibility with respect to siting; improved safety performance; reduced construction times; and reduced upfront investment requirements [25]. Their smaller size may also permit new reactor designs and manufacturing methods to be utilised [35]. The challenges facing SMRs relate to development costs; uncertainty surrounding licensing (especially for innovative technologies that regulators are less familiar with); and uncertainties surrounding economic competitiveness, in terms of cost per kWe. The latter of which may be offset to some extent by cost reductions associated with mass production and new manufacturing processes [34,36].

3.7. Summary of Non-Electrically Derived Process Heat by Temperature Range

Using the information in this section, it is possible to estimate the heat demand in the key industrial sectors by temperature range. This information is summarised in Figure 2, noting the large uncertainty associated with wider industry due to the lack of data, as noted at the start of Section 3.

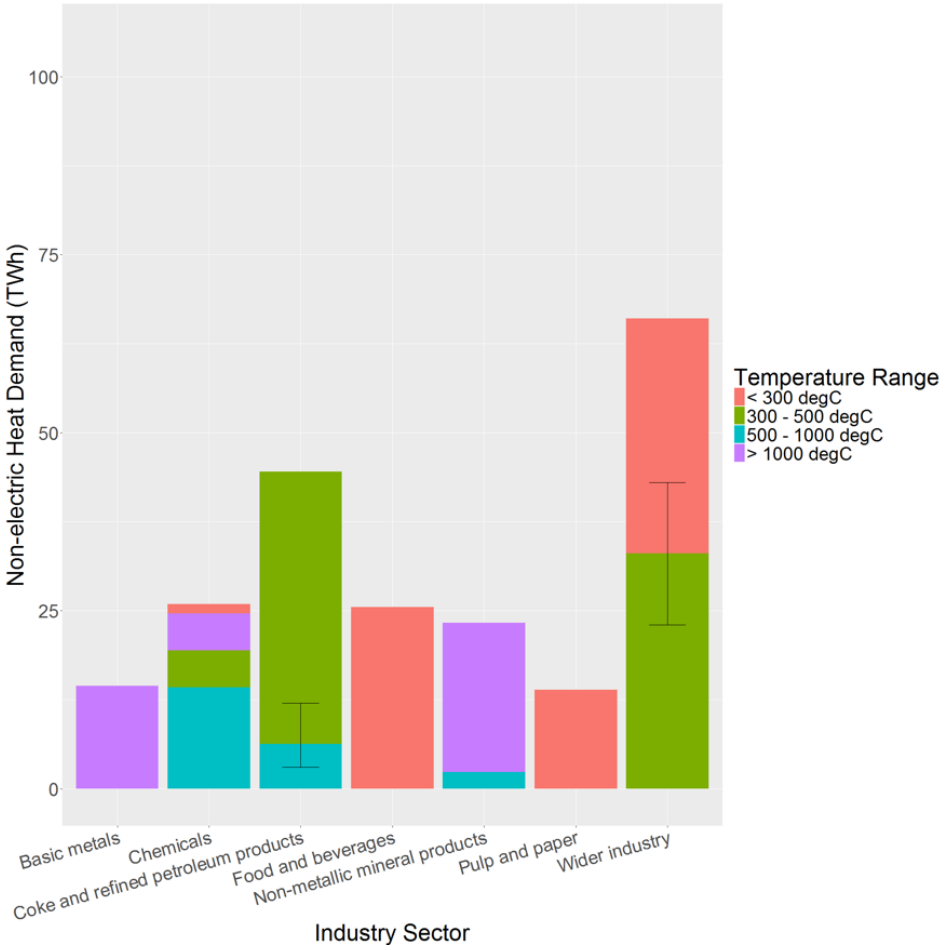

Figure 2. UK heat demand by temperature for non-electrically derived process heat. Error bars indicate uncertainty on the proportion of energy for a particular temperature range and highlight data gaps in a particular industrial sector.

4. Heat Demand Breakdown and Comparison with Reactor Systems

Using the information in Figure 2 and Table 2, it is possible to determine what proportion of the current non-electrically supplied heat demand could be met directly from different reactor systems. This information is summarised in Table 3.

Table 3. Current UK non-electric industrial heat demand and reactor systems that correspond to the required temperature range.

Defined Temperature Range	Proportion of Non-Elec. Heat Demand	Corresponding Reactor Systems
<300 °C	35%	LWRs, LMFRs, SCWRs, GFRs, MSRs, HTGRs and VHTRs
300–500 °C	35%	LMFRs, SCWRs, GFRs, MSRs, HTGRs and VHTRs
500–1000 °C	11%	GFRs [1], MSRs [1], HTGRs [1] and VHTRs [2]
>1000 °C	19%	No current reactor systems

[1] These systems are capable of operating over only a portion of the prescribed temperature range; [2] VHTRs currently target temperatures of 1000 °C.

It is important to note that there is considerable uncertainty on the heat demand by temperature range and fuel type (electric and non-electric) within wider industry. Therefore, it is reasonable to ask whether this sector biases the overall conclusions presented in Table 3. Furthermore, wider industry covers a large number of industries likely resulting in relatively low average heat demand per site (<10 MWth), potentially making it unsuitable for heat supplied from nuclear power if the economic penalty associated with deploying such small reactors is prohibitive compared with alternative sources of heat production (for e.g., electric boilers). To assess the impact of any potential bias associated with the uncertainty on wider industry, Table 4 shows the proportion of non-electrically supplied industrial heat demand, ignoring the heat demand within wider industry. Table 4 clearly shows that the overall result is the same, with the majority of heat demand based on UK data still below 500 °C.

Table 4. The proportion of non-electrically supplied industrial heat demand and corresponding reactor systems that can provide the applicable temperature range.

Defined Temperature Range	Proportion of Non-Elec. Heat Demand	Corresponding Reactor Systems
<300 °C	28%	LWRs, LMFRs, SCWRs, GFRs, MSRs, HTGRs and VHTRs
300–500 °C	29%	LMFRs, SCWRs, GFRs, MSRs, HTGRs and VHTRs
500–1000 °C	15%	GFRs [1], MSRs [1], HTGRs [1] and VHTRs [2]
>1000 °C	28%	None

[1] These systems are capable of operating over only a portion of the prescribed temperature range; [2] VHTRs currently target temperatures of 1000 °C.

The information contained in [28], relating heat demand per site over a 12-month period, makes it possible to infer the average industrial heat demand per site and determines the demand in terms of power and whether the heat demand is sufficiently large (>10 MWth) for the application of small nuclear reactors to directly supply heat. This information is summarised in Table 5. It is important to note that the information in [28] only relates to the average heat demand over the year, which could fluctuate over a seasonal basis or in the event the industrial sectors employ discontinuous batch production. Interestingly, Table 5 shows a wide variety of heat demands for the different sectors, with oil refineries standing out with very large heat demands (around 0.5 GWth per site). Two industrial sectors (chemicals and wider industry) are identified as having a lack of data on the heat demand per site. The chemicals industry may be suitable for heat derived directly from a nuclear power source, but the lack of data makes determining the suitability of nuclear power in the chemical industrial sector with a high degree of confidence difficult.

Table 5. Suitability of direct nuclear process heat to particular industrial sectors.

Industrial Sector	Suitable for Direct Nuclear Process Heat	Average Demand per Site	Amount of Non-Elec. Heat Demand (TWh)
Basic metals	No (temperature too high)	-	14
Chemicals	Yes	Not Available	26
Coke and refined petroleum products	Yes [1]	Approx. 500 MWth	45
Food and beverages	Yes [2]	Approx. 3 MWth	26
Non-metallic mineral products	No (dominated by heat demand >1000 °C)	-	23
Pulp and paper	Yes	Approx. 30 MWth	14
Wider industry	Yes	Not Available	67

[1] Note that a large proportion of heat demand is met via (currently inexpensive) by-products; [2] The low heat demand per site and low temperature may mean that electric heating would be more suitable; unless, perhaps many more businesses are clustered together.

As outlined in Section 3.4, the estimated demand per site in the Food and Beverages sector is around 3 MWth. This heat demand is probably too low for heat supplied directly from nuclear power plants located on site unless there are many more businesses clustered together per site.

5. Hydrogen as a Future Driver for High Temperature Heat

There are future demands that may not currently be captured in Figure 1—for example, demands for hydrogen. As detailed above, there are a number of industrial sectors that may in practice be difficult to decarbonise (e.g., the temperature demand is too high, the demand is dispersed over many sites or issues related to public acceptance). Furthermore, there is an increasing realisation that relying heavily on electricity to achieve decarbonisation of heating and industry is very challenging and the barriers may be so large that it is not practical [37,38]. Hydrogen offers an alternative means to decarbonise many areas of the economy and could be produced in large quantities via energy from nuclear plants. It should be noted, however, that hydrogen is a relatively poor energy carrier and will very likely be superseded by electricity where practical—for example, in light vehicles [39].

There are three key areas where hydrogen may offer unique benefits and is particularly well-suited; these are [37,38]:

- as a means of energy storage for relatively long periods of time (∼weeks);
- for industrial users (both as an important feedstock but also as a means to decarbonise heat demand in industry); and
- for meeting residential and commercial heating demands.

The above list does not include the use of hydrogen in the transport sector. Recent advances in battery technology are likely to result in hydrogen being used only as a means to decarbonise Heavy-Goods Vehicles (HGVs) [38].

Energy storage becomes increasingly important in scenarios with high levels of variable renewables energy production (e.g., high deployment rates of wind and solar energy systems). There are a number of technologies suitable for energy storage [37] including: lithium-ion batteries; redox batteries; flywheels; and hydrogen. Hydrogen has been identified [37] as the only current means to store energy over long periods of time (of the order weeks).

For industry, hydrogen could in principle meet a large proportion of heat demand. Work outlined in Reference [40] indicated a reasonable upper limit for hydrogen in industry as approximately 30% of industry demand in the year 2050 being met via hydrogen.

Residential and commercial heating demands in countries with similar climatic conditions to the UK are particularly problematic. As Figure 3 highlights, heat demand fluctuates rapidly over the year, with peaks of ~300 GWth and lows of ~30 GWth. This presents issues with meeting demand via electricity or combined heat and power, as directly meeting this demand with power plants would result in plants operating for only a few weeks over the year, which carries a large economic penalty [5].

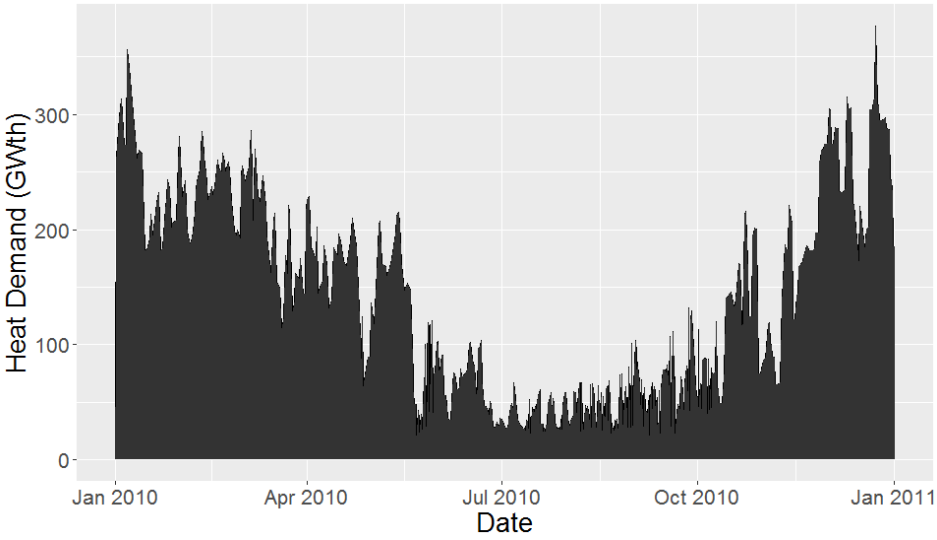

Figure 3. Heat demand (domestic and commercial) variability across the year in 2010 [41].

If any one of the above target groups were to create even modest demands on hydrogen, then the demand would be considerable. Current global hydrogen production (predominantly as a feedstock for the chemical industry) has an energy content of around 6×10^{18} J per year = 6 EJ per year [42], with is primarily produced from fossil fuels. Global residential and commercial heating final energy demand is around 60 EJ per year [43], and the world-wide industrial heat energy demand is also around 60 EJ per year [44].

The preferred means to produce low-carbon hydrogen in the literature is via steam methane reforming with Carbon Capture and Storage (CCS). However, there are number of issues with this:

1. Energy security—the use of natural gas with CCS will only provide a secure source of energy to those countries with large natural gas reserves.
2. Storage capacity of captured CO_2, with only countries having the geology to store large quantities of CO_2 able to deploy CCS at large scale.
3. It becomes very difficult to rely heavily on steam methane reforming with CCS as a predominant source of energy for sectors such as heating since the lifecycle emissions reduction is around 60–85% relative to natural gas in boilers [38]. Therefore, if countries target greenhouse gas (GHG) emission reductions of 90% or more, then this is not compatible with a heavy reliance on hydrogen from steam methane reforming with CCS.

The Challenges of Producing Hydrogen from Nuclear Reactors

Three predominant methods have been considered for producing hydrogen with nuclear derived energy [45]:

- Low temperature electrolysis (LTE);
- High temperature steam electrolysis (HTSE); and
- Sulphur-Iodine cycle (SI).

LTE is the most mature technology and could employ any reactor technology since all that is required is an electric current to drive the process. Of the three methods, LTE is the most mature

but also the least economically attractive [38,45]. Therefore, for nuclear derived hydrogen HTSE and SI have gained the most attention, whereby the ability to also make use of the high temperatures offered by some reactors systems can be used to improve the efficiency of the process and reduce the economic barriers.

HTSE improves the efficiency of hydrogen production relative to LTE via decomposition of high temperature steam (up to 950 °C) rather than liquid water. HTSE operates most efficiently at high temperatures, with efficiencies of ∼55% at temperatures of around 850 °C. At lower temperatures (∼750 °C), the efficiency is still reasonable (∼40%). From Table 2, producing hydrogen via HTSE is clearly well-suited to HTGRs, VHTRs, MSRs and GFRs. However, even with the improved efficiency relative to LTE, the economic barrier is very high when natural gas prices are low—the relative cost difference to steam methane reforming with an assumed carbon price of $27 per tonne of CO_2 in 2014 prices is around a factor of 3 to 3.5 higher for the HTSE/HTGR route operating at ∼750 °C [45].

The SI process is the most technically challenging of the three methods outlined here. The efficiency of the process is around 50% for temperatures ∼900 °C and drops off significantly at temperatures around 800 °C. Previous published work on the economics of SI have employed very optimistic overnight capital costs for the HTGR used to drive the SI process, with [46] using data from [47], which has a HTGR capital cost of $840 per kWe in 2002 dollars. For comparison, the HTGR/HTSE analysis in [45] uses an assumed an overnight capital cost of $6000 per kWe in 2014 dollars. There are also significant uncertainties relating to the costs associated with the chemical plant [48]. Therefore, in the medium-term, the HTSE method with a HTGR operating ∼750 °C offers a reasonable trade-off between high efficiency, reduced cost uncertainties and reduced technical challenges compared to LTE and SI methods.

It should be noted that, for hydrogen produced from a nuclear reactor such as a HTGR, a key safety concern is the ability of tritium to pass through metallic walls, penetrating the water/steam and/or product gas cycle. Tritium's extreme mobility requires effective retention mechanisms in a process heat plant [49]. For hydrogen produced via nuclear process heat to be usable as a commodity, it must have a tritium contamination below the tolerated limits specified by national legislation [50]. Therefore, one important safety requirement is to minimise tritium contamination in the downstream products. There are three principal sources of tritium production in a HTGR; these are [49]:

- Ternary fission, which accounts for around 50% of total tritium (T) production. However, tritium produced during the fission process in HTGRs will be completely retained within intact TRISO coated fuel particles. Only a small fraction originating from fuel particles with a broken coating or from uranium contamination of the core graphite is expected to escape into the coolant.
- Activation reactions from traces of lithium [^{6}Li (n,α) T] and boron [^{10}B (n,2α) T] in the graphite components, control rods and burnable poisons. These reactions account for around 35% of the total tritium production. Tritium originating from boron is usually assumed to be completely released into the coolant. Tritium produced from lithium impurities in the graphite can rapidly diffuse through the graphite components into the coolant.
- Helium-3 activation which accounts for around 15% of the total tritium production.

Hence, to minimise tritium contamination, it is essential to keep the fraction of defective/failed TRISO coated fuel particles and the level of ^{3}He and Li impurities as low as possible, in addition to designing an effective helium purification system. Nevertheless, there will always be some level of tritium that can be transported to the process side by permeation through the heat exchanger tubes into the downstream products [50].

6. Alternative Demands from Industry Users

Heat is not the only demand industry users may have when investigating the possible application of a nuclear reactor system as a source of heat. Industrial users may necessitate simplifications in siting, for instance a reduced emergency planning zone and reduced times for commissioning of a

nuclear facility. The ability of SMRs to enable reductions in siting constraints is highly uncertain and no clear consensus has come forward for this possibility. However, in the authors' opinion, it is very likely that any reduction in siting constraints will almost certainly be design dependent. Here, systems that offer clear safety performance advantages, such as indefinite decay heat removal or highly robust fuel forms with very low probability of fission product release [25], could offer the potential for improvements in siting considerations.

7. Pathways to Decarbonise Industrial Heat Demand

Nuclear reactor systems can clearly play a role decarbonising industrial heat demand, and the available UK data appears to indicate that around 70% of non-electrically supplied heat, in terms of energy, is for temperatures below 500 °C, with around 10% for temperatures in the range 500–1000 °C. Whilst electrically supplied heat could be expanded, this will place extra demands on any future electricity grid which will likely become under increasing demands if heat pumps are used to decarbonise homes and business, along with demand from electrification of transport [37]. This extra demand would likely require large-scale investment in the electricity distribution system, in addition to the investment needed to build low-carbon sources of electricity. Whilst HTGR, VHTR, GFR and MSR systems have an advantage in terms of capability to achieve higher temperatures, the relative benefit over LMFRs and LWRs is actually smaller than indicated in the literature [51–53], since major parts of the heat demand could be served by almost all reactor types.

The literature indicates Carbon Capture and Storage and electrification of industrial processes as the preferred mechanisms to decarbonise industrial emissions, including industrial heat demand [54]. Carbon Capture and Storage (CCS) is a key technology for achieving significant reductions in global CO_2 emissions. CCS has been highlighted [40] as potentially important under a range of scenarios, including capturing emissions from power plants, district heat networks and capturing emissions from the production of hydrogen, both as a chemical feedstock and as a means to provide energy for homes, business and industry. CCS is seen [54,55] as potentially playing a major role in reducing emissions from industry, especially because of the inherent chemical reactions in industrial processes that produce CO_2 (for example iron & steel, cement and aluminium production). It is important to distinguish between: (1) process emissions, which are produced in inherent chemical reactions; and (2) fuel consumption. For example, in iron production, the reduction of iron ore (Fe_2O_3) produces CO_2: $Fe_2O_3 + 3\,CO \longrightarrow 2\,Fe + 3\,CO_2$ and those related to fuel consumption, which are dominated by the combustion of natural gas. Hence, it is very difficult to eliminate entirely greenhouse gases from industrial processes because of the inherent chemical reactions that produce CO_2, even in a scenario where all energy is produced via low-carbon sources [56]. CCS has been highlighted as of high interest to the cement, iron & steel, petroleum and chemical sectors mainly because of their high CO_2 production rates [31].

Many of the individual components of CCS are well-tested, for instance capturing CO_2 emissions has been demonstrated in industry and at power plants [54]. However, the issue of storing CO_2 and the amount that can be stored for long periods of time remains highly uncertain [56]. Currently, the only means to store CO_2 at relatively low cost, with low environmental impact, and high confidence regarding storage integrity, is using depleted oil and gas reservoirs [56]. The estimates of the amount of CO_2 that can reasonably be stored vary widely with estimates for the UK being between 9 billion and >75 billion tonnes of CO_2 [57]. The lower estimates focus on storage in oil and gas wells, and represent the highest confidence with regards to storage integrity and minimal environmental impact [54]. Given that the primary reason for capturing CO_2 is to avoid atmospheric release, the most conservative approach is to assume that only oil and gas wells are suitable for CO_2 storage, which in the UK corresponds to 9 $GtCO_2$ [57].

Under high CCS scenarios (with CCS used in electricity production, heat and industry), annual emissions could be as high as 210 $MTCO_2$ [57], which would use the 9 billion tonnes of CO_2 storage

capacity in around 40 years. Therefore, CCS is seen as a medium-term solution in scenarios with high CO_2 outputs requiring capture, unless more speculative storage capacity for CO_2 is utilised.

Industries highlighted as particularly suitable for CCS (iron & steel, oil refining and cement production) are generally ill-suited to nuclear power derived heat. This is especially true for basic metals and non-metallic mineral production due to their high temperature demands (>1000 °C); see Figure 2. There is arguably some role for coke and petroleum production; however, around 40% of emissions are from chemical processes [28], implying a need to use CCS, even if nuclear power can provide a competitive means to supply low-carbon heat. It should be noted from Table 5 that coke and refined petroleum makes up a substantial proportion of current heat demand; however, in scenarios with large reductions in emissions from transport, demand in this sector would be expected to significantly decline. Therefore, CCS appears to generally complement nuclear power to achieve decarbonisation of industrial processes.

An alternative to both hydrogen and direct nuclear process heat for industrial applications is the use of biofuels. Reference [40] indicates that a feasible limit of around 20% of industrial energy use could be derived from biofuels.

Note that the above analysis has focused on current heat demand. The UK government has looked at future industrial energy demand under a variety of scenarios [4]. The scenario with the largest industrial energy demand assumes strong economic growth of around 2.5% per year (compared with 1.8% per year in 2017) and accompanying high growth in industry. For the first 10 to 15 years, much of the industrial energy demand is driven by the need to manufacture new low-carbon technologies (for example heat pumps, wind turbines, nuclear power plants, insulation and electric vehicles). Thereafter, demand in low-carbon technologies continues, but much of the demand is driven by growth in wider industry, with a high proportion of consumer goods produced domestically on the basis that a global carbon price and/or ambitious international agreement on emissions is reached to allow UK industries to compete on a level playing field [4]. Hence, whilst demand for basic metals, non-metallic minerals and chemicals would rise, the rise would be dominated by wider industry, implying a larger proportional demand for heat below 500 °C and electrically derived heat.

8. Conclusions

The lack of quantitative information in the open literature relating to UK industrial heat demand by temperature and energy consumption impacts the ability for rigorous analysis regarding the role of current and advanced reactor systems could play in providing industrial heat. This study has been able to determine, based on using a number of UK and European studies, the current industrial heat demand by energy use in the UK. This information enables future studies to quantify the current benefit conventional and advanced reactor systems could provide in reducing greenhouse gas emissions from industrial emissions associated with burning fossil fuels to supply heat. It has been found that, of the current 300 TWh of industrial heat demand, around 35% of heat demand is at temperatures below 300 °C and could be provided using all reactor types including conventional PWRs and BWRs; 35% falls into the range 300 to 500 °C which could directly be provided from LMFRs, SCWRs, HTRs, VHTRs; 10% falls into the range 500 to 1000 °C, which could be provided using HTRs, VHTRs and potentially some role and MSRs and GFRs; and the remaining 20% of heat demand is for temperatures above 1000 °C, which to date no reactor has been demonstrated capable of operating at. For heat demand >1000 °C, it would be necessary to:

- continue to use fossil fuels;
- use hydrogen or biofuels; or
- artificially raise the outlet temperature of reactor systems, for example via the use of heat pumps.

Current heat demand will unlikely be representative of future heat demand. The UK government has investigated future industrial energy demand; see reference [4]. This analysis predicts that heat demand from wider industry would likely constitute a higher proportion of overall heat demand

in future scenarios where the UK industrial sector plays a more dominant role in the UK economy. Scenarios with a large industrial heat demand are of particular interest when considering the role nuclear power in industrial heat applications. This investigation has inferred that, for wider industry, heat demand is dominated by temperatures below 500 °C, implying that LMFRs and SCWRs, and to some extent LWRs would be suitable candidates or MSRs, GFRs, HTRs and VHTRs operating at lower temperatures.

Author Contributions: Conceptualisation, A.P.; methodology, A.P.; validation, B.M.; formal analysis, A.P.; investigation, A.P.; writing—original draft preparation, A.P.; writing—review and editing, B.M.; visualisation, A.P.; supervision, B.M.

Funding: This research was funded by the UK government's Department for Business, Energy and Industrial Strategy, as part of the Nuclear Innovation Programme (Nuclear Facilities and Developing a Strategic Toolkit) Grant No. 13070002346.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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