THE ROYAL SOCIETY

CLIMATE CHANGE : SCIENCE AND SOLUTIONS | BRIEFING 3

Low-carbon heating and cooling: overcoming one of world's most important net zero challenges

In brief

Heating and cooling, or thermal energy, should be high on the decarbonisation agenda as it is the world's largest form of energy end use and its largest source of carbon emissions when compared with power and transport. Varied low-carbon solutions are available for heating and cooling in residential, commercial and industrial settings in all areas of the world. Some are in early adoption and require scaling up, others are at the demonstration stage and require concentrated research, development and deployment (RD&D). This briefing looks at routes to reduce emissions through increasing energy efficiency, applying technology options to replace fossil fuel heating and cooling, and innovating in the storage and transport of thermal energy.

INSIGHTS

- Heating and cooling for homes, industry and commercial premises, is a major source of carbon dioxide emissions and as such merits a prominent place in net zero strategies, with its own dedicated targets.
- Differing national conditions and legacies will require a range of approaches to reduce carbon dioxide emissions from heating and cooling. However there is also scope for greater international co-operation and networking.
- Using less energy to heat or cool buildings through improved insultation, heat reflection and other means should be the first target of any decarbonisation programme.
- Many forms of low-carbon heating and cooling are in their infancy compared to fossil-based systems and require significant demonstration and deployment to test their relative cost-effectiveness.
- Key areas for research, development and deployment across low-carbon heating and cooling include: heat pumps, electric heaters, district systems, renewable heat and hydrogen.
- Interesting options are emerging to create new ways of providing heating and cooling whereby the thermal energy required is generated in one place, stored and transported for use in another, sometimes including conversion from electricity to heat or vice-versa.

1. Heating, cooling and climate change

Globally about 50% of heat is used in the industrial sector. Another 46% is consumed in buildings.

Heat and cold energy, (or thermal energy), provides heating and cooling for space, water, cooking, industrial processes, air conditioning and refrigeration. The sector is estimated to account for around half of the world's end-use energy and 40% of its energy-related global carbon dioxide (CO_2) emissions[1]. Fossil fuels dominate heat supply, with renewables other than biomass meeting only around 10% of global demand[2]. Globally about 50% of heat is used in the industrial sector. Another 46% is consumed in buildings, mainly for space and water heating. The IEA projects that the application of efficiency improvements, the replacement of fossil fuels and decarbonising electricity generation could reduce space heating emissions by 30% by 2030[3].

Heating and cooling in residential and commercial buildings are expected to grow by around 80% over the period 2010 – 2050 in a 'business-as-usual' scenario[4]. Climate change is expected to reduce the projected demand for heating and increase demand for cooling[5], with some estimates forecasting that space cooling will account for more global energy demand than space heating by 2060[6].

Heating and cooling are hard to decarbonise because their generation and use are diverse and highly decentralised, unlike electricity with its large centralised generating facilities and distribution system. Heating and cooling are provided in many ways, from simple open fires to gas fired boilers and air conditioning units. They are usually installed as standalone items in homes or in larger systems for office blocks and factories, but often several different solutions are employed together, such as gas heating for the winter and electric cooling for the summer. Heat generation and use has tended to be co-located, from boilers in homes to high-temperature heat for industry.

District heating, whereby heat is generated at a central point and piped into buildings, is an exception, providing much of the heat for northern European homes. Low temperature heat has been transported by pipeline for up to 80 km in countries such as Austria and Denmark[7].

The production of heat for industry accounts for an estimated 20% of global CO_2 emissions[8]. The choice of heating method in industry is dictated by several factors including the process parameters (control, temperature, cleanliness etc.), the quantity of heat required and the cost. Examples include melting, drying, baking, cracking (breaking down molecules) and reheating. Industrial operations generally use electricity, fossil fuels or biomass to produce heat when and where it is needed. A wide range of zero carbon heating options will therefore be required.

A low-carbon transition in heating and cooling requires innovation in new technologies and infrastructure; investment to scale them up; and the transformation of millions of domestic and industrial units.

2. Actions needed in research, development and deployment

Heat may appear an intractable obstacle on the road to net zero, but many solutions are available for all regions of the world, some are established but still with challenges, others are just emerging. These solutions include: more efficient use of thermal energy, alternative zero carbon technologies for heating and cooling and using new technologies to store and transport heat from source to points of use.

2.1 Don't lose heat – increasing energy efficiency

The simplest way to decarbonise heat is to use less of it, through increased energy efficiency, better insulation and waste heat recovery and use. Residential space heating intensity or energy consumption per floor area has significantly improved in many countries. Finland, France, Germany and South Korea have experienced reductions of over 30% since 2000[9].

Most work so far has focused on residential and commercial buildings. Heat loss due to industrial and energy conversion processes has not been addressed so effectively and represents an important area of research.

2.2 Heating and cooling without the carbon

2.2.1 Decarbonising domestic heating and cooling

While energy efficiency can reduce demand, new options are required to provide the zero carbon heating and cooling that homes will still require.

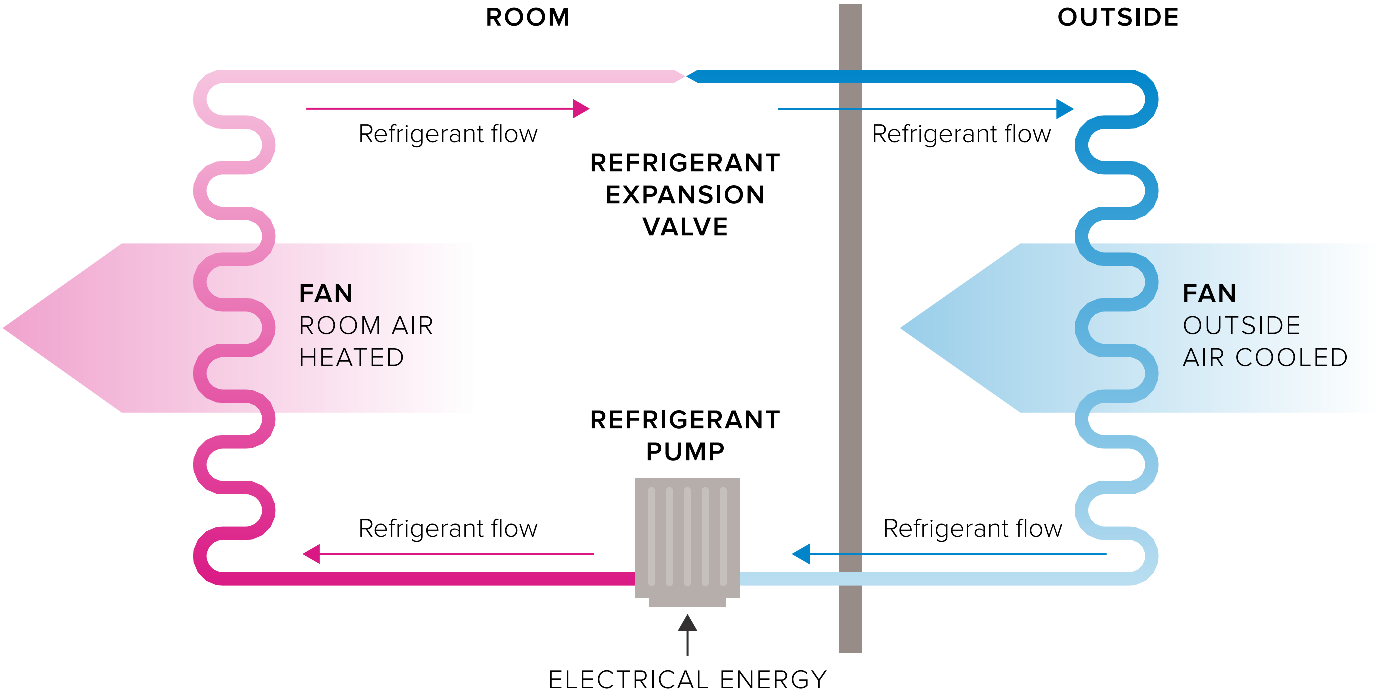
Electrifying heating

Electrical resistance heaters remain in use in many parts of the world and can offer a cheap to install low-carbon option if supplied by low-carbon electricity. However, if more widely used, these would require new power generation capacity and grid reinforcement[10]. Modern storage heaters, using ceramic bricks (for example the Dimplex Quantum heater) and composite phase change material modules (for example the Jinhe PCM heater) to store and release thermal energy, can provide a cost-effective option that uses off-peak or surplus electricity and reduces the need for grid reinforcement[11].

Alternatively, heat pumps driven by low-carbon electricity can be used and, as they principally move heat rather than generate it, they use less electricity than direct electrical heating[12]. They essentially work like refrigerators in reverse (Figure 1), using similar technology to warm a space rather than cooling it. Evaporators collect low-temperature heat from the air, water, or ground outside a building and upgrade it in a condenser via a compression process for use in heating the building. The performance of heat pumps is measured by a parameter called Coefficient of Performance (COP), which is the ratio between the heating/cooling provided and the electrical input. The COP is usually between 2 and 5, the higher the COP, the higher the efficiency. Reversible heat pumps can also deliver cooling for air-conditioning which may drive up electricity usage if homeowners have that option in the summer.

FIGURE 1

Schematic of an air source heat pump. Heat is transferred from outside to inside a building using a refrigerant liquid.



In the US, for example, around 40% of new homes now have a heat pump.

Heat pumps are widely seen as a leading low-carbon solution, with, for example, the UK projecting the use of 5.5 million by 2030[13], and potentially 21 million by 2050[14]. Globally, as of 2019, heat pumps met only 5% of residential heat demand, although they have grown strongly in some areas. In the US, for example, around 40% of new homes now have a heat pump[15] and the EU market is growing at around 12% per year[16]. Air source heat pumps are reaching cost-competitiveness with gas boilers in regions of the US with milder climates and cheap electricity[17]. Conversely, their use is more difficult in cold and wet conditions where their efficiency is at its lowest when heat is needed most[18]. Studies have also identified upfront purchase costs and power prices as major barriers[19], along with the need to greatly expand the power grid.

Researchers are investigating ways to improve performance, such as new condenser designs[20] and the use of small temperature difference fan coil units as the terminals for air source pumps[21].

Natural gas replacement

Replacing the natural gas in a gas network with a low or zero carbon alternative gas is very attractive from an infrastructure point of view.

One transitional option is to blend natural gas with renewable biomethane, produced from organic waste products, for which Europe is the leading producer globally. It currently represents a small component of the gas supply mix, at 2 billion cubic metres (BCM) in 2019 in a market of 514 BCM, but studies suggest it could grow to provide 3% of gas in 2030[22, 23].

A low-carbon variant on gas-fuelled heating being considered in some countries is to replace some or all of the natural gas in the network with 'green' hydrogen, produced from renewable energy through electrolysis, or 'blue' hydrogen produced from natural gas using carbon capture and storage (CCS). However, this option faces several challenges. Costs of green and blue hydrogen are currently uncompetitive with those of fossil-fuel derived hydrogen[24]. Boiler conversion has significant costs, estimated for example at £2,000 – 4,000 per household in the UK. Hydrogen can also cause embrittlement in conventional iron or steel gas network pipes[25], although these can be converted to plastic pipes suitable for hydrogen[26, 27]. Public acceptability in terms of safety also needs to be considered. Demonstration projects in the 2020s should show if such challenges can be overcome. In the UK a major project known as H21 is being planned to provide millions of homes with 100% hydrogen. In the Netherlands, the small-scale 'Hydrogen on natural gas on Ameland' project has demonstrated blending of up to 20% green hydrogen in the network[28]. (See briefing 4: *The role of hydrogen and ammonia in meeting the net zero challenge*.) In addition, hydrogen can also be used in fuel cells in combined heat and power systems (CHP). In Japan, the national basic hydrogen strategy plans to install 5.3 million domestic CHP units (called Ene-Farm cells) by 2030[29], providing both heat and distributed electricity generation.

Solar heating

In some places, such as in the EU and China, medium temperature (80 – 150°C) solar heating is being used to partly replace fossil fuelled boilers. Solar systems range from small installations for hot water in family homes to large-scale solar thermal plants for centralised systems. Solar cooling, where solar thermal panels are used in the refrigeration circuit, are also gaining popularity as they have the potential to reduce electricity consumption by more than 30%[30].

Centralised heating and cooling

Low-carbon centralised or district heating for water and space, or cooling for space, is used in many countries, particularly where it is already installed and can be decarbonised[31], but it is also a possibility for new-build housing in urban areas. In the UAE, district cooling accounts for 23% of the cooling load[32]. Networks served by combined heat and power units are making way for lower carbon '5th generation' versions where low temperature heat is upgraded as needed by heat pumps and heating and cooling are matched, for example with supermarket refrigeration supplying heat to residential blocks[33].

The centralised heat can come from several zero carbon sources. Geothermal energy using heat from the Earth's crust makes up a tiny fraction of heating worldwide but has a role in countries with high volcanic activity and accessible hot springs such as El Salvador, New Zealand, Kenya, and Philippines[34]. In Iceland geothermal energy provided about 65% of primary energy in 2016, including around 27% of electricity[35]. Nuclear power stations produce large amounts of heat (typically around 3.4GW) which is traditionally used to generate electricity. The waste heat (around 60%) can be used for district heating. Alternatively, the heat produced, which can be between 300°C and 800°C, can be used directly for large scale district heating or to drive industrial processes[36].

Table 1 shows the approximate installation costs, energy sources and the advantages and disadvantages for zero carbon domestic heating options for a typical 3-bedroom UK house with gas central heating.

In the UAE, district cooling accounts for 23% of the cooling load.

TABLE 1

Comparison of domestic heating system installation costs[37], energy source, advantages, and challenges.

Heating type	Approximate installation costs	Energy source	Advantages	Challenges
Heat pumps	£10k scale.	Clean electrical and external thermal energy.	>1 COP for electrical power – uses less electricity per kWh heat output, uses existing electricity supply network – less reinforcement/new generation needed.	Large area needed for ground/water source heat pumps. Poor performance of air source pumps at low ambient temperatures. Relatively low temperature output – changes needed to domestic central heating system.
Hydrogen boilers	£3k scale.	Chemical energy (green hydrogen).	Partial use of existing gas distribution network and central heating system (new boiler needed).	Large-scale green hydrogen supply, high pressure transmission / enlarged pipelines needed, materials compatibility issues, safety and public acceptance issues.
Electrical storage heaters	£2k scale.	Clean electrical energy.	Known technology using existing electricity networks. Can be used to time shift electrical load.	Not as flexible/instant, might require replacement of central heating system.
Electrical heaters (no storage)	~£1k scale.	Clean electrical energy.	Known simple technology using existing electricity supply networks and minimal change to domestic wiring.	Additional load on electricity supply – additional generation and network reinforcement likely, creation of demand spikes.

2.2.2 Decarbonising industrial heating

Replacing the use of fossil fuels in industry is very application dependent, with the main low carbon options outlined below. Decarbonising heat used in heavy industry is a particular challenge due to the scale of energy required. One route is to continue using fossil fuels but with carbon dioxide capture and storage (CCS) to remove some of the CO_2 emissions. (See briefing 5: *Carbon dioxide capture and storage*.)

Low-carbon electricity

Low-carbon electrical heating technologies are well developed, while other alternatives to fossil fuels (see below) are largely at very early stages of demonstration. Electrical heating is a mature technology which is easily controlled and has a wide temperature range. Examples include electric arc furnaces for steel-making where induction furnaces used for smelting scrap steel operate at over 1000°C. However, using electrical heating for applications such as cement, glass and ceramic production is very likely to be expensive compared to other options. The price of energy will, as ever, be critical.

Hydrogen

Low-carbon hydrogen may be a suitable heat source for industries such as steel, cement, glass and chemicals as it burns at very high temperatures. However, despite having technical potential to eliminate emissions from industrial heating, hydrogen remains an expensive alternative to bioenergy, even when CO_2 prices reach \$100/tCO_2[38]. (See briefing 4: *The role of hydrogen and ammonia in meeting the net zero challenge*)

Biomass

Biomass can be used for high-temperature heating but is limited by resource availability and cost[39]. Biomass already supplies 6% of total thermal energy for cement production globally[40]. It is also used in industries that can use biomass residues to meet heat demand, such as sugar, wood processing, pulp and paper. Biomass can only be considered at best to be low carbon rather than zero-carbon unless CCS is employed.

Alternative heat sources

Solar thermal technologies have already been used at small scale for functions including drying, washing and sterilisation at temperatures below 250°C in industries such as textiles, food and paper[41]. However, although some early commercial projects are appearing, solar process heating for industry is still chiefly at the research and demonstration stage[42]. Researchers around the world are now exploring concentrated solar power (CSP) for very high temperature industrial processes. In Europe, for example, one company has developed a technology using around 500 movable mirrors to heat ceramic particles to up to 1000°C. A pilot plant is being built at a pasta factory in Italy[43]. As mentioned above, the heat from nuclear reactors can also be used to directly drive chemical processes such as hydrogen production.

For relatively low-temperature heating, heat pumps have potential applications in industry as well as in homes. Studies have identified possibilities for their use in industries such as paper, food and chemicals[44]. Another low temperature option is to harness wind energy directly for heating by using a wind-powered thermal energy system (WTES) where rotating energy is converted to heat by methods such as a brake mechanism.

2.3 Future thermal energy storage, transport and distribution – shifting thermal energy through time and space.

While future options for space and industrial heating mainly continue the pattern of heating and cooling being generated at the sites where it is consumed, research is rapidly expanding to consider possibilities where heat or cold is moved from where and when it is created to where and when it is needed. This is particularly important where waste or excess heat unavoidably produced in industrial processes could be recovered and used to replace fossil fuel heating.

Waste heat can be recovered for use, directly or after upgrading with heat pumps and projects are now underway around the world to reuse industrial heat[45]. In Sweden, for example, industrial waste heat recovery provides 9% of the heat supplied in residential district heating[46]. In one UK funded project, waste heat from a 'peaking' power plant is to be stored using a phase change material (PCM) and used to supply heat to local buildings[47]. Tata Steel is working with Swansea University to capture and re-use the waste energy from its Port Talbot steelworks, which could potentially offset more than a million tonnes of carbon dioxide emissions each year[48].

2.3.1 Thermal energy storage

Thermal energy storage is the storage of energy in the form of heat or coldness, enabling it to be used a later time for heating, cooling or power generation – whether hours, days, weeks or months. Systems range from the familiar domestic hot water tank or storage heater to novel PCMs now being demonstrated, and thermochemical routes being explored in research[49]. However, social and cultural barriers may affect the adoption of the technology[50]. The following examples illustrate a few of the many options.

One company has developed a technology using around 500 movable mirrors to heat ceramic particles to up to 1000°C.

A 130 MWh thermal/30MW electrical hot rock store was built to support the Hamburg electricity grid in Germany.

Storing heat through chemical reactions

Thermal energy can be stored through reversible chemical reactions. For example, metallic iron, with an energy density similar to fossil fuels can be transported and then oxidised with agents such as air or water to produce heat, offering a potential high energy density and low-cost solution[51]. After being oxidised for industrial use, iron can be regenerated using hydrogen, providing a potentially carbon-free cycle (Figure 1)[52].

Storing solar heat

Recent years have seen some very large concentrated solar power installations which store heat at scale as well as generating power. For example, the 280MW Solana plant in Arizona, has over 3,000 400ft long mirrors that reflect sunlight onto a pipe containing a heat transfer fluid (HTF), which is heated to around 400°C. Some of the HTF is used to produce steam for electricity, while the remainder flows into molten salt storage tanks which retain the heat to be converted to power when there is no sunlight[53].

Carnot batteries

A 'Carnot battery' stores surplus energy from renewable generation in the form of heat in rocks, phase change materials or molten salts. The technology is also sometimes known as pumped thermal electricity storage or electro-thermal electricity storage. The heat can be converted back into electricity when required making it an option for storing power in a renewables-dominated grid. The system is potentially flexible, storing heat, cold or electricity using various materials and conversion methods, noting that energy is lost in all conversions. Heat can be retained for direct use, or for a combination of heating, cooling and power. However, it faces the challenge that lifting the temperature up to a high-level using a heat pump currently leads to a low coefficient of performance. Several prototypes and demonstrators have been built, including a 130 MWh thermal/30MW electrical hot rock store built to support the Hamburg electricity grid in Germany[54].

Cryogenic energy storage

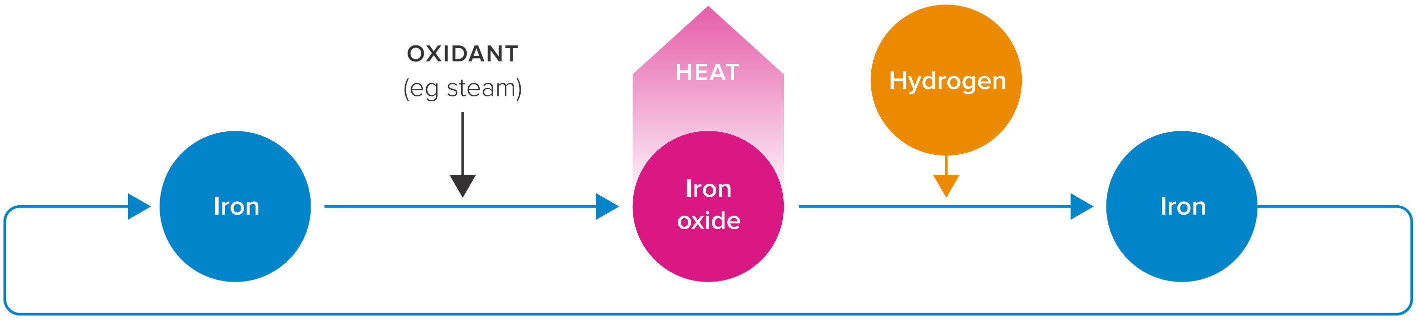
Projects such as the EU's CryoHub are investigating storing renewable energy as a cryogenic liquid such as liquid air (at -194°C) which can be used to refrigerate industrial facilities while being stored and also be boiled to generate electricity through a turbine[55].

New options for the cold chain

PCMs have been demonstrated for cooling as well as heating applications. In one project for the refrigerated 'cold chain' supply, UK scientists and China's railway rolling stock company CRRC Shijiazhuang created the world's first shipping container using PCMs based on salt hydrates to store coldness. The container used for transporting fresh produce was given one charge for about two hours, which kept the temperature at 5 – 12˚C for up to 190 hours for 35,000 kilometres of road and 1000 kilometres of rail transport across different climate zones[56].

FIGURE 2

Iron heat loop. Energy input in hydrogen reduction process.



BOX 1

Cooling core cargoes: a green solution for transporting Antarctic ice samples

Cylinders of ice drilled out of Antarctic ice for climate change research are to be kept frozen on their journey to laboratories in Europe by an innovative zero-carbon cooling technology. The British Antarctic Survey (BAS) research involves drilling, packaging, transferring, storing and transporting the ice cores from Greenland and the Antarctica to the UK for analyses (Figure 3).

A major challenge, however, has been that the cargoes have had to be transported in thermally insulated boxes in refrigerated containers powered by diesel engines. Now, however, BAS is working with a UK University to develop a zero-emission cold chain system for transporting the ice cores. The key technology is a composite phase change material (cPCM) which, combined with vacuum insulation, can maintain the temperature at any part of the ice cores below -45˚C for over 20 hours (Figure 4).

FIGURE 3

Transporting ice cores from Antarctica to Europe.

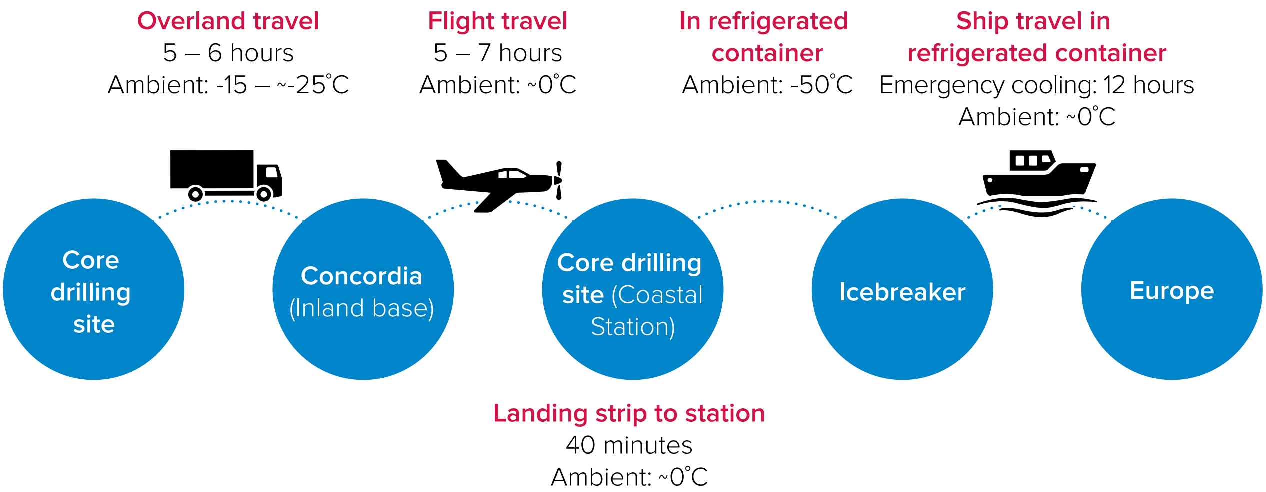
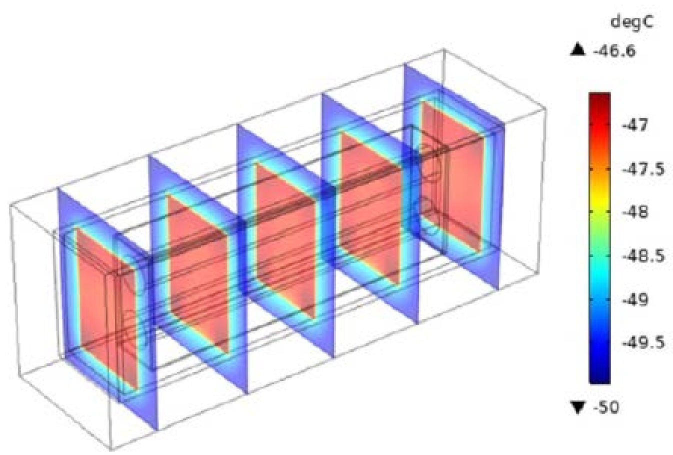


FIGURE 4

Thermal cross section of ice core storage.



2.3.2 Heat distribution

The capacity to store and transport heat and cold in materials such as PCMs and thermochemical storage materials opens up a range of new ways to acquire, store, transport, trade and use low-carbon thermal energy.

In principle, the service station of the future might not only offer pumps for hydrogen, biofuels and charging points for electric vehicles but packs of hot or cold energy for use in vehicles or homes. In cars such packs could be accommodated in specially made compartments – the 'heat and cooling tank' – being filled whilst the battery is charged. It has been estimated that power used by cabin heating can decrease the range of an electric vehicle (EV) by around 50% in a cold climate[57]. Air conditioning has a low COP in converting power to thermal energy at low temperatures and is better served by having its own energy source, rather than using the EV battery. In homes, larger modules could be used to heat or cool a property, being replaced and recharged on a weekly basis. Similar technologies could be used in the health service to keep medicines such as vaccines at the required temperatures.

2.3.3 The road to net zero for heat storage and distribution

By 2030, a new thermal energy storage sector should be emergent in all areas of the world, largely based on converting existing energy infrastructure such as service stations into multi-vector energy hubs or by presenting new methods of heating and cooling to areas without a grid infrastructure.

By 2050, net zero could be supported by entirely new thermal energy supply chains using thermal energy storage to convey heating and cooling efficiently where it cannot be generated locally. Consumers may be routinely obtaining heating and cooling for vehicles and home use from the local energy distribution points.

3. Conclusion

Specialists in heating and cooling technologies have identified a need for increased collaboration in ways similar to those seen in other areas, such as renewable power and batteries, where national and international partnerships have been formed in an effort to accelerate progress in research, development and deployment.

The IEA has suggested that "a wide array of countries and stakeholders" need to act together. Greater international co-ordination to accelerate progress in developing solutions to the world's greatest source of carbon emissions could be critical in bringing new technologies to scale and shaping the low-carbon heating and cooling sector of the future.

This briefing is one of a series looking at how science and technology can support the global effort to achieve net zero emissions and adapt to climate change. The series aims to inform policymakers around the world on 12 issues where science can inform understanding and action as each country creates its own road map to net zero by 2050.

To view the whole series, visit **royalsociety.org/climate-science-solutions**
To view contributors to the briefings, visit **royalsociety.org/climate-solutions-contributors**

References

1. The IEA. 2019. Energy-related CO_2 emissions 2019. Heat 40%. Power 35%. Transport 25% (provided by email 28 April 2021)

2. The IEA. 2019 Renewables 2019: Heat. See https://www.iea.org/reports/renewables-2019/heat (accessed 15 April 2021)

3. The IEA. Heating. See https://www.iea.org/reports/heating (accessed 15 April 2021)

4. Lucon O. *et al*. 2014: Buildings. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panelon Climate Change. See https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_chapter9.pdf (accessed 15 April)

5. Arent, D.J. *et al*. 2014: Key economic sectors and services. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. See https://www.ipcc.ch/site/assets/uploads/2018/02/WGIIAR5-Chap10_FINAL.pdf Accessed 15 April 2021)

6. Isaac M, van Vuuren D. Modeling global residential sector energy demand for heating and air conditioning in the context of climate change *Energy Policy* **37** 507-521 (https://doi.org/10.1016/j.enpol.2008.09.051)

7. Euroheat & Power and Austrian Institute of Technology. 2020. The barriers to waste heat recovery and how to overcome them? See https://ec.europa.eu/futurium/en/system/files/ged/20200625_discussion_paper_v2_final.pdf (accessed 15 April 2021).

8. The IEA. 2019. Renewables 2019: Heat. See https://www.iea.org/reports/renewables-2019/heat (accessed 15 April 2021)

9. The IEA, 2020, Energy Efficiency Indicators. See https://www.iea.org/reports/energy-efficiency-indicators-overview (accessed 15 April 2021)

10. Ofgem. 2016. Future Insights Series: The Decarbonisation of Heat. See https://www.ofgem.gov.uk/system/files/docs/2016/11/ofgem_future_insights_programme_-_the_decarbonisation_of_heat.pdf (accessed 15 April 2021)

11. Darby, S.J. Smart electric storage heating and potential for residential demand response. Energy Efficiency 11, 67–77 (2018). https://doi.org/10.1007/s12053-017-9550-3

12. Office of Energy Efficiency & Renewable Energy. Heat Pump Systems. See https://www.energy.gov/energysaver/heat-and-cool/heat-pump-systems. (accessed 15 April 2021)

13. The Climate Change Committee. 2020 Sixth Carbon Budget. See https://www.theccc.org.uk/publication/sixth-carbon-budget/ (accessed 15 April 2021)

14. The Climate Change Committee. 2021. Development of trajectories for residential heat decarbonisation to inform the Sixth Carbon Budget (Element Energy). See https://www.theccc.org.uk/publication/development-of-trajectories-for-residential-heat-decarbonisation-to-inform-the-sixth-carbon-budget-element-energy/ (accessed 15 April 2021)

15. National Association of Home Builders. 2019. Air Conditioning and Heating Systems in New Homes. See https://eyeonhousing.org/2019/12/air-conditioning-and-heating-systems-in-new-homes-4/ (accessed 15 April 2021)

16. The IEA. 2020. Heat Pumps tracking report. See https://www.iea.org/reports/heat-pumps (accessed 15 April 2021)

17. Center on Global Energy Policy at Columbia University SIPA. 2019. Decarbonizing space heating with air source heat pumps https://www.energypolicy.columbia.edu/research/report/decarbonizing-space-heating-air-source-heat-pumps (accessed 15 April 2021)

18. Center on Global Energy Policy at Columbia University SIPA. 2019. Decarbonizing space heating with air source heat pumps https://www.energypolicy.columbia.edu/research/report/decarbonizing-space-heating-air-source-heat-pumps (accessed 15 April 2021)

19. Center on Global Energy Policy at Columbia University SIPA. 2019. Decarbonizing space heating with air source heat pumps https://www.energypolicy.columbia.edu/research/report/decarbonizing-space-heating-air-source-heat-pumps (accessed 15 April 2021)

20. Byeongsu Kim, Sang HunLee, Dong Chan Lee,Yongchan Kim. Performance comparison of heat pumps using low global warming potential refrigerants with optimized heat exchanger designs. *Applied Thermal Engineering* **171** (https://doi.org/10.1016/j.applthermaleng.2020.114990)

21. Liu D., Li P.K., Zhai X.Q., Wang R.Z., Liu M. (2017) Small Temperature Difference Terminals. Handbook of Energy Systems in Green Buildings. Springer (https://doi.org/10.1007/978-3-662-49088-4_23-2) Byeongsu Kim, Sang Hun Lee, DongChan Lee, Yongchan Kim. Performance comparison of heat pumps using low global warming potential refrigerants with optimized heat exchanger designs. *Applied Thermal Engineering* **171**. (https://doi.org/10.1016/j.applthermaleng.2020.114990.).

22. Wood Mackenzie. 2020. Can biomethane decarbonise Europe's gas market? See https://www.woodmac.com/news/opinion/can-biomethane-decarbonise-europes-gas-market/ (accessed 15 April 2021)

23. European Biogas Association. Biomethane with bright opportunities towards the 2030 target See https://www.europeanbiogas.eu/biomethane-bright-opportunities-towards-2030-target/ (accessed 15 April 2021)

24. European Commission. 2020. A hydrogen strategy for a climate-neutral Europe. See https://ec.europa.eu/energy/sites/ener/files/hydrogen_strategy.pdf (accessed 15 April 2021)

25. The Climate Change Committee. 2018. Hydrogen in a low carbon economy. See https://www.theccc.org.uk/wp-content/uploads/2018/11/Hydrogen-in-a-low-carbon-economy-CCC-2018.pdf. (accessed 15 April 2021)

26. Energy Networks Association. 2020. Replacing Britain's old gas pipes and laying the foundations of a zero-carbon gas grid. See https://www.energynetworks.org/newsroom/replacing-britains-old-gas-pipes-from-safeguarding-the-public-to-laying-the-foundations-of-a-zero-carbon-gas-grid (accessed 15 April 2021).

27. The European Plastic Pipe and Fittings Association. Plastic pipe data around Europe. See https://www.teppfa.eu/media/reference-projects/french-gas-company/ (accessed 15 April 2021).

28. Kiwa Technology.2012. Management Summary "Hydrogen blending with Natural Gas on Ameland" See https://www.netbeheernederland.nl/_upload/Files/Waterstof_56_7c0ff368de.pdf (accessed 15 April 2021).

29. METI. 2019. The Strategic Road Map for Hydrogen and Fuel Cells. See https://www.meti.go.jp/english/press/2019/pdf/0312_002b.pdf (accessed 15 April 2021).

30. XiaoZhi Lim. How heat from the Sun can keep us all cool. *Nature* **542**. (http://doi:10.1038/542023a)

31. C40 Cities Climate Leadership Group. How to decarbonise your city's heating and cooling systems. See https://www.c40knowledgehub.org/s/article/How-to-decarbonise-your-city-s-heating-and-cooling-systems?language=en_US (accessed 15 April 2021).

32. IRENA. 2017. Renewable energy in district heating and cooling a sector roadmap for remap. See https://www.irena.org/publications/2017/Mar/Renewable-energy-in-district-heating-and-cooling (accessed 26 April 2021)

33. Millar, M.-A.; Elrick, B.; Jones, G.; Yu, Z.; Burnside, N.M. Roadblocks to Low Temperature District Heating. *Energies 2020*, **13**. (https://doi.org/10.3390/en13225893)

34. International Renewable Energy Agency. See https://www.irena.org/geothermal (accessed 16 April 2021)

35. Government of Iceland. See https://www.government.is/topics/business-and-industry/energy (accessed 16 April 2021)

36. Royal Society. 2020. Nuclear Cogeneration: civil nuclear in a low-carbon future. See https://royalsociety.org/topics-policy/projects/low-carbon-energy-programme/nuclear-cogeneration. (accessed 16 April 2021)

37. Delta Energy and Environment, 2018. The Cost of Installing Heating Measures in Domestic Properties. BEIS Research Paper Number: 2020/028Final

38. The IEA. 2019. The Future of Hydrogen. See https://www.iea.org/reports/the-future-of-hydrogen (accessed 16 April 2021)

39. The IEA.2018. Clean and efficient heat for industry. See https://www.iea.org/commentaries/clean-and-efficient-heat-for-industry (accessed 16 April 2021)

40. The Global CCS Institute. 2019. Bioenergy and carbon capture and storage. See https://www.globalccsinstitute.com/wp-content/uploads/2019/03/BECCS-Perspective_FINAL_18-March.pdf (accessed 16 April 2021)

41. IEA-ETSAP and IRENA.2015. Solar Heat for Industrial Processes. See http://www.inship.eu/docs/sh5.pdf (accessed 16 April 2021)

42. IEA-ETSAP and IRENA.2015. Solar Heat for Industrial Processes. See http://www.inship.eu/docs/sh5.pdf (accessed 16 April 2021)

43. Hiflex project. An Innovative Renewable Energy System. See http://hiflex-project.eu/ (accessed 16 April 2021)

44. Kosmadakis, G. Estimating the potential of industrial (high-temperature) heat pumps for exploiting waste heat in EU industries, *Applied Thermal Engineering*, **156**. (https://doi.org/10.1016/j.applthermaleng.2019.04.082.)

45. van de Bor D, Ferreira, C, Kiss, A. Low grade waste heat recovery using heat pumps and power cycles. *Energy*. **89**. (https://doi.org/10.1016/j.energy.2015.06.030.)

46. Euroheat & Power and Austrian Institute of Technology. 2020. The barriers to waste heat recovery and how to overcome them? See https://ec.europa.eu/futurium/en/system/files/ged/20200625_discussion_paper_v2_final.pdf (accessed 15 April 2021).

47. Amp Clean Energy.2019. AMP Clean Energy and The University of Birmingham to develop ground-breaking heat storage solution. See https://www.ampcleanenergy.com/news/amp-clean-energy-and-the-university-of-birmingham-to-develop-ground-breaking-heat-storage-solution (accessed 15 April 2021).

48. Swansea University. Decarbonising the steel industry. See https://www.swansea.ac.uk/business-and-industry/business-partnerships/tata-steel/research-collaborations/decarbonising-the-steel-making-process/ (accessed 30 April 2021)

49. Dept. Business Energy and Industrial Strategy. 2016. Evidence Gathering: Thermal Energy Storage (TES) Technologies. See https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/545249/DELTA_EE_DECC_TES_Final__1_.pdf (accessed 16 April 2021)

50. Simó-Solsona M, Palumbo M, Bosch M, Fernandez AJ. Why it's so hard? Exploring social barriers for the deployment of thermal energy storage in Spanish buildings. *Energy Research & Social Science*.**76**.2021. (https://doi.org/10.1016/j.erss.2021.102057).

51. Zhongliang Yu *et al*. Iron-based oxygen carriers in chemical looping conversions: A review, Carbon Resources Conversion,2. (https://doi.org/10.1016/j.crcon.2018.11.004)

52. Swinkels Family Brewers. 2020. See https://swinkelsfamilybrewers.com/content/bcorporate/en/media/persberichten/tu-e-demonstrates-iron-fuel-at-brewery-bavaria--a-new-circular-a.html (accessed 16 April 2021)

53. Power Technology. Solana Solar Power Generating Station, Arizona, USA. See https://www.power-technology.com/projects/solana-solar-power-generating-arizona-us/ (accessed 16 April 2021)

54. Siemens Gamesa Renewable Energy GmbH & Co. See https://www.siemensgamesa.com/en-int/-/media/siemensgamesa/downloads/en/products-and-services/hybrid-power-and-storage/etes/siemens-gamesa-etes-ad-teaser-industrial-decarbonization.pdf (accessed 16 April 2021)

55. Cryohub. Cryogenic Energy Storage for Renewable Refrigeration and Power Supply. See https://cryohub.info/en-gb/ (accessed 16 April 2021)

56. University of Birmingham. 2018. UK and China scientists develop world-first cold storage road/rail container. See https://www.birmingham.ac.uk/news/latest/2018/12/scientists-develop-world-first-cold-storage-roadrail-container.aspx (accessed 16 April 2021)

57. Zhang, Ziqi & Wang, Dandong & Zhang, Chengquan & Chen, Jiangping. Electric vehicle range extension strategies based on improved AC system in cold climate – a Review. *International Journal of Refrigeration*. **88**. (https://doi.org/10.1016/j.ijrefrig.2017.12.018.)