UK Energy Research Centre

UKERC Technology and Policy Assessment

Expectations and sources of cost reduction in low/zero carbon domestic heat technologies: the case of heat pumps

UKERC project scoping note

Phil Heptonstall (Imperial College London)
Mark Winskel (The University of Edinburgh)
Rob Gross (Imperial College London)

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Introduction to UKERC

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Technology and Policy Assessment (TPA) within UKERC

The Technology and Policy Assessment (TPA) team was set up to inform decision-making processes and address key controversies in the energy field. It aims to provide authoritative and accessible reports that set very high standards for rigour and transparency. Subjects are chosen after extensive consultation with energy sector stakeholders.

The TPA has been part of UKERC since the centre was established in 2004 and is now in its fourth phase, which started in 2019. The primary objective of the TPA is to provide a thorough review of the current state of knowledge through systematic reviews of literature, supplemented by primary research and wider stakeholder engagement where required.

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1. The subject of this TPA project

1.1 Context and project scope

Net zero and decarbonising domestic heat

The UK government is committed to achieving net zero levels of carbon dioxide and other climate-changing emissions by 2050, with a recently revised interim target of a 78% reduction by 2035, relative to a 1990 baseline (BEIS, 2020a; BEIS, 2021b). The power generation sector has made substantial progress towards these goals but this has not been matched in other sectors (CCC, 2021). Although very significant improvements will be required in many areas including transport, agriculture and industry, the decarbonising of heat provision to the UK's 29 million homes represents a particular challenge, not least because of the costs involved (CCC, 2019c). Compounding this is the perception in some quarters that it will be 'disruptive and uncertain' (Lowes and Woodman, 2020), and that the industry incumbents are focused on protecting their investments in the current infrastructure such as the gas transmission and distribution networks (Lowes, Woodman and Speirs, 2020).

Domestic heating and hot water provision accounts for around a quarter of total UK energy demand (CCC, 2019c) and 17% of carbon dioxide emissions (BEIS, 2021c). UK domestic heating is dominated by natural gas boilers which, together with the inherent flexibility of the gas supply network, are well suited to meeting the very large diurnal and seasonal fluctuations that are a feature of UK domestic heat demand (Carmichael *et al.*, 2020). Current deployment of low carbon heating in the UK is very low, accounting for only 5% of total heating demand, suggesting that the overwhelming majority of UK homes will need upgrading to a decarbonised heat solution by 2050 (Carmichael *et al.*, 2020; Rosenow *et al.*, 2020).

In respect of policy, the UK government is expected to publish its Heat and Buildings Strategy later this year which will set out the measures to be adopted to increase the energy efficiency of buildings and decarbonise the provision of heat. Although no details of the strategy are available at this stage, current proposals include a grant-based scheme for supporting heat pumps (BEIS, 2020b), and there is speculation that the strategy will include a ban on new gas boilers for homes by 2035 (Holder, 2021). The Scottish Government already has a target that new homes will have 'zero direct emissions heating' (which in effect means a ban on gas boilers) by 2024 (Scottish Government, 2021).

Low-carbon domestic heat may be delivered by a range of technologies and approaches, including district heating (provided the heat source is low carbon), decarbonising of the gas grid through hydrogen or biomethane, and improving the thermal efficiency of homes. However it seems very likely that heat pumps will play a very significant role (Rosenow *et al.*, 2020). In their sixth carbon budget, the UK Climate Change Committee suggested that heat pumps are likely to dominate in the

provision of domestic heat, representing around three quarters of new installations (CCC, 2020).

UK heat pump sales have increased recently and are expected to rise again this year (edie newsroom, 2021). The UK Climate Change Committee reported that domestic heat pump installations had risen by 9% to 36,000 in 2020 (CCC, 2021). However, these numbers must be seen in the context of the aspirations for future deployment. The UK government have set a target of 600,000 installations per year by 2028 (HMG, 2020). This compares with the Climate Change Committee's assessment that the installation rate should reach more than one million per year by 2030, corresponding to a cumulative installed total of 5.5 million by that date (CCC, 2021). The Scottish Government has set a target for 50% of homes to be converted to low-carbon heating by 2030 (Scottish Government, 2021), with heat pumps expected to be a major contributor to this target. Other analyses, such as the Future Energy Scenarios by National Grid ESO (2020, 2021) have also concluded that the UK is likely to need a dramatic rise in the use of heat pumps if decarbonisation targets are to be met. Taking a global perspective the IEA recently estimated that worldwide heat pump installations will need to rise from a current level of less than 20 million per year to more than 100 million per year by 2050 (IEA, 2021).

In response to UK aspirations, in late 2020 the Environmental Audit Committee ran a call for evidence for increasing heat pump uptake, lowering costs, building the skills required to support increased deployment, and identifying the issues around consumer acceptance. In their response to that call for evidence, the Department for Business, Energy and Industrial Strategy said that 'the forthcoming Heat and Buildings Strategy will set out our overall ambition for the market growth of heat pumps' (EAC, 2020). To support this, in May of this year BEIS held a workshop on the innovation requirements to support the rollout of their target of 600,000 heat pumps a year by 2028, and to identify barriers, cost reduction requirements, training needs, business models and financing (BEIS, 2021a).

The focus and scope of this project

It is clear that domestic heat decarbonisation is a key challenge if the UK is to continue its journey to net zero. This was also reflected in the topics consultation events undertaken by the UKERC Technology and Policy Assessment team in late 2019 and early 2020, where the issues around the provision of low carbon heating, and the implications for buildings, households and consumers were raised several times (Gross, Hanna and Heptonstall, 2020).

This TPA project will focus on heat pumps because many analyses have concluded that they will be a more cost effective route to decarbonising heat provision and that they are therefore likely to play a major role in achieving carbon reduction targets. This is not to say that the alternatives cannot make a valuable contribution, not least because some of the lower estimates for future costs of these alternatives suggest that they may be comparable. There may also be circumstances where the technical characteristics of these alternatives makes them more suitable (Speirs *et al.*, 2017).

We will bear in mind the need to recognise other technology options for the provision of low carbon domestic heating such as hydrogen and district heating networks which are at different stages of technological maturity, deployment, and cost reduction trajectories.

However, the required pace of emissions reductions in the domestic heat sector represents a very significant challenge, and a key part of that challenge is the current high cost of heat pumps and the associated heating system changes required to make best use of the different operating characteristics of heat pumps, relative to the incumbent gas boilers. There is also a very large difference between the typical estimated total costs in a new build home versus a retrofit to an existing property. In a new property, a heat pump and the required high levels of building fabric energy efficiency might cost around £5k, whereas the equivalent cost of retrofitting to an existing home might be around £26k (CCC, 2019c). The consequences of this differential are further exacerbated by the slow rate of housing stock renewal in the UK.

In respect of heat pump cost reductions, there is evidence of positive learning rates[1] for heat pumps (Weiss *et al.*, 2010; Kiss, Neij and Jakob, 2012) and some analyses have assumed markedly positive rates (Knobloch *et al.*, 2019). There is also evidence from other countries that suggests that widespread and large-scale shifts in heating provision are possible (Gross and Hanna, 2019). However, some of the experience in the UK to date suggests that cost reductions have been relatively small. An analysis by Renaldi *et al.* (2021) covering the period from 2010 to 2019 concluded that capital costs of heat pumps had declined modestly, with an experience rate of 5.5% for air-source heat pumps and a rate of 3.3% for ground-source heat pumps. Comparing these cost reductions to two other countries, the authors found that they were less than in Sweden, and particularly so in relation to Switzerland. When installation costs were included the analysis found that UK costs had actually risen, with an experience rate of -2.3% for air-source heat pumps and a rate of -0.8% for ground-source heat pumps. For comparison, in their 2019 net zero analysis, the Climate Change Committee assumed an 11% cost reduction (an absolute value, not a learning rate) for air-source heat pumps between 2025 and 2050, taking into account the capital costs of the units and installation costs, but not the cost of any other home system upgrades that might be required such as a hot water cylinder or new radiators (CCC, 2019b; 2019a).

The evidence for reductions in capital costs of heat pumps is a key part of the analysis for this project, but there are other factors which bear upon the final cost of a delivered unit of heat. These include the coefficient of performance (COP) [2] of the heat pump, the costs of installation, any heating system or building fabric upgrades that may be required to maximise overall efficiency, the generating, transmission and

[1] The learning rate in this context is the cost reduction associated with a doubling of installations. A positive rate means that costs are reducing, a negative rate means that costs are rising.

[2] COP is a measure of heat pump efficiency, and is the ratio of heat produced per unit of electricity consumed. Because this ratio varies with the external temperature, a Seasonal Performance Factor (SPF) is also used, to show the average COP of a heat pump over the heating season.

distribution costs of the electricity used to run the heat pump, and any wider energy system impacts. In respect of the cost of electricity, some commentators have raised the concern that the relative economic case for heat pumps is weakened by the policy costs which are applied to electricity but not gas (Barnes and Bhagavathy, 2020).

Although this project aims to bring together the evidence from past cost trends and future expectations of costs for heat pumps, there is also an opportunity to link the analysis to earlier cost forecasting efforts for other technologies, and the propensity for those forecasts to turn out to be wrong, sometimes quite dramatically so (Heptonstall *et al.*, 2012; Candelise, Winskel and Gross, 2013; Wiser *et al.*, 2016; Wiser *et al.*, 2021). Part of the analysis will also be to compare decarbonisation scenarios in respect of the assumptions and forecasts of the technologies used for heat provision (and any assumed cost reductions). There is also a geographical dimension to the provision of heat since there are often considerable differences between countries in areas such as the standard of home insulation, which affects the costs of home heating and the suitability of different low carbon heating technologies for differing climatic conditions.

It is important to recognise the difficulties in the definition of system boundaries when analysing the costs of heat provision e.g. whether or not to include the electricity distribution network upgrades that may be required to support widespread domestic heat pump deployment. Linked to this boundary-setting issue is that some analysts have suggested that it may be better to think of heat pumps as a part of an integrated solution for the provision of energy-related services, that use a cluster of elements including smart meters, time-of-use electricity tariffs, heat pumps, electric vehicles, solar PV and storage (Carmichael *et al.*, 2021).

Finally, it may be that there are technologies which have some similarities with heat pumps (e.g. air conditioning units) which can be examined if there is insufficient evidence available for the cost trajectories of heat pumps. This, and the need to keep in mind the other technology options for domestic heat decarbonisation may lend itself to a case study approach. The project will also explore the opportunities for linkages with other ongoing and forthcoming heat-related projects within the UKERC research programme.

1.2 Work plan

Key project deliverables and the overall timeline are set out below:

- The first task of this project is to produce a scoping note (this document), and then set up the project webpage, where the scoping note and any subsequent outputs will be published. The aim is to complete this task in August 2021.
- The project expert group will be convened (see Section 2.4), and the first meeting of this group will be held after the scoping note has been published.

- The systematic review (see Section 2.5) will be carried out during the Autumn and Winter 2021, with the findings analysed and synthesised after that.
- A draft output, in the form of a report or briefing paper, will be produced in late Q1/early Q2 2022 and shared with the project expert group for their comments.
- The output will then be finalised, and published on the UKERC website, to be followed by activities to disseminate the findings.

1.3 Research questions

The overarching research question which this project will address is:

What is the potential for cost reductions in heat pumps for decarbonising domestic heat supply?

Potential sub-questions which the project may consider include:

- Is there evidence of learning rates and learning curves for heat pumps?
- What are the past trajectories and forecasts of heat pump deployment in the UK and other countries?
- What is the range of heat pump cost forecasts and deployment scenarios, and what explains the ranges?
- To what extent do the characteristics of heat pumps align with those energy technologies which have experienced significant cost reductions?
- Are there any directly analogous technologies whose cost and deployment experience can inform heat pump cost projections?

These questions will be further informed by the initial analysis and in consultation with the expert group (see section 2.4).

2. The UKERC TPA Approach

2.1 Overview

The TPA approach learns from the practice of systematic review, which aspires to provide more convincing evidence for policymakers and practitioners, avoid duplication of research, encourage higher research standards, and identify research gaps. This *evidence based* approach is common in areas such as education, criminal justice, and healthcare.

The goal is to achieve high standards of rigour and transparency. However, energy policy gives rise to a number of difficulties for prospective systematic review

practitioners and the approach is not common in energy. We have therefore set up a process that is inspired by the evidence based approach, but that is not bound to any narrowly defined method or techniques.

This assessment protocol describes this process. It provides a specification of the means by which we will consult stakeholders and solicit expert input, specifications for searching the literature, and criteria against which relevant findings will be assessed.

2.2 Assessment sequence

The TPA team has identified a series of steps that need to be undertaken in each of its assessments. These steps, derived from the practice of *systematic review* in non-energy policy analysis, are outlined in Figure 1 below.

Whilst this project will follow this generalised approach, developed for all TPA work, it will be adapted to reflect the available resources, which may mean that some of the steps in Figure 1 are not appropriate or may need to be revised.

Scoping prospective issues	Solicit expert input	Define criteria for assessment	Review literature	Synthesis and analysis	Prepare draft report	Consult, peer review and refine	Publish and promote
Questions/issues							
What are key problems and issues	Need to reflect a range of informed opinion	Ensure transparent, rigorous and replicable process	Need to review literature thoroughly	Need to apply rigorous criteria to evaluation of relevant studies	Need to identify key issues and discuss initial findings with stakeholders	Need to seek peer review and gain wide ranging criticism of initial work	Need to ensure report reaches key audience
Actions							
Write scoping note Seek feedback from advisory group Seek feedback from online listing of initial scoping	Appoint expert group Hold expert/ stakeholder workshop	Develop assessment protocols Discuss expert group and AG Place protocols in public domain	Apply protocol to literature search Detailed and transparent 'trawl' Identify relevant sources	Apply protocol to evaluation and synthesis of literature Detailed and transparent assessment of evidence base	Write preliminary draft assessment	Host stakeholder workshop to discuss draft report Send draft report for peer review Make appropriate revisions to draft report	Design and graphics Publication Launch events
Outputs							
Scoping note	Web publication of expert group	Assessment protocols			Draft report	Final report	Published report

Figure 1: Typical process for TPA studies

2.3 Stakeholder engagement

The project will seek input and comment from relevant stakeholders in the academic, policy-making, and industrial communities. The project scoping note will be published on the UKERC website.

2.4 Expert advisers

We will engage with a small group of expert advisers who can bring their experience and perspectives to bear on the subject. The expert advisers will be asked to comment on the scope of the project and the proposed approach, advise and assist us in the selection of relevant evidence sources, and review draft results. The expert advisers will be announced in due course and will be listed in the project output(s).

2.5 Research sources and review protocol

A systematic review protocol typically provides a rationale for the choice of sources and lists the main databases, bibliographies, catalogues, personal contacts, and other sources that are to be searched. It will also specify the years to be covered and the search criteria that will be used. As identified in the Assessment Sequence section above, we will adopt an approach that is consistent with the available timescale.

We plan to use the selection of key words or phrases shown in Table 1 below, combined into search strings. We will apply these strings in Science Direct, Google Scholar, and Google. We will also use the Google 'Advanced Search' settings to conduct targeted searches of the specific organisation websites listed at the end of this subsection. All searches will be restricted to English language only.

For each search string and database combination we will inspect the first 100 returned results. Where more than 100 results are returned by a search, and we find that directly relevant material is still being found as we approach the 100th result, then we will go on to examine the next 50 results to ensure that we capture as much relevant material as possible, within the constraints imposed by the time available. The search terms will be revised as results are reviewed and following discussion with the expert advisers, and input from stakeholders where appropriate.

To help inform this scoping note, an initial experimentation with searches in Science Direct and Google was carried out. This suggests that many of the results returned from Science Direct relate to analyses of the technical aspects and physical or economic performance of heat pumps, and/or their optimisation and integration with the electricity and wider energy systems. The results returned by the Google searches undertaken so far appear to be more immediately productive with respect to answering the research questions set out above. The intention therefore is to conduct the Google searches (both the general and targeted institutions) first. Citation trails from the most relevant material will be followed up but only where these are very clearly directly relevant i.e. we would expect them to fall into the highest relevance rating as defined below. Science Direct and Google Scholar searches will then be conducted.

Category 1	Category 2	Category 3
“heat pump”	cost	history
heating	“cost reduction”	domestic
	“learning rate”	home
	“learning curve”	building
	“experience rate”	house
		household

Table 1: Proposed search terms for scoping review[3]

Relevance ratings

Returned results will be filtered manually for relevance based on their title and abstract. If this is not sufficient to determine relevance, further inspection of the main text will be performed. This will allow us to subsequently focus attention only on those documents which are most directly useful in addressing the research question. Each document will be assigned a relevance rating from 1 to 4 according to the following criteria:

1. Article shows clear discussion and/or data that is directly focussed on some or all of the research questions.

2. Article shows clear discussion and/or data that is related to but is not directly focussed on any of the research questions.

3. Article mentions at least one of the search terms, but is of only limited relevance to the research questions.

4. Article is found to be irrelevant or duplicate on closer inspection.

Databases / sources

Science Direct

Science Direct provides access to Elsevier journals and e-books including on physical sciences and engineering and social science topics.

Google scholar

[3] Quotation marks are used for terms with more than one word to denote that the entire specific string will be searched for.

Searches using Google scholar include a range of relevant journal paper databases in addition to those published by Elsevier, such as Taylor & Francis, Wiley Online and IEEE.

Google

In addition to a set of general Google searches, documents published by the following institutions will be searched by using the combinations of search terms described above and restricting the search to the site name of the institution.

- Association for Decentralised Energy
- BEIS
- Committee on Climate Change
- European Commission
- European Heat Pump Association
- Ground Source Heat Pump Association
- Heat Pump Association
- IEA
- Institute for Public Policy Research
- National Grid

3. References

Barnes, J. and Bhagavathy, S. M. (2020) 'The economics of heat pumps and the (un)intended consequences of government policy', *Energy Policy*, 138, p. 111198. doi: 10.1016/j.enpol.2019.111198.

BEIS (2020a) *Energy White Paper - Powering our Net Zero Future*. Department for Business, Energy and Industrial Strategy, London. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/945899/201216_BEIS_EWP_Command_Paper_Accessible.pdf.

BEIS (2020b) *Future support for low carbon heat: consultation*. Department for Business, Energy and Industrial Strategy, London. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/888736/future-support-for-low-carbon-heat-consultation.pdf.

BEIS (2021a) *Heat pumps-Innovation requirements for the deployment of heat pumps in the UK*. Department for Business, Energy and Industrial Strategy, London.

BEIS (2021b) *UK enshrines new target in law to slash emissions by 78% by 2035*. Department for Business, Energy and Industrial Strategy, London. Available at: https://www.gov.uk/government/news/uk-enshrines-new-target-in-law-to-slash-emissions-by-78-by-2035.

BEIS (2021c) *Unicorn or silver bullet? Filling evidence gaps on decarbonising heat (Presentation by John Saltmarsh)*. Department for Business, Energy and Industrial Strategy, London. Available at:

https://www.youtube.com/watch?v=JbRx95MRIkk&t=580s.

Candelise, C., Winskel, M. and Gross, R. J. K. (2013) 'The dynamics of solar PV costs and prices as a challenge for technology forecasting', *Renewable and Sustainable Energy Reviews*. Elsevier Ltd, pp. 96–107. doi: 10.1016/j.rser.2013.05.012.

Carmichael, R. *et al.* (2020) *Smart and Flexible Electric Heat, An Energy Futures Lab Briefing Paper*. Imperial College London. Available at: https://www.imperial.ac.uk/energy-futures-lab/policy/briefing-papers/paper-6/.

Carmichael, R. *et al.* (2021) 'The Demand Response Technology Cluster: Accelerating UK residential consumer engagement with time-of-use tariffs, electric vehicles and smart meters via digital comparison tools', *Renewable and Sustainable Energy Reviews*, 139, p. 110701. doi: 10.1016/J.RSER.2020.110701.

CCC (2019a) *Net Zero – Technical Report*. Committee on Climate Change, London. Available at: https://www.theccc.org.uk/publication/net-zero-technical-report/.

CCC (2019b) *Net Zero – The UK's contribution to stopping global warming*. Committee on Climate Change, London. Available at: https://www.theccc.org.uk/publication/net-zero-the-uks-contribution-to-stopping-global-warming/.

CCC (2019c) *UK housing: Fit for the future?* Committee on Climate Change, London. Available at: https://www.theccc.org.uk/publication/uk-housing-fit-for-the-future/.

CCC (2020) *The Sixth Carbon Budget, The UK's path to Net Zero*. Committee on Climate Change, London. Available at: https://www.theccc.org.uk/publication/sixth-carbon-budget/.

CCC (2021) *2021 Progress Report to Parliament*. Committee on Climate Change, London. Available at: https://www.theccc.org.uk/publication/2021-progress-report-to-parliament/.

EAC (2020) *Technological Innovations and Climate Change: Heat Pumps*. Environmental Audit Committee, UK Parliament. Available at: https://committees.parliament.uk/work/684/technological-innovations-and-climate-change-heat-pumps/publications/.

edie newsroom (2021) *Low-carbon heat: UK's heat pump sales set to almost double this year*, *edie*. Available at: https://www.edie.net/news/6/Low-carbon-heat--UK-s-heat-pump-sales-set-to-almost-double-this-year/.

Gross, R. and Hanna, R. (2019) 'Path dependency in provision of domestic heating', *Nature Energy*, 4(5). doi: 10.1038/s41560-019-0383-5.

Gross, R., Hanna, R. and Heptonstall, P. (2020) *UKERC Technology and Policy Assessment, 2019-2020 Topics consultation summary*. UK Energy Research Centre, London. Available at: https://ukerc.ac.uk/research/tpa/.

Heptonstall, P. *et al.* (2012) 'The cost of offshore wind: Understanding the past and projecting the future', *Energy Policy*, 41, pp. 815–821. doi: 10.1016/J.ENPOL.2011.11.050.

HMG (2020) *The Ten Point Plan for a Green Industrial Revolution*. HM Government,

London. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/936567/10_POINT_PLAN_BOOKLET.pdf.

Holder, M. (2021) *Reports: Government considering 2035 'ban' on home gas boilers*, *Business Green*. Available at: https://www.businessgreen.com/news/4031830/reports-government-considering-2035-ban-home-gas-boilers.

IEA (2021) *Net Zero by 2050. A Roadmap for the Global Energy Sector* . International Energy Agency, Paris. Available at: https://www.iea.org/reports/net-zero-by-2050.

Kiss, B., Neij, L. and Jakob, M. (2012) 'Heat Pumps: A Comparative Assessment of Innovation and Diffusion Policies in Sweden and Switzerland.Historical Case Studies of Energy Technology Innovation', in Grubler, A. et al. (eds) *The Global Energy Assessment*. Cambridge, UK: Cambridge University Press. Available at: https://www.cambridge.org/core/books/energy-technology-innovation/heat-pumps-a-comparative-assessment-of-innovation-and-diffusion-policies-in-sweden-and-switzerland/E978A074F743FADA1047CA544EA1AA4C.

Knobloch, F. *et al.* (2019) 'Simulating the deep decarbonisation of residential heating for limiting global warming to 1.5 °C', *Energy Efficiency*, 12(2). doi: 10.1007/s12053-018-9710-0.

Lowes, R. and Woodman, B. (2020) 'Disruptive and uncertain: Policy makers' perceptions on UK heat decarbonisation', *Energy Policy*, 142, p. 111494. doi: 10.1016/j.enpol.2020.111494.

Lowes, R., Woodman, B. and Speirs, J. (2020) 'Heating in Great Britain: An incumbent discourse coalition resists an electrifying future', *Environmental Innovation and Societal Transitions*, 37, pp. 1–17. doi: 10.1016/j.eist.2020.07.007.

National Grid ESO (2020) *Future Energy Scenarios*. National Grid. Available at: https://www.nationalgrideso.com/document/173821/download.

National Grid ESO (2021) *Future Energy Scenarios*. National Grid. Available at: https://www.nationalgrideso.com/future-energy/future-energy-scenarios/fes-2021/documents.

Renaldi, R. *et al.* (2021) 'Experience rates of low-carbon domestic heating technologies in the United Kingdom', *Energy Policy*, 156, p. 112387. doi: 10.1016/j.enpol.2021.112387.

Rosenow, J. *et al.* (2020) *The pathway to net zero heating in the UK. A UKERC policy brief*. UK Energy Research Centre, London. Available at: https://ukerc.ac.uk/publications/net-zero-heating/.

Scottish Government (2021) *Heat in buildings strategy - achieving net zero emissions: consultationn*. Available at: https://www.gov.scot/publications/heat-buildings-strategy-achieving-net-zero-emissions-scotlands-buildings-consultation/.

Speirs, J. *et al.* (2017) *A Greener Gas Grid: What are the options?* Sustainable Gas Institute, Imperial College London. Available at: www.sustainablegasinstitute.org/a-greener-gas-grid.

Weiss, M. *et al.* (2010) ‘A review of experience curve analyses for energy demand technologies’, *Technological Forecasting and Social Change*, 77(3), pp. 411–428. doi: 10.1016/j.techfore.2009.10.009.

Wiser, R. *et al.* (2016) ‘Expert elicitation survey on future wind energy costs’, *Nature Energy*, 1(10). doi: 10.1038/nenergy.2016.135.

Wiser, R. *et al.* (2021) ‘Expert elicitation survey predicts 37% to 49% declines in wind energy costs by 2050’, *Nature Energy*, 6(5). doi: 10.1038/s41560-021-00810-z.