MISSION POSSIBLE

REACHING NET-ZERO CARBON EMISSIONS FROM HARDER-TO-ABATE SECTORS BY MID-CENTURY

ENERGY TRANSITIONS COMMISSION

SECTORAL FOCUS

BUILDING HEATING

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The **Energy Transitions Commission (ETC)** brings together a diverse group of leaders from across the energy landscape: energy producers, energy users, equipment suppliers, investors, non-profit organizations and academics from the developed and developing world. Our aim is to accelerate change towards low-carbon energy systems that enable robust economic development and limit the rise in global temperature to well below 2˚C and as close as possible to 1.5˚C.

In November 2018, the ETC published ***Mission Possible: Reaching net-zero carbon emissions from harder-to-abate sectors by mid-century***. This flagship report is available on our website.

This report describes in turn:

- Why reaching net-zero CO2 emissions across heavy industry and heavy-duty transport sectors is technically and economically feasible;
- How to manage the transition to net-zero CO2 emissions in those harder-to-abate sectors of the economy;
- What the implications of a full decarbonization of the economy are for the energy system as a whole, in particular in terms of demand for electricity, hydrogen, bioenergy/bio-feedstock, and fossil fuels, as well as carbon storage requirements;
- What policymakers, investors, businesses and consumers must do to accelerate change.

This Sectoral Focus complements the *Mission Possible* report by providing **details on the decarbonization of building heating**, which was not covered in the main report.

We warmly thank all experts from companies, industry initiatives, international organizations, non-governmental organizations and academia, who have provided feedback on this consultation paper. Their insights were instrumental in shaping the *Mission Possible* report and this updated Sectoral Focus.

The *Mission Possible* report and the related Sectoral Focuses constitute **a collective view of the Energy Transitions Commission**. Members of the ETC endorse the general thrust of the arguments made in this report but should not be taken as agreeing with every finding or recommendation. The institutions with which the Commissioners are affiliated have not been asked to formally endorse the report. The list of our Commissioners at the time of publication can be found in the *Mission Possible* report.

The Energy Transitions Commission continues to engage actively and work with key policymakers, investors and business leaders around the world, using our analysis and the unique voice of the ETC to inform decision-making and encourage rapid progress on the decarbonization of the harder-to-abate sectors. We are keen to exchange and partner with those organizations who would like to progress this agenda. Please contact us at info@energy-transitions.org.

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REACHING NET-ZERO CARBON EMISSIONS FROM BUILDING HEATING

Globally building energy demand amounts to **123EJ, or roughly 30% of final energy demand**. Within this space and water heating represent about 50% (63EJ), and 2.2Gt CO_2. Space & water heating are often served by direct use of fossil fuels in buildings (e.g., natural gas boilers).

Building heating is a geographically localized energy use. For countries with building heating needs, it can represent **15-35% of total energy demand**. However, needs are concentrated in northern countries with stable populations and improving energy efficiency (in buildings and heat systems), thus **global demand outlook is flat to declining.**

With seasonal and daily variations, peak heat demand is considerable and **solving for peak** is a challenge facing any low-carbon solution. If building heating was to be electrified, this could double the electricity demand in winter, increasing the challenge of deploying sufficient renewables. However, since the load could be semi-flexible, this could also smooth integration of renewables into the system.

Building energy efficiency (e.g., insulation, glazing, improved heating controls) is a **fundamental first step** in decarbonization of building heating. Doing so delivers multiple critical benefits: reduced demand, reduced peak, ability to deploy heat pumps more broadly, ability to pre-heat space and use this as a form of energy storage, improved comfort, reduced heating bills (particularly important for low-income households). However, encouraging customers to implement energy efficiency retrofits has proven challenging and significant incentives will be required (e.g., fiscal support, mandated energy efficiency improvements with large renovations).

There are **multiple options for low-carbon heating solutions**, each with differing characteristics; the most appropriate will differ by country, region and even local area. The options include electric heating (resistive, heat pumps), accessing local renewable resource (solar thermal, geothermal), drawing on waste heat (e.g., from industry), or burning a molecule (bioenergy, hydrogen). District heat networks and heat storage – while not heat sources per se – are often critical enablers. **All options can eventually provide zero-carbon heat,** given right enabling circumstances (e.g., decarbonization of the power system).

For building heating as for energy efficiency, **consumer adoption considerations are paramount**: different low-carbon heating solutions entail varying levels of in-house investment requirements. Successful transitions to low-carbon heating have seen packages of measures employed to incentivize these switches (e.g., subsidies, taxes on fossil fuel for heating, installer training, public education campaigns, government procurement).

From a macroeconomic point of view, **the increased costs of low-carbon heating appear to be manageable.** For example, in the UK, the cost of heating is likely to be declining from 1.2% of GDP today to less than 1% of GDP in 2050 even with a transition to low-carbon heating.

Reaching full penetration of decarbonized heating solutions will take at least 20 years given lengthy asset lives, therefore reaching net-zero by 2050 requires **steady progress at pace starting now**.

<table>
<tr><th colspan="3">Top actions to accelerate the transition for…</th></tr>
<tr>
<td>… R&D
Reduce cost and improve efficiency of air-source heat pump (ASHP)
Develop smart integration of heat systems (e.g., multiple sources of heat combined with storage)
Ensure the technical feasibility and safety of hydrogen use in buildings</td>
<td>… Businesses across the buildings value chain
Construction: Adopt zero-carbon solutions in new buildings and deep retrofits
Equipment providers, installers, utilities: Develop new business models like “heat as a service” to facilitate deployment
Energy providers: Anticipate new energy and peak energy needs, especially in power</td>
<td>… Policy
Support energy efficiency improvement with package of coherent policies, including subsidies (e.g., capital grants) and geographically-coordinated roll-out plans
Support deployment of best low-carbon heat option (in the same way), pursuing no-regrets policies in the 2020s
Tax use of fossil fuels for heating</td>
</tr>
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INTRODUCTION

To date, the Energy Transition Commission (ETC) has developed a shared fact-base and set of recommendations on:

a. **How to deliver a well below 2˚C scenario** by 2040, through a combination of rapid energy productivity improvement, power decarbonization and clean electrification of 'easy-to-electrify sectors'(e.g. light-duty road transport), underpinned by a shift in investment and a coherent and predictable policy framework – this was described in the *'Better Energy, Greater Prosperity'* report published in 2017;

b. **How to decarbonize the "harder-to-abate" sectors** of the economy in heavy-duty transport (trucking, shipping, aviation) and heavy industry (steel, cement, petrochemicals) – this was described in the *'Mission Possible'* report published in 2018.

This paper focuses on decarbonization of one sector which had not yet been analyzed by the ETC – building (space and water) heating. It aims to complete the ETC's vision of how to achieve net-zero carbon emissions energy and industry systems globally by mid-century.

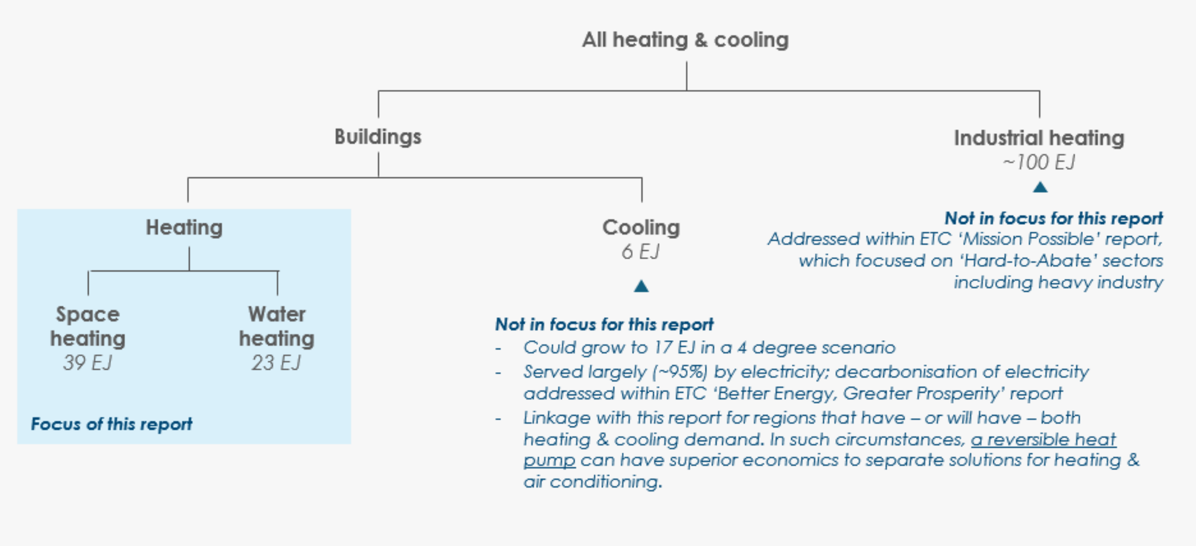
A. SCOPE OF THE PAPER

The focus of this paper is on space and water heating in buildings. There are two closely related areas: industrial heat and space cooling. These are not covered in this paper as the relevant components have been covered in other ETC analyses as illustrated in Exhibit 1 and described below.

Industrial heating is very material, representing about 100EJ globally. The *'Mission Possible'* report, focused on heavy industry, described how industrial heat could be decarbonized through a range of technology options – including direct electrification, use of hydrogen, use of biomass or continued use of fossil fuels combined with carbon capture. The relative importance of each option will vary by industry sector (depending also on technology readiness) as well as by region (depending on the relative local resource prices).

Building cooling is a small component of overall energy use within buildings, though growing considerably in a large number of geographies, especially in developing countries. It represents 6EJ today, but could grow to 17EJ by 2050 under a 4˚C scenario. It is predominantly served by electricity; as such emissions are already lower than for heating and would eventually reach zero once the power system has been decarbonized. Pathways to the decarbonization of electricity were covered in the *'Better Energy, Greater Prosperity'* report. There is, however, an important linkage in this report: in regions where buildings have both heating and cooling demands, a reversible heat pump can serve both needs with superior economics over a combined solution with both air conditioner and heat pump. Moreover, the economics for a reversible heat pump already outperform those for a combined solution with air conditioner and gas boiler.

Exhibit 1: building heating & cooling; industrial heat



SOURCES: IEA Reference Technology Scenarios (2017), IEA World Energy Outlook

B. SUPPORTING ANALYSIS AND REPORTS

The Energy Transitions Commission work on building heating has drawn from:

- A number of **reports** on decarbonizing building heating, including:
  - IEA, *Renewable Heat Policies* (2018), and IEA *World Energy Outlook* data;
  - Vivid Economics, *International Comparison of Heating, Cooling, and Heat Decarbonization Policies* (2017)
  - Two full-cost studies for UK heat decarbonization:
    - Element Energy & E4 Tech for UK National Infrastructure Commission, *Cost analysis of future heat infrastructure* (2018);
    - Imperial College of London for UK Committee on Climate Change, *Analysis of Alternative UK Heat Decarbonization Pathways* (2018);
- **Expert input** from both ETC members and a broader set of organizations, gathered through expert working groups and bilateral exchanges.

This paper presents a synthesis of the relevant conclusions and draws implications for policymakers.

1. OVERVIEW OF THE CHALLENGE

Globally building energy demand amounts to **123EJ, or about 30% of final energy demand**. Within this, space and water heating represent roughly 50% (63EJ). Space and water heating are often served by direct use of fossil fuels. Conversely cooling, lighting and appliances are typically served by electricity and will decarbonize as we decarbonize our power systems. To fully decarbonize buildings, it is therefore critical to switch away from fossil solutions for space and water heating.

The **global final energy demand for heating is expected to remain flat or decline**. Growth drivers are muted since heating demand is primarily in northern countries which are already developed and have stable populations, while energy efficiency is helping to reduce heating energy demand.

Building heating accounts for **2.2Gt of CO_2 today**. As a result of energy efficiency, flat to declining demand, and shifts to lower-carbon solutions, this is likely to decline to 1.6Gt of CO_2 even under a 4˚C scenario. It should be recognized that this only represents emissions at point of use of the heating fuel. **Methane flaring, venting and leaking across the full supply chain can double the total emissions from natural gas.**

Building heating is very much a problem solved at national, regional and even highly local level. This is due to differences in climate, efficiency of building stock, availability of natural resources, and existing infrastructure. Starting points vary considerably and are often influenced by available natural resources. The most appropriate portfolio of low-carbon heating solutions will similarly vary geographically.

For countries with heating demand, energy consumption from building heating can represent a **large percentage of final energy demand** (15-35%). This large volume is generally concentrated in one season and can fluctuate considerably within a day. Therefore, fundamental to all solutions is an ability to meet the **seasonal and daily peaks.**

A. GLOBAL VIEW

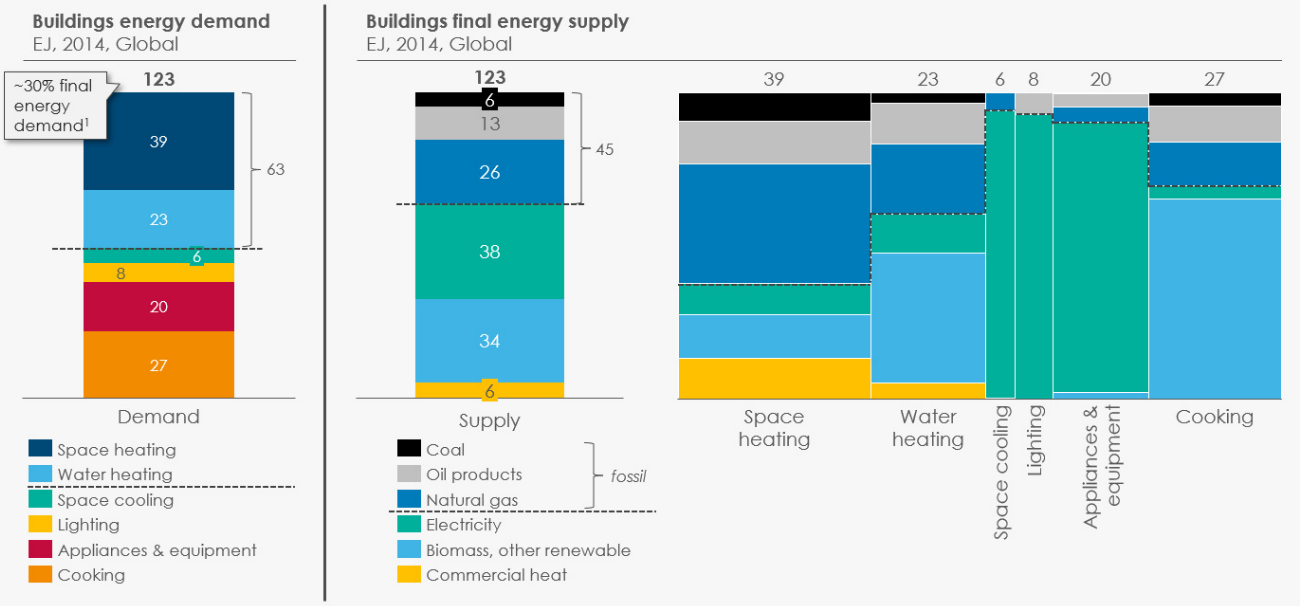
Exhibit 2 outlines current energy demand in buildings, including how it is split across applications (space heating, water heating, lighting, etc.) and how each of the energy demand categories are served by different energy sources (direct use of fossil fuels, electricity, biomass, etc.).

As we see on the left-hand side of Exhibit 2, **building energy demand stands at 123EJ, representing about 30% of final energy demand.** Within this, 63EJ are for space and water heating[1].

On the right-hand side of Exhibit 2, the breakdown by energy sources indicates that **direct fossil use (coal, oil, natural gas) accounts for 45EJ** in the buildings sector, and that the **majority of this (75%, 34EJ) is used to serve space and water heating.** Conversely, space cooling, lighting, appliances and equipment are largely served by electricity and will be decarbonized as we move to low-carbon electricity. **Cooking represents about 18% of direct fossil use in buildings**; as we decarbonize space and water heating this too would be decarbonized (e.g., shift from natural gas cookers to electric).

[1] IEA, *World Energy Outlook* (2017)

Exhibit 2: Building demand is ~30% final energy, of which ~half is for heating and cooling; heating (space & water) represents the majority of direct fossil energy use in buildings



[1] 402 PJ of Final Energy demand in IEA 2017 Reference Technology Scenario
SOURCES: IEA Reference Technology Scenarios (2017)

Heating needs are located predominantly within northern hemisphere countries, which are already developed and have more stable populations [Exhibit 3]. As a result, **underlying drivers for increasing heating demand are limited**.

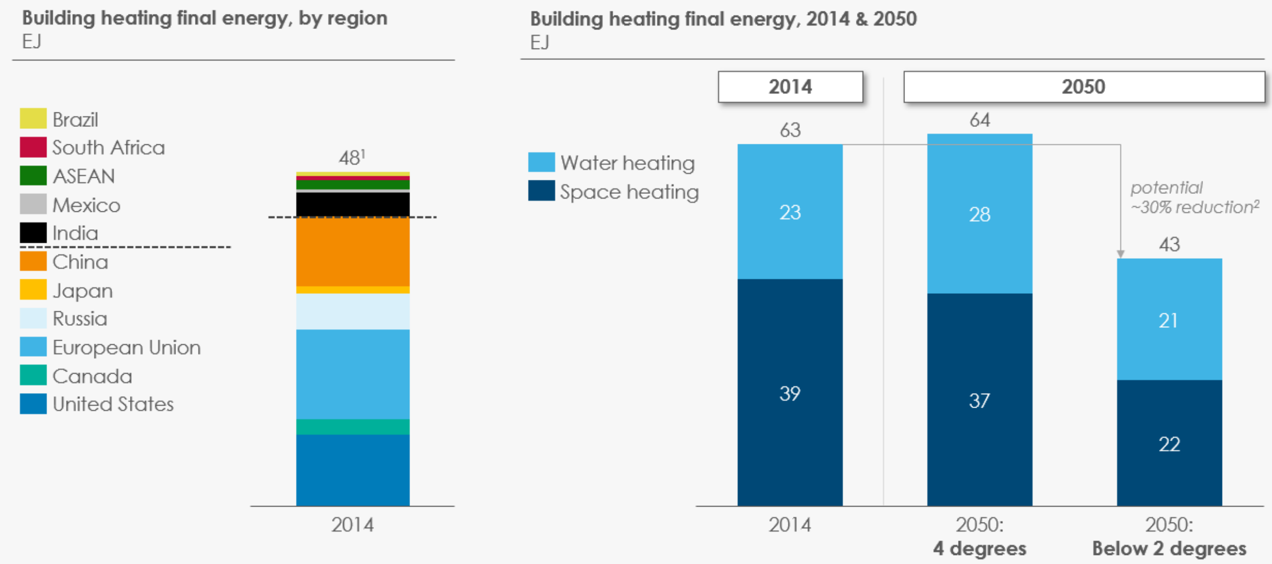
Additionally, there are two **underlying drivers reducing heating demand** at play: (1) building energy efficiency is improving (in both new builds and retrofits); (2) heat is being delivered through more efficient devices (e.g., heat pumps have 300%+ energy efficiency and are increasingly being deployed).

As a result, final energy demand for space and water heating is **expected to be flat (even in a 4˚C scenario) or could decline by about 30% (in a 2˚C scenario)** by 2050. The emissions resulting from building heating today stand at **2.2Gt of CO_2.** Given flat demand and a shift to lower-carbon heating, even under the IEA's 4˚C scenario, expectation is to see a decline to **1.6Gt by 2050**; and, under their 2˚C scenario, emissions would fall drastically to **0.4Gt of CO_2** or lower. Our analysis, however, aims to assess whether and how this could be brought down to zero.

It is important to realize that these estimates **only cover CO_2 emissions, not methane losses which occur throughout the gas supply chain.** Globally, CO_2 emissions from using natural gas across all sectors of the economy are about 7.2Gt p.a. However, flaring and venting of methane take place during the oil and gas extraction process, and there are often leaks in the downstream transmission and use of the gas (transmission pipes and inside buildings). **Methane is up to 84 times more potent as a greenhouse gas** than CO_2 if considered on a 20-year timeframe. As result methane leakages add as much as a further 2.6Gt p.a. to CO_2e emissions, and flaring and venting a further 4.3Gt p.a. In total, this roughly **doubles the greenhouse gas emissions we associate with natural gas**[2]. This should encourage both short-term action to drastically reduce methane emissions across the gas value chain and search for longer-term heating solutions which do not rely on natural gas – i.e., away from hybrid heat pumps.

[2] Capterio, *Insight 2019-12-17*

Exhibit 3: majority of heating occurs in more developed countries with more stable populations; with energy efficiency this leads to potential material decline



[1] not exhaustive set of countries, hence total is not entire 63EJ for building heating
[2] major drivers would include (a) building energy efficiency, (b) heat delivery energy efficiency e.g., ~2.5-3.0x efficiency from heat pumps
SOURCES: IEA; Vivid Economics; NR Can factbook; Canada Senate Committee on Energy; The Institute of Energy Economics Japan

B. COUNTRY-LEVEL VIEW

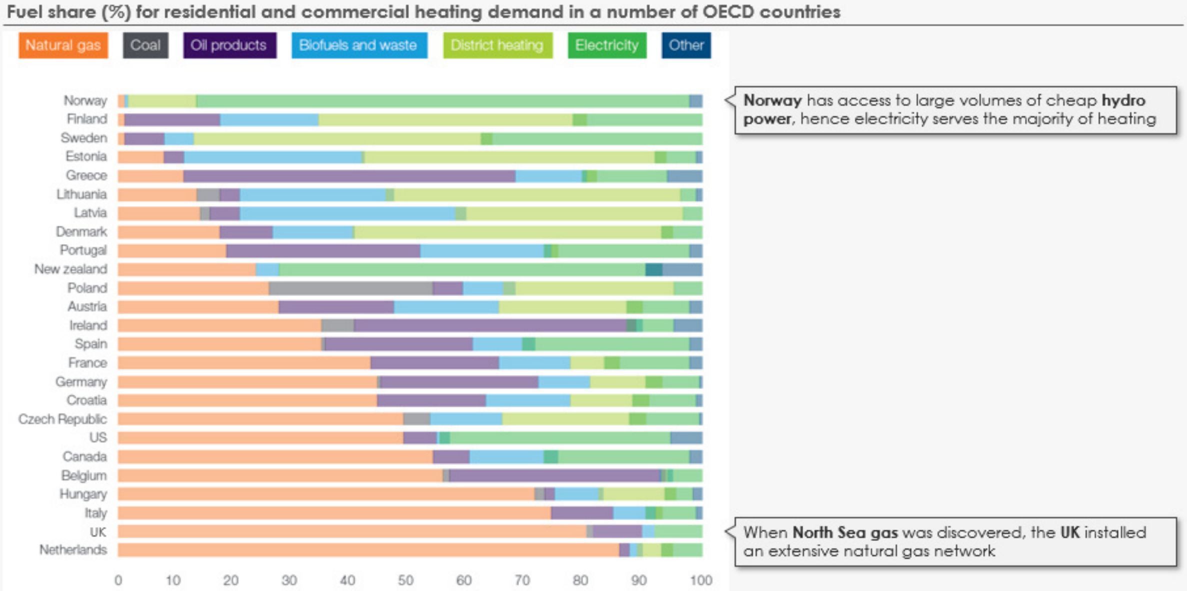
Transitioning to low-carbon building heating systems is very much **a problem that needs to be solved at national, regional and even highly local level.** This is due to differences in climate, efficiency of building stock, availability of natural resources, and existing infrastructure. There are multiple low-carbon heating solutions, and the most appropriate for a given location is influenced by these locally-specific factors.

Heating options used currently already differ considerably by country as seen in Exhibit 4 below. Current solutions are often the result of natural resource endowments. For example, Norway serves the majority of its heat demand with electricity, drawing on its abundant volumes of cheap hydro power. Conversely the UK discovered gas in the North Sea, which precipitated the build-out of a natural gas network which now serves about 85% of buildings. Within larger countries (e.g., US, China), individual regions often differ considerably from each other, not least as reflection of different climates. Rural and urban solutions will also differ, influenced by considerations including the space available for heating equipment in the house, or whether the density of buildings is sufficient to support the economics of a district heat network.

In each geography, the nature of the current predominant heating solution is also likely to influence the most appropriate low-carbon heating solution. For example, where district heat networks are pervasive, there can be a wider option set of cost-effective clean heat source solutions (e.g., geothermal).

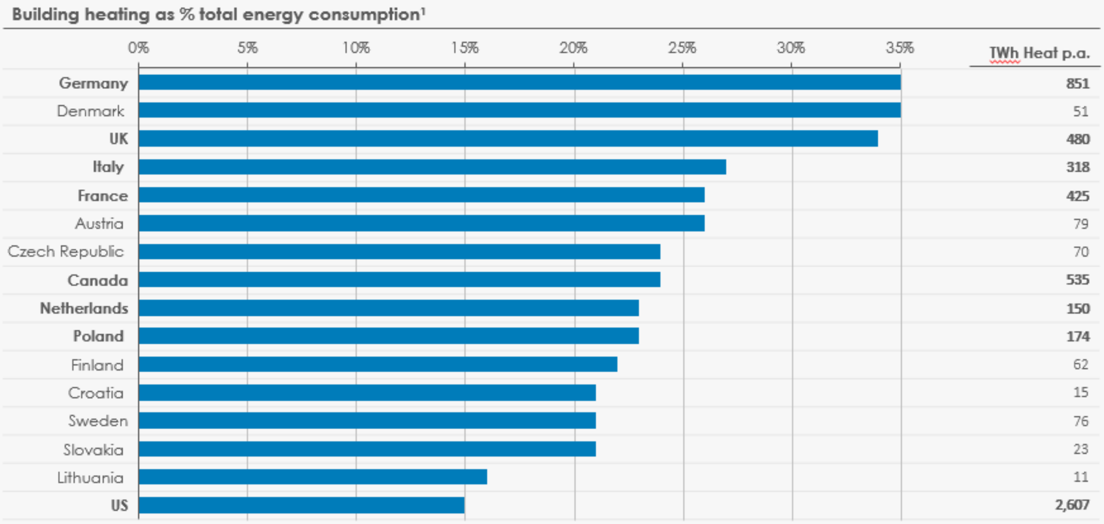
For the countries seeking solutions to low-carbon heating, this is a fundamental aspect of their national energy transition. As illustrated in Exhibit 5, **heating demand can represent a very material proportion (15-35%) of total final energy demand** in these countries. It can also be a material portion of GDP (e.g., 1.2% in the UK), and of customer bills (e.g., up to 20-30% of income for low-income customers in the US).

Exhibit 4: current solutions to building heating in sample of countries



SOURCES: Vivid Economics for the Department for Business Energy and Industrial Strategy (2018)

Exhibit 5: heating as percentage of overall energy consumption in sample of countries



[1] Heating & cooling, however for this sample of countries heating represents 98% of heating & cooling energy demand
SOURCES: Vivid Economics for the Department for Business Energy and Industrial Strategy (2018)

C. SEASONAL AND DAILY VARIATIONS

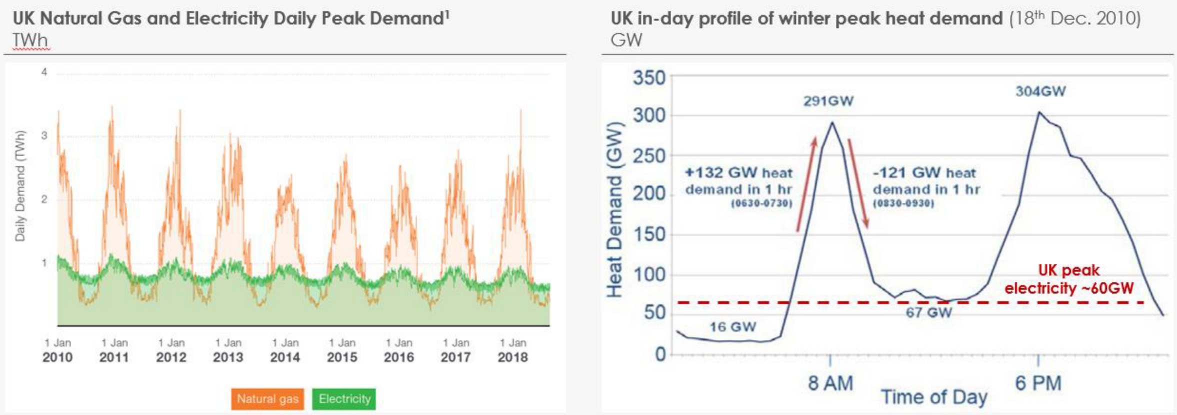
In addition to heating demand being a significant component of energy demand within the countries that have heating needs, this demand is **concentrated seasonally** and has **daily variations**. This can create significant peak demands, which, when they occur, can overshadow other energy demands. Any low-carbon heating solution will need to be able to meet such peaks.

Exhibit 6 below highlights **seasonal and within-day variations** using the UK as an example:

- The left-hand side shows daily demand across several years. The orange peaks and troughs highlight **gas demand can vary from only 0.5TWh per day in summer to more than 3TWh in winter**, which is 3 times the energy demand from the whole UK electricity system. The seasonal variations in the electricity system are also much less pronounced.
- The right-hand side shows the **within-day variations**. Here we also see extreme peaks, resulting in heat demand in terms of output (not energy) reaching about 300GW in this example day, as compared to an electricity system peak of about 60GW in the UK – i.e. a factor 5 in terms of scale of the peak.

While this does frame a fairly stark challenge, especially as we consider electrification of heat, **the challenge is unlikely to be as extreme as these charts make it appear.** Heat pumps offer a **higher energy efficiency** (300% or more) meaning that the volume of energy which would have to be provided by the electricity system to meet the same peak of heat demand would probably double rather than quintuple. In addition, improved energy efficiency of buildings and heat storage solutions can both help to considerably **smooth the within-day peaks** (see Section 2). Further heat storage can shift heating load within a day (e.g., domestic hot water tank) or even across weeks and months (e.g., large hot water tank as part of district heat network, potentially undergrounded).

Exhibit 6: volumes of energy for heat – daily total, within-day fluctuations [UK example]



[1] This is non-daily metered demand, and therefore does not cover all non-domestic buildings; [2] ~50GW = heat pumps + all EE measures; also accounts for diversity across stock, assumes favourable consumer behaviour (e.g., pre-heating, DSR); ~80GW = direct electric heating. [3] For peak impact to be held to ~50-80GW relies on potentially optimistic levels of energy efficiency retrofits as well as pre-heating & heat storage, and heat pumps whose efficiency does not drop considerably in cold weather
SOURCES: BEIS 'Clean Growth – Transforming Heating' (2018); Energy Technologies Institute 'Smart Systems and Heat: Decarbonising Heat for UK Homes' (2015)

Heat storage solutions can considerably bring down and smooth out demand peaks, and also enable deeper variable renewable penetration into the power system. The majority of commercially deployed systems use water as a heat storage medium – e.g., domestic hot water tanks, and large water tanks as part of district heating systems. Electric storage heaters have been in use for decades as well, which use solid material (e.g., ceramics). New solutions are being developed with new mediums for sensible heat, or leveraging phase change materials (PCMs) or thermo-chemical energy (TCS) which bring the benefit of higher energy density [Exhibit 7].

Exhibit 7: heat storage solutions

Type		Sensible Thermal Energy storage (STES)	Phase Change Materials (PCM)	Thermo-chemical energy (TCS)
Description		▪ Liquid (e.g., water, molten salts) & solid media (e.g., cements, ceramics, rocks) – **water** is most popular / commercial (domestic water tanks, large tanks for DH) ▪ Can be **underground**, often for large-scale applications – e.g., pit storage, borehole (vertical heat exchanger with ground layers – clay, sand, rock) ▪ **Combinations**, e.g: solar-combi-systems combine seasonal storage of solar thermal heat w. small district heating systems	▪ E.g.: Ice, Na-acetate Trihydrate, paraffin, erytritol ▪ Can **fix discharge temp**	▪ **Adsorption** (e.g., water vapour to silica-gel or zeolites) ▪ High capacity enables thermal energy **transport**
		▪ Can be **incorporated into building walls** (STES, PCM) to increase building thermal mass (e.g., paraffin wax into gypsum walls or plaster)		
Characteristics	Status	**Commercial**	Mostly under development and demonstr'n	
	Cost *(€ / kWh)*	0.1 – 10	10 - 50	8 - 100
	Storage period	**Hours** *(domestic hot-water tank, storage heaters)* → **weeks / months** *(large tank as part of DH system)*	**Hours → days / weeks** (higher capex, thus economic only with a high # of cycles)	
	Energy density	Low	High	High
	Capacity (kWh/t)	10-50	50-150	120-250
	Efficiency	50-90%	75-90%	75-100%
Examples		▪ France: 13 M electric water heaters, 50% resi hot water systems (20 TWh p.a., peak 8GW) → with time-of-use pricing flattened demand curve considerably ▪ Denmark: 2016, DH systems had 400MW of electric boilers; 13 large electric heat pumps at 11 CHP plants, 30MW in total; produce at times of high VRE output ▪ Germany: "Am Ackermann-bogen" solar DH for 320 apartments in 12-multi-story dwellings, covers 50% annual heat demand	▪ *Limited given largely pre-commercial status*	

Source: IRENA, *Thermal Energy Storage Tech Brief* (2013); IRENA, *Renewable Power-to-Heat Innovation Landscape Brief (2019)*; IRENA, *Electricity Storage and Renewables: Costs and Markets to 2030* (2017); IRENA, *Demand-side flexibility for power sector transformation* (2019)

2. REDUCING CARBON EMISSIONS THROUGH DEMAND REDUCTION

As seen in Exhibit 3, **final energy demand from heating could be reduced by about 30% globally thanks to improved energy efficiency.** This could come from a combination of building energy efficiency and efficiency of heating equipment (e.g., shift to heat pumps with 300%[3] efficiency uplift or more).

In terms of **building efficiency**, while it is very important to build new buildings to net-zero operational emissions standards[4], **retrofitting existing buildings represents the key challenge** in delivering energy efficiency improvement since:

- Heating is present in countries with stable populations, thus **limited new constructions**, and today's buildings will be the large majority of buildings in 2050.
- **New buildings are easier** to build in an energy-efficient manner thanks to the availability of relatively low-cost energy-efficient designs and technologies.

The value from improved building energy efficiency cannot be overstated. In addition to the most obvious benefit of reduced overall heating demand, there are a host of other benefits including: reduced peak heat (including enabling 'pre-heating' of space to reduce peak even further), enabling heat pumps to be viable low-carbon heating solutions where they might not have been, improved comfort, and reduced monthly heating bills.

Encouraging customers to implement energy efficiency retrofits has to date proven very challenging. The logistical inconvenience, upfront capital cost and misaligned incentives are all major barriers. Though there are companies exploring innovative solutions to deploy energy-efficiency solutions – e.g., heat as a service business models.

Beyond building energy efficiency, there are a few **other demand reduction solutions** which could deliver some benefit, although to a much smaller degree. These include: boiler energy efficiency, direct infrared heating, heat exchange loops, and increased utilization of the building stock.

A. BUILDING ENERGY EFFICIENCY

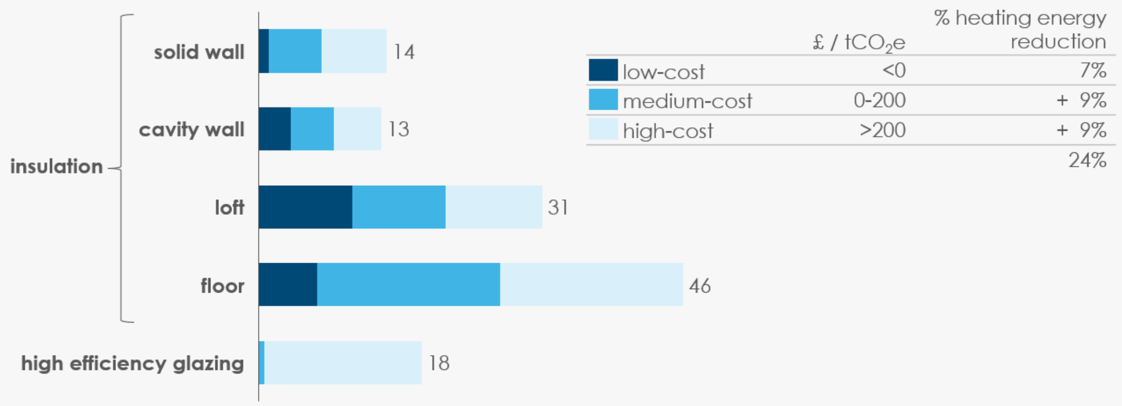
Building energy efficiency measures include both **physical upgrades** to building envelope – e.g., insulation (cavity wall, loft, solid wall, floor), double glazing – and **digital upgrades** – e.g., improved analytics and operation of heating controls to deliver heat only when needed and in a cost-optimal manner, or micro-zone control.

- Exhibit 8 below provides an example of the volume of physical upgrades applicable to housing in the UK, the associated energy efficiency savings, and resulting cost-effectiveness. In the case of the UK, **up to 7% of residential heat energy demand could be reduced through cost saving measures**, with a total technical potential of 24%.
- Digital solutions have been seen to **improve commercial building energy efficiency in range of 10-30%** without any net additional investment in physical upgrades required.

[3] Heat pumps have been demonstrated to achieve up to 400-600% on average across the year.
[4] New buildings should also increasingly aim for net-zero embodied emissions via the use of zero-carbon building materials.

Exhibit 8: physical energy efficiency measures in housing and scale of impact

Physical energy efficiency measures in UK housing to reduce heat demand
volume of individual measures (m); note UK has 27m homes



SOURCES: Element Energy & E4tech for UK National Infrastructure Commission (2018)

Beyond the direct savings from reduced overall heat demand, energy efficiency in buildings provides a host of other crucial benefits:

- **Peak heat demand volumes are also reduced**, and since heat provision systems are often sized to meet peak demand, the size of the overall system – and amount of investments required to decarbonize it – can be reduced. This reduction in peak demand is achieved through:
    i. **Reduced heat loss** from buildings during times of peak heat demand (coldest temperatures) resulting in less demand for heat output from heating systems;
    ii. **Ability to pre-heat**, i.e., smooth out the heating supply over the course of the day – this is only feasible if the space can be heated ahead of time and the building is sufficiently insulated to retain that heat until it is needed (e.g., home heated during the day ahead of residents coming home in evening).
- **Heat pumps** – one of the most promising low-carbon heating solutions for broad deployment – have a lower rate of heat output than gas boilers. Further, their performance dips in colder temperatures as they are trying to extract heat from colder air[5]. In colder outdoor temperatures, heat pumps can only maintain a comfortable indoor temperature if the building is well insulated. A certain level of building energy efficiency is therefore a pre-requisite to deploying heat pumps.
- **Improved comfort** as result of reduced drafts can also be an important co-benefit for customers and can help drive uptake of energy efficiency retrofits.
- **Reduced monthly heating bills** – although energy efficiency measures require an outlay of upfront capital, they usually result in reduced monthly energy bills, which can be a significant proportion of income for some customers – e.g., in the US, low-income populations can spend 20-30% of their income on energy.

[5] The Northeast Energy Efficiency Partnerships program maintains a 'Cold Climate Air Source Heat Pump Specification' which requires products to demonstrate efficiency >175% at -15°C. Select models on this list achieve 245% efficiency. Heat pumps can also be paired with a smaller amount of electric resistive heating (e.g., to provide <10% heating) to enable higher heat output when needed. Regardless, well-insulated buildings are paramount to heat pumps serving as source of heating.

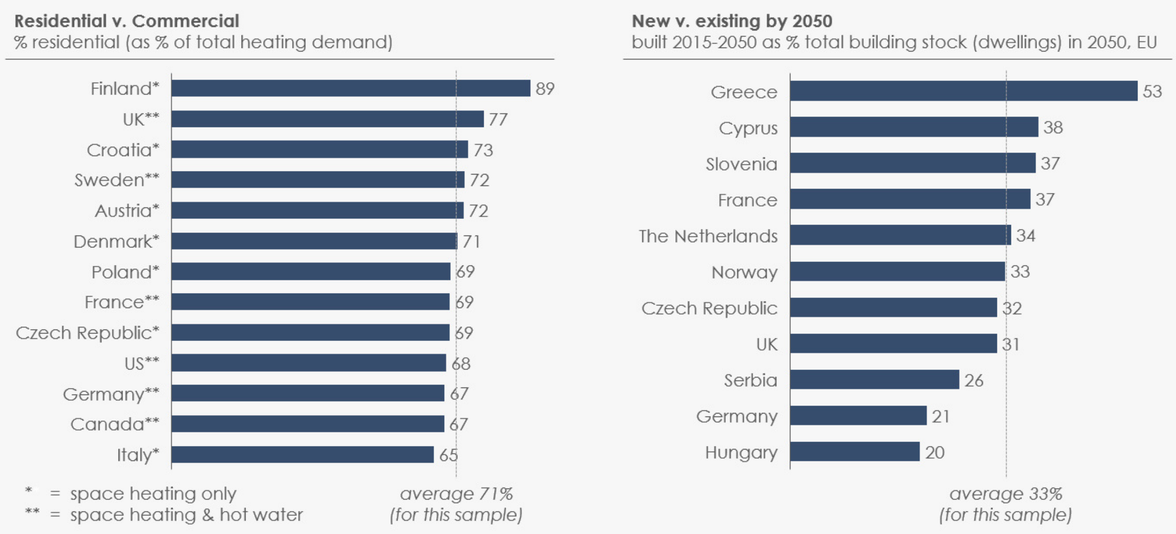
While the value to be gained from improved energy efficiency is considerable, **this value has so far proven elusive: driving consumer adoption of energy-efficient is proving to be a considerable challenge.** As we have seen most measures are cost effective, and yet to date they remain unimplemented for a large proportion of houses.

- A key challenge to deployment is the **upfront capital cost of renovation**, which can easily reach $10,000 or more. Low-income populations in particular have a higher average energy bill per m^2 given their inability to invest in energy efficiency solutions. In this context, subsidized investments in energy efficiency can be a critical step to reduce energy poverty, while also reducing system costs of meeting heating demands.
- In addition, customers are clearly placing **considerable negative value on the inconvenience of investing time** to make renovation decisions, and to undergo the renovation.
- Finally, in rental properties, **misaligned incentives** between landlords – who would face the upfront capital expenditure – and tenants – who would benefit from higher comfort and lower energy bills – also slows down progress.

It is worth highlighting that implementing energy efficiency will take on different facets depending upon whether buildings are:

- **Residential v. commercial:** Circa 70% of building heating is residential [Exhibit 9]. Challenges exist in driving uptake of energy efficiency in both sectors, though commercial has seen more traction to date as building managers have responsibility to manage costs, while homeowners or landlords are less motivated.
- **New v. retrofit:** A sample of 11 European countries points to an average of 33% of building stock (dwellings) in 2050 being buildings constructed 2015-2050, as seen in Exhibit 9 below. For these countries, about 70% of the building stock in 2050 will be buildings that exist today. The percentage of "new builds" will be higher in more rapidly growing economies such as China. Retrofits are considerably harder to promote than implementing higher standards of energy efficiency in new builds.

Exhibit 9: sector breakdown: residential v. commercial; new v. existing by 2050



Source: Vivid Economics for the Department for Business Energy and Industrial Strategy (2018); N.H. Sandberg et al., "Dynamic building stock modelling: Application to 11 European countries to support the energy efficiency and retrofit ambitions of the EU" (2016)

There are **select spotlights** which provide some optimism that house owners can be encouraged to **implement energy efficiency retrofit** measures at scale. These include:

- **Social housing:** In the UK, for instance, the former CESP program targeted social housing and, in its final six months, delivered energy efficiency measures at an equivalent rate of 340,000 homes per year.
- **New business models:** The rooftop solar market in the US accelerated when players began offering a new financing model to customers – solar rooftop lease. In energy efficiency, similar innovations in financing and business models are being explored. Examples include:
  - *Sealed:* a US-based company offering financing for energy efficiency measures, with payments funded by savings in energy bills.
  - *Heat as a service:* such models are being explored in multiple geographies and remove the hassle of decisions and payment for energy efficiency measures.
  - *Combined energy efficiency and heat pump provider:* Energiesprong is delivering full home retrofits and low-carbon heating solutions, and is now operating in multiple countries – Netherlands, Germany, France, UK, US (California, NY).

B. OTHER POTENTIAL DEMAND REDUCTION LEVERS

Building energy efficiency measures represent the lion's share of the energy demand reduction potential in buildings. However, there are other measures which hold some potential for demand reduction:

- **Boiler energy efficiency & improved controls:** Boiler efficiency can be improved primarily via replacing older less efficient models (i.e., replace older models with ~60% efficiency with newer ones operating at ~90% efficiency). Improved boiler controls can improve efficiency, i.e., many condensing boilers are used in an 'on/off' manner to provide instantaneous heat. As a result, they operate in condensing mode less often than is optimal. Building in ramp-up / ramp-down controls can improve efficiency.
- **Zone controls:** An ability to heat only rooms in use, and heat to different desired temperatures (e.g., bedrooms at lower temp.) can both deliver an improved comfort experience and reduce energy usage.
- **Directional infrared heating:** There are technologies that aim to 'heat the person' instead of heating the entire space, using directional infrared heating. This is most relevant to large commercial and industrial buildings (e.g., warehouses, factories).
- **Heat exchange loops:** Where buildings in proximity to each other have both heating and cooling demands (e.g., cold food storage), a heat exchange loop – in effect a district heat network – can pull heat from one location to the other, serving both needs highly efficiently.
- **Increase utilization of the building stock:** There is potential to increase utilization of the current building stock (e.g., through increasing shared use). This would reduce the demand for new building stock, and thus further reduce heat demand in future.

3. DECARBONIZING BUILDING HEATING SOURCES

We have seen that demand reduction is a critical first step and foundational enabler of a transition to zero-carbon heating. To fully decarbonize building heating, however, we also need to **shift entirely to zero-carbon heat sources**. As can be observed in Exhibits 2 & 4 above, a meaningful percentage of buildings already use heat sources which can in principle be low- or zero-carbon, e.g. waste heat, biomass (if sustainable), electric resistive heating and heat pumps (if electricity supply is clean). But a greater proportion of heating is currently delivered via direct use of fossil fuels, e.g. natural gas boilers, oil boilers, coal (e.g., used extensively for heat networks in China).

There are **multiple options of low- and eventually zero-carbon heating solutions,** each with their own characteristics: some are more broadly applicable (e.g., heat pumps), others well-suited only in certain areas or regions (e.g., solar thermal, district heating); some are ready for deployment (e.g., heat pumps), others require considerable further research and development before any deployment at scale (e.g., pure hydrogen for residential space heating).

As previously described, any solution deployed will **need to be able to meet peak heat demand.** In the case of heat pumps, this could be the driver of peak demand in the power system (dependent on geography and flexibility options available[6]). Meeting firm capacity requirements for peak power in systems with high variable renewable power penetration, will require firm back-up power generation, that will be only lightly utilized. However, similarly, gas boilers and the gas network are only partially utilized as it stands given the seasonal swings in natural gas demand (in countries that use natural gas for heating).

The different solutions also carry **different impacts on reduction of greenhouse gases from building heating:**

- The carbon intensity of hybrid systems combining heat pumps with gas boilers will depend on whether customers operate their system optimally to reduce use of the gas boiler.
- The solutions which electrify heating (heat pumps, resistive heating) will reflect the electricity system's level of decarbonization. They will also add considerable, partially flexible load to the electricity system, increasing the challenge of deploying sufficient scale of renewables, but also possibly easing the integration of those renewables in the grid thanks to added flexibility.
- Solar thermal or geothermal inherently draw on renewable resources and thus are fully zero-carbon.
- The carbon impact of different forms of bioenergy will vary depending on the type of bio-resource used, impact on land use, and level of emissions from processing.

There are also **key differences in cost considerations:**

- Certain options may be lowest-cost only in a subset of suitable locations (e.g., solar thermal, ground-source heat pumps, biomass).
- Within the electrified heating options, electric resistive provides lower upfront CapEx v. a heat pump, though much higher operating costs as it operates at ~100% efficiency v. ~300%+ for heat pumps[7].
- Hydrogen could be a cost-competitive solution in a few select geographies (e.g., UK, Netherlands), however, while the system-investments (gas network, hydrogen production & storage) are often considered, the costs of in-home piping upgrades also need to be weighed.

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[6] Seasonal flexibility options (e.g., H_2 production could be reduced in peak season), but also peak smoothing e.g., via heat storage

[7] The scale of network investment to support electrified heating remains uncertain, but could also be considerable.

Perhaps more fundamental than cost considerations, are **consumer adoption considerations** more broadly. Consumers usually resist energy efficiency retrofits given upfront costs and inconvenience. Heat pumps in particular are sizable, can be unsightly and noisy, may require an additional hot water tank as well as deep energy efficiency retrofits. Hydrogen may be seen by consumers as unsafe and undesirable thus any forced roll-out could come at a political cost, deterring politicians from enacting a transition. Regardless, certain countries have seen success in incentivizing uptake of lower-carbon heating solutions, often through packages of supportive measures (e.g., subsidies, taxes on fossil fuel for heating, installer training, public promotion). There are also benefits to the customer beyond the economics that can be promoted, i.e., improving the heating experience including reduced drafts, better heating control, reduced heating appliance maintenance, eliminated carbon monoxide risks.

A. OPTIONS FOR LOW/ZERO-CARBON HEAT SOURCES

There are four major categories for potential sources of low-carbon heat [Exhibit 10]:

- **Electric**: includes electric resistive (e.g., electric radiator, electric storage heater) and heat pumps (air-, ground- or water-sourced). Air-source heat pumps are presented separately since they are more broadly applicable than ground- or water-source heat pumps, which need very specific locations.
- **Local renewables:** includes two forms of local renewable resources – i.e. heat from the sun (solar thermal) and heat from the core of the earth (geothermal)[8]. The investment case for installing the equipment to tap into these resources obviously depends on the availability of each natural resource in a given location.
- **Waste heat:** is provided from commercial or industrial sites which produce waste heat, e.g., from an industrial process. A district heat network is needed to access and distribute such waste heat amongst a large number of buildings.
- **Molecules:** includes bioenergy (biomass, biomethane) and hydrogen.
    - Biomass is a traditional source of heat (e.g., wood). However, its use on a large scale can result in major sustainability issues and must therefore be subject to tight sustainability regulations, which is likely to lead to limited availability for building heating. Some forms of non-traditional biomass could be particularly suited for building heating, including in the form of waste incineration or biomethane which can directly displace natural gas in the gas grid as it is the same molecule.
    - Hydrogen is a combustible gas like natural gas, and, in the same manner, it would be delivered through the (retrofitted) gas grid to be combusted in (adapted) gas boilers. There is also the option to run hydrogen through a micro-CHP unit to deliver power and heat at high-efficiency levels (~95%), and hydrogen as heat source for district heat networks is also being considered.

There are also two key enablers, which do not generate heat of themselves, but can be fundamental to low-carbon heat systems. These are:

- **District heat networks:** These capture heat in water and distribute it amongst several buildings. They enable access to waste heat and make it possible to switch to low-carbon heat sources is a less invasive way than solutions requiring in-building changes.

[8] Note this is distinct from ground-source heat pumps which draw heat from the ground at shallower depths, where the heat is not supplied by the earth's core and can be reduced over time if too much heat is extracted or summer is not hot enough to replenish.

- **Heat storage:** These can take the traditional form of hot water tanks (either in buildings, or under-ground in large heat systems) or more advanced forms like phase-change material (earlier stage technology). Heat storage can enable smoothing of the heat demand profile, as well as considerable demand-side response to the electricity system if the source of heat is electric. This benefit can be critical in reducing peak heat demand.

The **different low/zero-carbon heat solutions are applicable in different circumstances.** Electric resistive and air-source heat pumps are the most broadly applicable. The rest of the portfolio of solutions are either specific to climate (solar thermal), geology (geothermal), highly local attributes (e.g., outdoor space needed for ground-source heat pump), local activities (e.g., nearby source of waste heat, or sufficient density of buildings for district heating), or infrastructure (hydrogen requires a gas grid). Exhibit 10 also indicates that each solution is already, or could be, a **very meaningful part of the answer for different countries or regions.**

Growing focus on net-zero emissions targets and pathways, and on reducing air pollution in cities[9] are at the origin of a growing focus on decarbonizing heating. This is **driving R&D developments to improve a number of the technology options**, e.g. improvements in efficiency factor of heat pumps, innovations in heat loops and long-distance heat transfer to expand applicability and effectiveness of district heat networks, innovations in installation technology and business models to expand applicability of ground source heat pumps.

[9] E.g., the heat source for 90%+ district heat networks in China is currently coal which creates emissions in urban centres.

Exhibit 10: options for low-carbon building heating

		Solution	Description	Applicability	Example
Low-carbon heat sources	Electric	**Electric resistive**	▪ Radiators, storage heaters. Cheap upfront capex however 100% efficient thus result in higher electricity costs (i.e., less efficient than heat pumps)	Technically **ubiquitous**; though often not cost-competitive	
Low-carbon heat sources	Electric	**Air-source heat pumps (ASHP)**	▪ Transfer heat from air into indoor space; 250-300%[1]+ efficient; lower rate of heating requires well-insulated building; hydrid HP (HP + gas boiler) possible	**Broad-reaching**; buildings with **sufficient insulation**	300k ASHPs sold in US Northeast & mid-Atlantic in 2015
Low-carbon heat sources	Electric	**Ground or water-source heat pump**	▪ Transfer heat from ground or water to air; more efficient operation than ASHP (ground, water warmer in winter) however higher installation costs	**Sufficient space** to install ground-source loop, or **access to body of water**;	~20% Swedish buildings use GSHPs
Low-carbon heat sources	Local renewable	**Solar thermal**	▪ Often used for water heating but can also support space heating, especially to 'pre-heat' water used in hot water radiator circuit, or 'pre-heat' air	**Sunny locations**	324GW of solar thermal installed in China as of 2016
Low-carbon heat sources	Local renewable	**Geothermal**	▪ Drill deep underground to access heat fuelled by earth's core; CapEx to install the underground loop can be considerable	**locations with suitable geology**; district heat network required (can be installed)	~0.4EJ geothermal heat use in 2017
Low-carbon heat sources	**Waste heat**		▪ Capture waste heat from industry or commercial buildings (e.g., grocery cold storage), transfer typically via district heat network to heat other buildings	Buildings in **sufficient proximity to waste heat source**	2% of UK heat demand estimated to be able to be served with waste heat
Low-carbon heat sources	Burn molecule	**Bioenergy**	▪ Biomass (e.g., wood) can be burned for heat; low carbon if sustainably sourced; biomethane can be produced sustainably and replace natural gas in gas grid	Biomass often used **off-grid**; biomethane used in gas grid, **volumes restricted[4]**	18k biogas plants in Europe
Low-carbon heat sources	Burn molecule	**Hydrogen**	▪ Gas which can be produced cleanly[2], can be burned in a boiler (similar to natural gas boiler) to produce heat, or run through a fuel cell for combined heat & power	**Extensive natural gas grid in place[3]**	UK investigating in depth[5]
Enablers	**District heat networks**		▪ Capture heat in water, transfer heat to multiple buildings; provides access to new sources of heat (e.g., waste heat), often easier to decarbonise source of heat	**Sufficient density of buildings[6]**	Sweden grew DH from ~0% (1960s) to >50% today, mostly biomass fuelled
Enablers	**Heat storage**		▪ Solutions applicable both in-buildings (e.g., water tanks, ceramic bricks, phase change material), and in heat networks (e.g., large underground tanks)	**Within-day, multi-day** smoothing in-building; **seasonal** potential in the case of underground thermal energy storage	5-10 GWh_{th} potential to installing heat storage in DH networks in France

[1] percentage refers to energy in heat delivered as compared to electrical input energy required to run the heat pump; efficiency drops when source of heat (e.g., outdoor air) is colder; R&D is currently making progress on improving efficiency rates including in colder temperatures; [2] via steam methane reformation with CCS (90% capture) or water electrolysis (can be 100% clean if using clean electricity); [3] though even with this, if the pipes have not be upgraded to plastic pipes this may not be viable; hydrogen is a small molecule which embrittles steel and iron pipes; [4] only limited volume of sustainable bioenergy globally, other harder to decarbonise sectors (e.g., aviation) likely best candidates for deployment of limited sustainable bioenergy; [5] the H21 project has conducted a detailed technical evaluation for switching the city of Leeds to hydrogen heating, and is now considering how to switch all of the North of England; multiple other projects are also investigating hydrogen heating in UK. [6]UK study deemed >=40kWh/m^2 required for district heating to be suitable, can be applicable to urban and ~suburban locations
SOURCES: NEEP, IEA, World Geothermal Congress, Element Energy & E4tech for UK National Infrastructure Commission (2018), Artelys & ENEA Consulting & G2ELab

B. SOLVING FOR PEAK AND ELECTRICITY IMPLICATIONS

Any low-carbon heating solution will **need to solve for peak heat** demand which can be very high as observed in Exhibit 6. As explained in Section 1, **energy efficiency** is a critical first step to manage peak regardless of the heat source deployed. It is also a pre-requisite to other measures to manage peak demand: **pre-heating and heat storage**. These solutions in particular can serve to not only smooth out heating demand, but to reshape heating demand to align with renewables energy output (which is relevant if heating is electrified).

In addition, biomass, solar thermal, geothermal, and waste heat are all either building-level or community-level **solutions which solve for peak heat** either through storage (e.g., hot water tank), sufficient stock of fuel (e.g., biomass), or endless natural resource (e.g., geothermal).

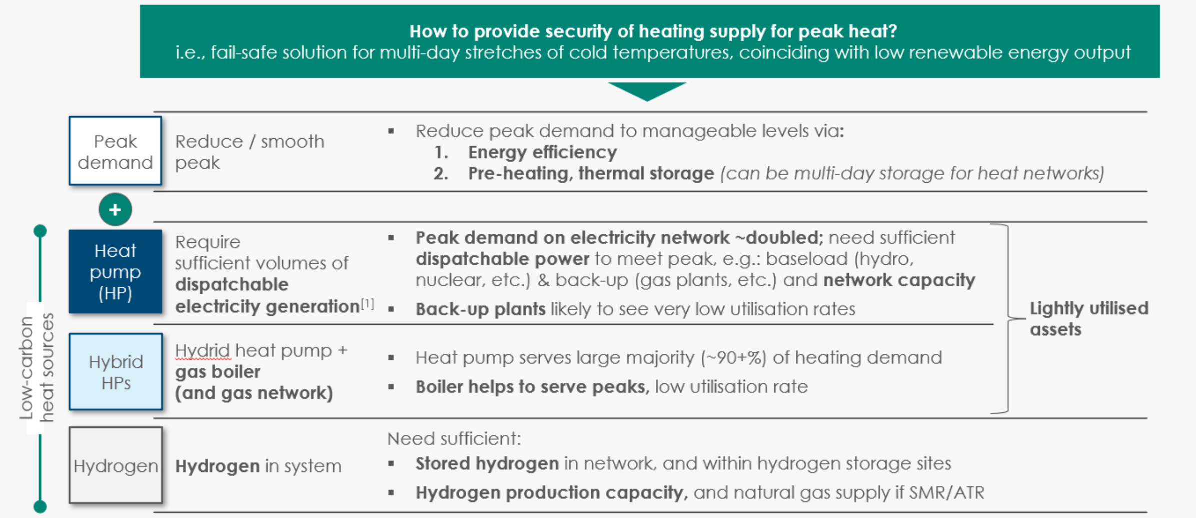
In the case of electrified heating (resistive or heat pump) and hydrogen, though, **how to meet peak demand becomes a system-level question**, which needs to be addressed either through the electricity or gas system, or both. Note that in certain systems with heating but also considerable summer cooling needs, peak electricity demand may occur in summer. Exhibit 11 below outlines how peak heat demand would be addressed in systems providing heat via heat pumps, hydrogen boilers or hybrid heat pumps (HP + boiler).

- In the case of **heat pumps**, the **demand for heat during a peak day could roughly double peak electricity demand**. But the electricity system needs security of supply to meet peak, and it cannot rely exclusively on variable renewable power sources (wind and solar) to do so. **Batteries and other power storage solutions** can significantly contribute to balancing the power system. However, to ensure sufficient electricity supply is available even during long cold stretches with no wind and solar output for a number of days (i.e., even multi-day storage would be depleted), the electricity generation fleet needs **sufficient dispatchable back-up power to meet peak**. Certain low-carbon generation baseload sources can serve this (e.g., hydro, nuclear). The rest of the capacity will need to come from back-up thermal generation, e.g. gas plants (which could use bio-methane, hydrogen or natural gas combined with carbon capture). These back-up plants would see very low utilization. Further, **electricity network capacity** will need to be sufficient to serve this doubling of peak demand.
- In the case of switching over a gas system to **hydrogen**, peak demand would be met in a similar fashion to the current situation of countries with a natural gas system – i.e., ensuring sufficient supply of gas. If the hydrogen is produced by electrolysis, security of supply could possibly be more easily managed, since supply would not be reliant on international natural gas markets, although it would require a parallel **deployment of renewables for hydrogen production and of hydrogen storage**[10]. The scale of additional renewables deployment required could, however, exacerbate the already considerable challenge of building sufficient renewable energy supply to meet our scaling demand for electricity as we electrify[11].
- Finally, **hybrid heat pumps** are designed specifically to have the heat pump provide the large majority of heating demand and the **gas boiler to be available to help serve times of high heating demand.** In this instance, total volume of electricity demand for heating would be similar to that from heat pumps; however, **impact on peak electricity demand would be much lower.** This would limit the scale of investment required in electricity generation back-up, and in building out the electricity network. However, conversely, there would require considerable investments into lightly-used gas assets to serve the peak: boilers in homes and the gas network.

[10] Only exception would be geographies such as Japan where importing hydrogen is expected to be a critical component of the supply of hydrogen.
[11] In particular, because with conversion of electricity to hydrogen and subsequent conversion to heat there is energy loss in the conversions. Conversely a heat pump can deliver 300+% efficiency.

In the cases of both heat pumps and hybrid heat pumps, the heat system would entail a very lightly utilized asset – in one instance back-up generation plants (paid for at a system level and charged to the homeowner through electricity bills), in the other a gas boiler (paid for upfront by the homeowner) and a gas network (paid through gas bills).

Exhibit 11: solving for peak



[1] Should renewables not be providing power for a number of days, need dispatchable power (gas, hydro, nuclear, etc.) that can meet the load; scale required determined by peak

There are very meaningful **implications for the electricity system** in almost any scenario.

- **Doubling of electricity peak demand:** If heating is electrified using heat pumps, this would roughly double the total electricity load in a peak winter week[12]. This incorporates electrified transport in the baseline, but, if broader electrification takes hold (e.g., of industry) then the increment from heating would be less than a doubling.
- **Significant added flexibility:** Heat pumps present a semi-flexible electricity load (especially if using heat storage and pre-heating, provided sufficient building insulation), which could help align energy demand for building heating with variable output from renewables in winter months. In the case of hydrogen, the electrolyzers would be fully flexible and could shift their demand to align hydrogen production with times of high renewable output, thus improving the utilization rate of renewables and their economics, as well as providing critical balancing services to the grid.

C. CARBON INTENSITY COMPARISON

The different low-carbon heating solutions described above can offer **varying degrees of carbon emissions reduction** [Exhibit 12].

In the case of **electrified heating solutions**, the degree of decarbonization will of course reflect the degree to which the electricity system is decarbonized. As the electricity system pushes towards a fully decarbonized state, this will in turn decarbonize heating. Electric resistive heating reflects a lower initial level of decarbonization, because it draws more electricity from the grid per unit of delivered heat than a heat pump. Conversely ground- or water-source heat pumps reflect a higher initial level of decarbonization as they are more efficient than air-source heat pumps.

[12] Based on analyses for the UK, includes electrical volumes from electrification of transport.

Hybrid heat pumps of course still use a gas boiler to serve a portion of heating demand, which will create emissions if the gas boiler still relies on natural gas (especially if methane leakages along the gas supply chain are not under control). This may be exacerbated if residents overuse the gas boiler[13]. Use of the gas boiler could also be fully decarbonized though if the gas system is eventually shifted over to clean hydrogen.

Solar thermal and geothermal are inherently fully decarbonized, since they draw heat directly from renewable resources (respectively the sun and the earth's core).

Waste heat can be considered low-carbon as the heat, by definition, otherwise would have been wasted, although its precise carbon intensity actually depends on the carbon intensity of the energy source used in the underlying commercial or industrial process.

Bioenergy emits carbon when combusted; however, it originally captures that same carbon from the atmosphere during its growth, therefore theoretically creating a closed loop. This process is only truly low-carbon if the bio-feedstock supply is sustainable – in particular if it does not trigger any land use change[14] and if continued biomass growth ensures constant renewal of natural carbon capture – and if the processing and refining of the biomass is carried out in a zero-carbon fashion.

When providing building heating via **hydrogen**, there are no emissions when the hydrogen is burned in boiler or converted back to electricity through a fuel cell. There may however be emissions in the course of producing the hydrogen. If the hydrogen is produced via electrolysis, then any emissions would be reflective of the emissions associated with the electricity used. Fortunately, the cheapest approach to electrolysis is generally to use dedicated renewables[15]. Therefore, hydrogen from electrolysis would provide fully decarbonized heating. If the hydrogen is produced via SMR or ATR, there are three aspects of emissions to consider: (1) SMR and ATR produce emissions if not combined with CCS/U; (2) even if combined with CCS/U, capture levels do not reach 100% of emissions (at best 90 / 96% respectively today); (3) natural gas is used as a feedstock to the process, and it carries inherent emissions associated with methane leaking in the supply chain of natural gas.

Exhibit 12: carbon impacts of low-carbon heating solutions **Indicative**

		Solution	0% decarbonization → 100% decarbonization	Additional points to note
Low-carbon heat sources	Electric	**Electric resistive**	Reflect electricity system decarbonization → reach 100% as electricity decarbonises	▪ Adds significant load, increases **scale of renewables** needed for 100% clean power ▪ Adds **flexible demand**, enabling smoother integration of renewables into system
		Air-source heat pumps (ASHP)	Reflect electricity system decarbonization + increased efficiency → Elec. decarb.	
		Hybrid heat pump (+ gas boiler)	Peak served by natural gas → Elec. decarb + move to H_2 boiler	▪ Risk customer **may overuse of gas boiler**
		Ground or water-source heat pump	Reflect electricity system decarbonization + increased efficiency → Elec. decarb.	▪ Solutions not applicable in all locations
	Local renewable	**Solar thermal**	Direct use of low carbon energy source	▪ Solutions not applicable in all locations
		Geothermal		
	Waste heat		Makes use of heat otherwise discarded (i.e., not additional emissions to create heat)	
	Burn molecule	H_2 SMR/ATR[2] + CCS	End-use decarbonised, supply chain not[3] → Low-leak CH_4 used	▪ In case of electrolysis, similar to above: [1] increases scale of renewables required, but [2] adds flexible demand
		H_2 Electrolysis	Can operate only at times of high renewable output, or run on dedicated renewables	
		Bioenergy	Only if sustainably sourced bioenergy	
Enablers	**District heat networks**		*Dependent on source of heat; can enable access to lower carbon heating sources (e.g., waste heat, geothermal, biomass)*	
	Heat storage		*Enables low carbon heating (e.g., enables smoother profile of electric heating demand)*	

[1] electric resistive is 100% efficient whereas heat pumps are 250-300%+ efficient, thus same heat load delivered via electric resistive would require ~3x the electricity v. heat pump
[2] SMR = Steam Methane Reformation which has up to 90% CO2 capture rate (currently), could also be ATR (Auto Thermal Reformation) with 96% CO2 capture rate
[3] methane is feedstock for SMR or ATR process, in the supply chain of delivering methane some proportion can be flared, vented, leaked with significant GHG impacts

[13] E.g., residents may end up in behaviour patterns where their homes are not sufficiently pre-heated and they frequently seek a high ramp-rate of heat output which would require the gas boiler.
[14] If the supply of bioenergy requires considerable volumes of land, which may have directly or indirectly precipitated deforestation, this would not be truly low-carbon.
[15] In the coming 10 years once CapEx of electrolysers drop down a learning curve to below $400/kW, the primary determinant of cost of hydrogen is the price of input electricity (provided it operates > ~2k hours). Since renewables are now the cheapest form of power generation, dedicated renewables (or connected to grid and running only during times of high renewable output) is the lowest cost approach.

District heat networks are not a source of heat of themselves – they need a source of heat as input on the network. However, they enable access to low-carbon heat sources (e.g., waste heat, geothermal, biomass) which otherwise may have been unreachable.

Heat storage similarly is not a source of heat. However, it can enable low-carbon energy systems by providing flexibility, which is particularly critical if heat source is electric.

D. COST TRADE-OFFS

In most cases, where fossil-based heating solutions are deployed today, these are the lowest-cost solutions[16]. One important exception is where heating and cooling demand are present and can be met by a reversible heat pump; this is often more economic than a combination of air conditioning and heating solutions (even if fossil). However, in many if not most cases, **shifting to low-carbon heating solutions incurs a cost.** The nature of this cost will differ by solution [Exhibit 13]:

- In some cases, there would be higher CapEx (e.g., heat pump); in others, higher OpEx (e.g., resistive electric).
- Any capital cost could constitute a system-level cost (e.g., power generation), be incurred at a community project level (e.g., district heating), or fall directly to the individual homeowner (e.g., heat pumps). In most cases, however, system- and community-level CapEx and OpEx will be reflected in consumers' energy bills.

In the cost comparison outlined on Exhibit 13, an investment in **energy efficiency** is assumed in all cases (represented by the light green segments across the bottom). The investment is measurably higher in the case of air-source heat pumps reflecting the fact that additional insulation measures may be required for some buildings to make them suitable for the lower heat output experienced with air-source heat pumps, particularly in cold temperatures.

Electric resistive heating solutions are inexpensive equipment (small dark green brick in Exhibit 13); however, they are roughly 100% efficient, which is low compared to heat pumps at more than 300% efficiency. Therefore, primary cost is seen in the electricity system, which would require additional generation and network investments.

Air-source heat pumps (ASHP) have higher upfront capital ($5-10k including installation); however, they are more efficient, thus lower operating cost once installed. This would still add considerable load to the electricity network (doubling during winter peaks), requiring investment in electricity generation and network. ASHP are likely to play a prominent role in decarbonizing heating in multiple geographies. As a result, they may benefit from further economies of scale and other learning curve effects to drive their costs down and improve their performance materially (especially performance in cold weather, which is a present focus of R&D).

Hybrid heat pump solutions (ASHP + gas boiler) represents a roughly similar total capital cost in the building to an ASHP-only solution. There is an additional cost of the boiler, however the heat pump can be measurably smaller since it does not need to be sized to meet peak heat demand. Lower investments in the electricity network (lower peak) are offset by continued re-investments in the gas network that could otherwise be decommissioned.

As we noted in Section 3B ('Solving for peak'), in the case of heat pumps or hybrid heat pumps, there would be **a lightly utilized asset**: respectively back-up generation in the electricity network, or gas boilers in the home and gas network. However, when evaluating these costs at a system-level, in the case of the UK, these assets only equate to about 10% of overall heating system annual costs[17]; thus, the cost is material but manageable.

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[16] There are some exceptions, e.g., off-grid buildings using oil heating in developed countries.

[17] For heat pumps, cost of ~100GW of gas plants @£350-500/kW (note: capital costs could double with CCS) equates to ~£35-50B. With hybrid heat pumps there would be: [a] ~23M homes (on gas network) with a gas boiler – though this additional cost equates to the savings from being able to use a smaller heat pump; [b] a gas network, with asset value similarly ~£30B. These costs annualised over 30 years at

Ground- and water-source heat pumps are of course only applicable in appropriate locations. Where they are suitable, the upfront cost could be considerable (including installation); however, operating costs are minimal as they are even more efficient than air-source heat pumps.

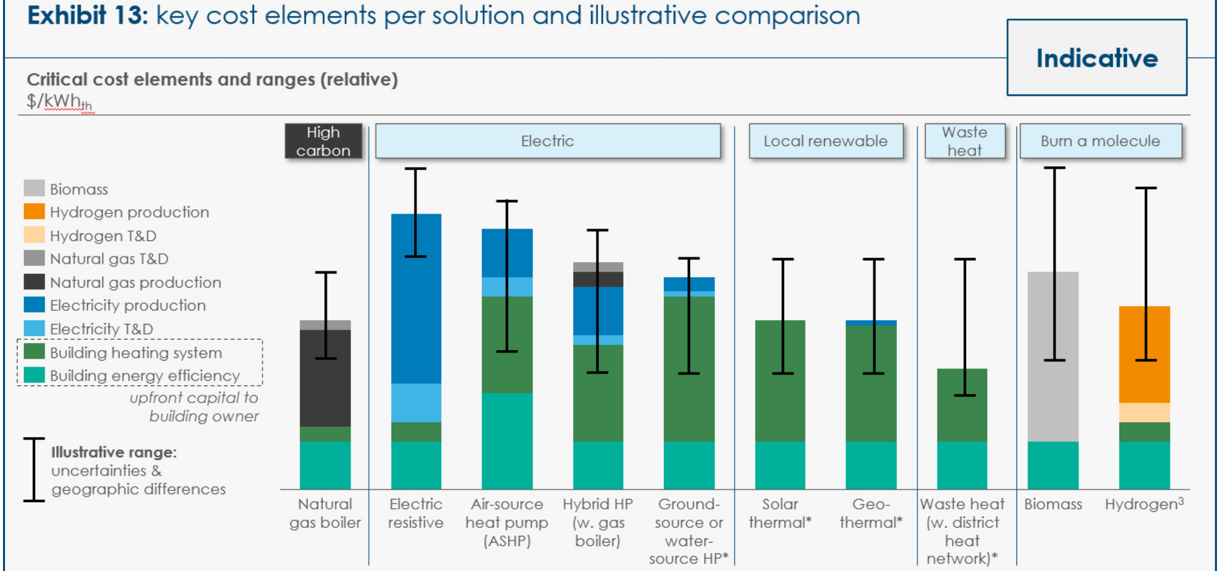
Solar thermal and geothermal are very much like ground- or water-source heat pumps: they entail high upfront capital expenditure with low operating costs.

Waste heat costs will be entirely determined by the cost of installing the heat network to gain access to, and distribute, the waste heat.

Biomass could, in certain locations, be very cost-effective. For example, Sweden's growth in district heat networks has seen these networks fueled by heat from biomass. Biomass might also be the most cost-effective solution for some off gas-grid locations. However, the cost almost entirely lies in the cost of the biomass itself (e.g., wood) and growing constraints on the truly sustainable volume of biomass supply could drive price increases and restrict biomass use for heating v. other sectors of the economy with more limited alternative decarbonization options (e.g., aviation).

Hydrogen would require limited upfront capital cost to the building owner since hydrogen boilers would be of similar cost to gas boilers. If in-building pipe replacement is required, this would present additional cost. If the gas network in the country is not already being converted to plastic pipes[18], then there could be considerable cost to upgrade the network. Importantly this assumes an existing gas network. If there is no existing gas network, there is not a case for installing a new gas network to serve heating with hydrogen. The technical and safety viability of hydrogen in buildings has not yet been proven; this is underway, but could uncover unforeseen costs (e.g., significant in-building piping upgrades).

Exhibit 13: key cost elements per solution and illustrative comparison



[*] Illustrative for locations where solution is at least reasonably appropriate; these solutions are not broadly applicable
[1] Assumes natural gas grid in place with upgrade to plastic pipes already completed thus not considered an additional cost
[2] Viable where electricity networks are present. Air-source heat pumps require sufficient building insulation and *currently* are not very effective in very cold temperatures (e.g., below -10ºC), however on-going R&D may address, they can be paired with electric resistive to increase peak heat output capacity, or use a hybrid HP solution.
[3] This assumes a retrofit of an existing gas network to flow hydrogen

7.5% discount rate result in ~£3-4B cost p.a. The total heating system cost in the UK is ~£32B p.a. (Element Energy for National Infrastructure Commission, 2018).

[18] Plastic pipes help to reduce methane leaks while using natural gas, and can carry hydrogen.

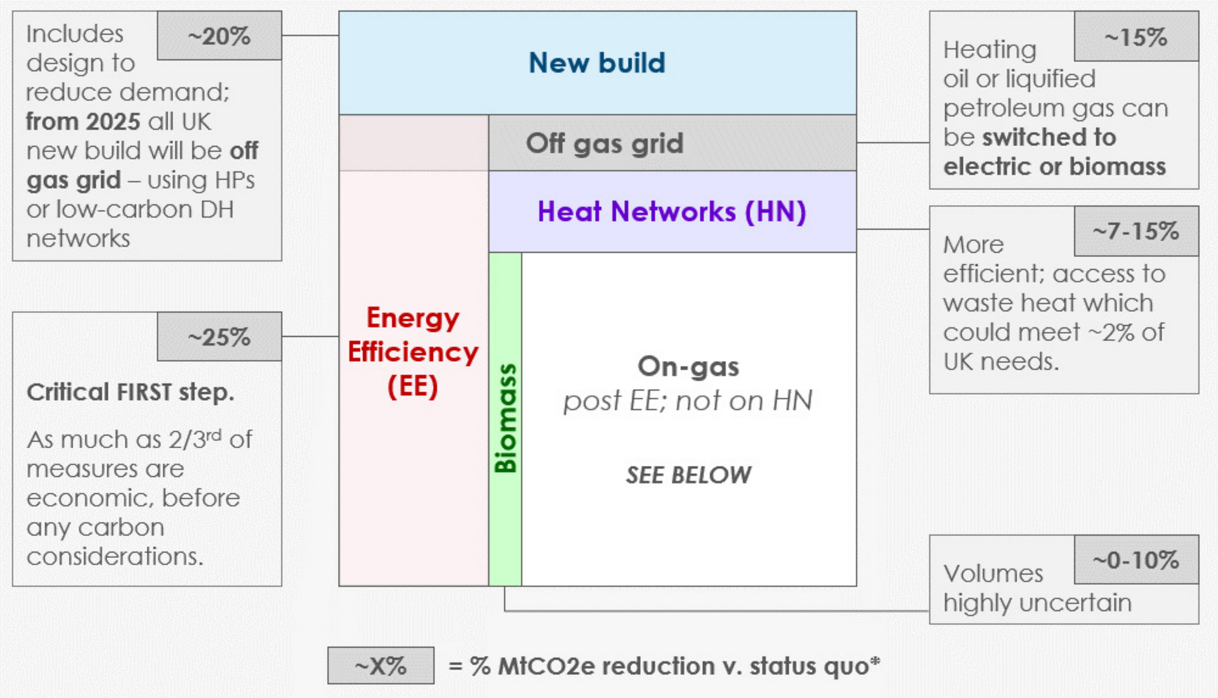
The most affordable low-carbon heating solution will **differ by country, region and even local area**. If a location has easy access to a cheap local heat source, this will often be the best solution, e.g., waste heat, sun (for solar thermal), ground heat (if easy deployment of a ground-loop). However, many locations will not have these options and thus will turn to broadly applicable solutions. **In most cases, electrified heating (resistive or air-source heat pumps) will be the most appropriate option due to the inherent efficiency of electric heating**, especially heat pumps, while hydrogen might be used where gas grid are in place to support its deployment. In the below frame, the UK is used as a case study for **how these solutions could come together** to decarbonize heating in one sample country.

Overall, **lower-carbon heat is expected to cost more than fossil-based heating.** In the case of the UK, cost of heating was 1.2% of GDP in 2015. Cost of heating is declining though, and thus, while low-carbon solutions will cost more than retaining the current natural gas network serving ~85% of homes in the UK, low-carbon heating would still represent less than 1.0% of GDP if we switch from now through 2050[19]. The critical element to consider is **how these costs are paid for**. For example, energy efficiency measures into low-income housing could perhaps be paid for through taxes or energy bills, as is already the practice in a number of countries.

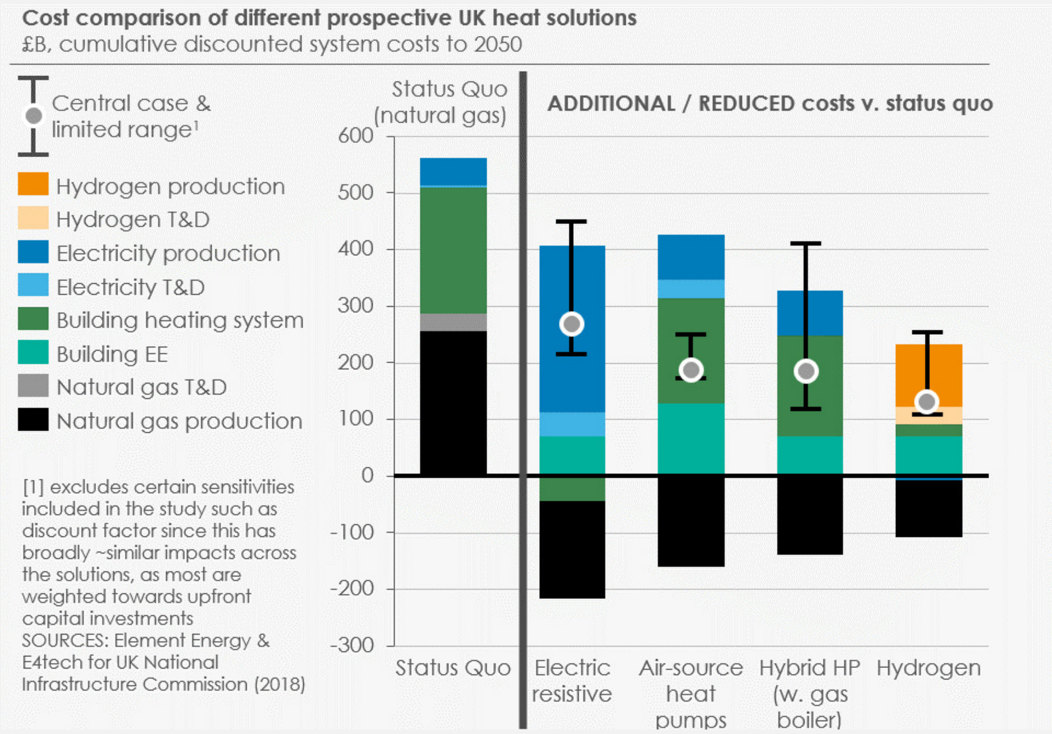
[19] Element Energy & E4tech, Cost analysis of future heat infrastructure options

Case study: Heating decarbonization in the UK

In the example of the UK, as with most geographies, decarbonizing heating will require a mix of solutions, given appropriate solutions will differ for different locations. Decarbonizing the UK building stock can **start with a series of 'lower-cost / low-regrets' solutions, i.e.:**



Beyond these solutions, the remaining set of **existing buildings on gas grid** would need to decarbonise their heat source via either **heat pumps** (including possibly hybrid heat pumps) or a system-level switch to **hydrogen** if all hurdles (technical, safety) can be overcome. It is not yet evident which of these solutions would be lowest cost, though **heat pumps are certainly immediately able to begin scaled deployment** while hydrogen is not.



E. CONSUMER ADOPTION CONSIDERATIONS

Perhaps more fundamental than cost considerations are **consumer adoption considerations.** As already referenced, **energy efficiency retrofits are notoriously hard** to encourage given high upfront costs and inconvenience to the building residents. Similar barriers could get in the way of the deployment of low-carbon heating solutions.

Heat pumps are sizeable, can be unsightly and noisy, and may require an additional hot water tank and potentially larger emitters installed. The upfront cost can also be prohibitive. Consumers may dislike not being able to achieve the heat output rate that is possible with a gas boiler, which allows them to relatively quickly warm-up their home on queue as opposed to having to warm up the home ahead of time. For some buildings, deep energy efficiency retrofits may be a pre-requisite, exacerbating an already invasive installation process.

Hydrogen is less of a consumer choice since entire regions would have to switch at once, thus an individual building owner would not be able to opt out. Consumers may not like the idea of being required to stay home for someone to switch over their appliances to run on hydrogen (boiler, cookers). There are also legitimate safety issues to be resolved (hydrogen is a smaller molecule and thus more likely to leak than natural gas, though dispersed when leaked since it is lighter than air). Even if they are resolved, these initial safety issues may result in a consumer aversion to having hydrogen running through the home, as hydrogen might continue to be viewed as quite dangerous. Before any policymaker mandates a switch to hydrogen, it will likely take considerable convincing of the electorate to create the right political space.

Ground-source heat pumps, even where they are feasible (i.e., sufficient outdoor space), often require a disruptive installation process (e.g., digging up an entire garden / yard).

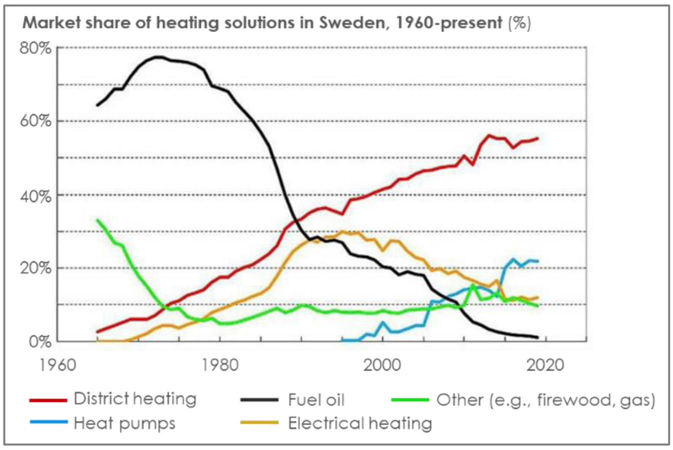
Regardless, certain countries have seen success in incentivising uptake of lower-carbon heating solutions, often through packages of measures (e.g., subsidies, taxes on fossil fuel for heating, installer training, public promotion).

4. CURRENT INITIATIVES IN SAMPLE COUNTRIES

The UK case study provided one example to lay out the applicability and relative strengths and weaknesses of different low-carbon heat options. However, the **answer for delivering low-carbon heating in any given country will be meaningfully different from the next**, as is the case for heating solutions currently (see Exhibit 4). Many countries are already driving their transitions to low-carbon heating, with varying degrees of success. A sample is included here[20]:

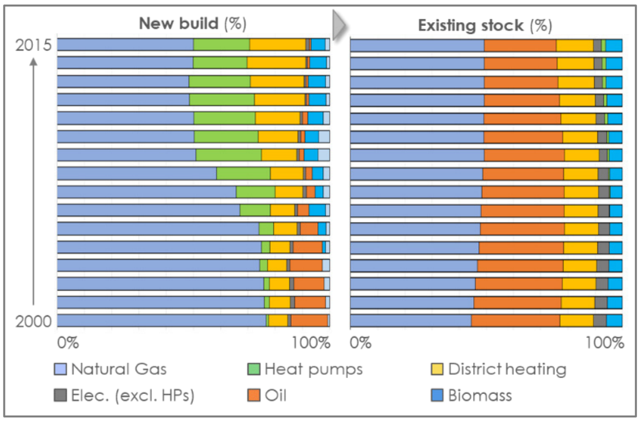
Sweden

In the 1970s, Sweden delivered almost 80% of its heat via fuel oil. Since then energy taxes were applied (among other policy measures) and today heating is dominated by cleaner solutions: **district heating** (>50%) mostly fueled by biomass; **electric heating** (10%); **heat pumps** (20% and growing, predominantly ground-source). This transition began as a reaction to the oil crisis and was enabled in part by municipalities who were able to invest large sums in the upfront capital for district heat networks.



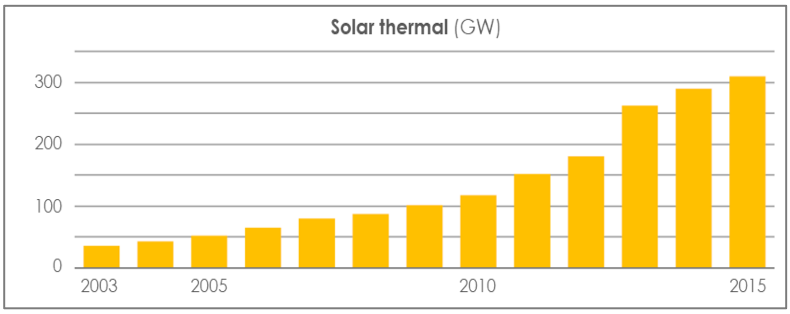
Germany

Packages of policy measures have been implemented to support **heat pumps and district heating** which have grown from below 10% of new builds in 2000 to now over 40% of new builds in 2015. However, encouraging existing stock to retrofit has proven extremely challenging, in no small part due to Germany's high residential electricity prices.



China

Solar thermal has already been gaining traction, having grown from <50GW in 2003 to >300GW in 2015. Targets for continued accelerated growth have also been set in the current 5-year plan, along with aggressive targets for **geothermal** and **biomass**. China is also investing in **long-distance district heat network** to transfer heat from industrial centers to cities in the region.



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[20] Drawn from IEA, *Renewable Heat Policies* (2018), Vivid Economics, *International Comparison of Heating, Cooling, and Heat Decarbonization Policies* (2017)

5. CONCLUSIONS AND IMPLICATIONS

The challenge of decarbonizing building heating is technically achievable. While it will incur increased costs v. maintaining status quo solutions (not accounting for externalities of greenhouse gas emissions), these **costs appear to be manageable** on a macroeconomic basis. For instance, in the case of the UK, cost of low-carbon heating in 2050 would be ~0.9% of GDP, which would be down from 1.2% today – status quo would have seen an even sharper decline.

Countries need to accelerate deployment of no-regrets measures: accelerated energy efficiency improvement, zero-carbon heating (most likely in the form of heat pumps) in new builds, shift to low-carbon sources in district heat networks (e.g., waste heat, solar thermal), switch to electricity in regions that are off gas grids, and, wherever possible, deployment of solar thermal, ground- and water-source heat pumps, as well as geothermal.

The most appropriate low-carbon heating solutions will differ by location, not only at national, but also at regional and even local level. The mix of solutions each country deploys will thus differ considerably, just as the mix of current solutions differs today.

At the same time, countries need to **begin to build out capabilities, supply chains, and customer readiness** to deliver zero-carbon heating at large scale, most of the time in the form of air-source heat pumps and, in some instances where a gas grid pre-exists (especially if that grid has already been retrofitted with plastic pipes to avoid leakages), in the form of hydrogen. The economics of these solutions will shift, though, for many if not most geographies, it is already clear that **air-source heat pumps will play a large role in decarbonizing heat**.

Customer adoption of energy efficiency technologies and lower-carbon heating solutions is a daunting challenge which has not yet been comprehensively cracked. Therefore, increased emphasis through packages of policies, regulatory changes and funding are needed to find ways of unlocking adoption. Because there is a customer adoption and diffusion component to deploying these heating solutions, **reaching full penetration will take decades**. The transformation in Sweden implied a steady shift over the course of 50 years. Therefore, reaching net-zero by 2050 requires steady progress at pace starting now.

There are **very meaningful implications for the electricity system in almost any scenario:** where heating is heavily electrified this could double electricity demand in winter weeks – and increase even more electricity demand peaks –, increasing the challenge of deploying sufficient renewable electricity resources for a fully low-carbon power system. However, this load would also be semi-flexible where able to leverage heat storage and pre-heating, which could add flexibility to the electricity system enabling smoother integration of renewables.

6. RECOMMENDATIONS

Key innovation, industry and policy recommendations to advance decarbonization of building heating include:

PRIVATE AND PUBLIC RESEARCH & DEVELOPMENT

Energy efficiency is the largest and most critical lever we have, and new innovations should be encouraged and supported. For example, Q-bot is a robot that can be placed under floorboards to spray underfloor insulation. Incentives and support should be designed to bring forward similar innovations.

Heat storage technologies can deliver considerable benefits to peak heat management. While water as a medium remains the most economic, improvements in Phase-Change Materials (PCMs) and Thermo-Chemical Storage (TCS) continue to progress and should be encouraged as they may in future provide solutions even more cost-effective than water, and at much greater energy density.

Heat pumps have already improved in their economics over the years. Further R&D will help to continue to reduce costs, and critically to further improve the efficiency they deliver in cold temperatures. If the heat pump is the only heating solution for a building, it needs to be sized to meet peak heat demand – i.e., on the coldest days when it is trying to draw heat from colder air, and the building will be losing heat at a faster rate (given higher differential between indoor and outdoor temperatures). Their efficiency performance in these cold temperatures, and deployment of building energy efficiency solutions, are paramount to adoption in a number of colder climates.

Hydrogen is currently only used in industrial settings (refineries, fertilizer plants, chemical plants). Adopting it into the gas grid and into residential and commercial buildings requires more work to prove out and design all appropriate technical and safety elements. This work is underway via a number of trials and demonstration projects in countries where hydrogen for building heating may play a significant role because of the pre-existence of a large gas network (e.g., UK, Netherlands).

BUSINESS ACTION ACROSS THE BUILDINGS VALUE CHAIN

Businesses across the buildings value chain have a role to play to accelerate the transition to low-carbon heating systems. These include:

- **The construction industry**, including architects, who should aim for maximum energy efficiency and use of zero-carbon heat sources in all new builds and major retrofits – and might therefore benefit from training programs for both new and seasoned professionals;
- **Equipment providers**, who will play a key role not only in R&D to improve the effectiveness and reduce the cost of their products, but also in improving their design and aesthetics and developing appropriate marketing strategies, so as to increase their desirability for consumers;
- **Equipment providers, equipment installers and utilities**, who could develop new business models, such as 'heat as a service', either independently or within joint ventures, to facilitate and lower the cost of the deployment of energy-efficient and low-carbon technologies in homes; and can also play an important role as educators to customers who need to educate themselves on new solutions (e.g., heat pumps);
- **Energy suppliers**, who should anticipate the implications of the decarbonization of building in terms of demand for underlying energy sources, in particular power, and build up their supply capacity accordingly to seize the business opportunities opened by such a switch;

- **Retail banks**, who can develop specific financing products to lessen the upfront costs of building envelope and equipment retrofitting;
- **Owners of large commercial or residential building stocks**, who should invest in the deployment of low/zero-carbon technologies and could also evolve towards new business models enabling them to extract value from greater energy efficiency;
- **Tenants, especially commercial tenants**, who can pay greater attention to the efficiency and carbon-intensity of buildings when considering different options.

In many cases, collaborations between these different stakeholders, possibly at the scale of specific neighborhoods, cities or regions, could enable coordinated action and faster deployment of energy efficiency and zero-carbon heating options.

PUBLIC POLICY

Policy is the single most important area to advance decarbonization of heat. In countries that have seen progress on the issue, it has been as a result of a **package of policy measures** each designed to address hurdles both economic, tactical and behavioral. These policy measures should be anchored in a robust **vision of decarbonization pathways at national level**, which should be informed by local specificities in terms of natural resources, geography, pre-existing infrastructure, and consumer behaviors, and which should also draw the implications for the energy system, in particular the power system.

In most cases, **no-regret policies** will include:

- Regulations stipulating all **new buildings** must be zero-carbon – or even energy-positive – through the adoption of high levels of energy efficiency and low-carbon heating;
- Regulations **mandating deep energy efficiency retrofits** as part of any large-scale renovation that requires planning permission or building inspection;
- **Energy taxes** to increase the costs of fossil-fuels for heat provision;
- **Deployment support for the most cost-competitive low-carbon heating option** in geographical areas where it is easily identifiable (e.g., switch in energy source of existing district heating systems, deployment of heat pumps in low-density residential areas), which can, in turn, include:
    - **Public campaigns** to help uplift customer familiarity and adoption of low-carbon heating solutions;
    - **Subsidies** to decrease the upfront capital cost of low-carbon heating solutions;
    - **Development of roll-out plans at neighborhood level** to lower the cost per house of new installations;
    - **Relaxing regulations** which might be hindering implementation of low-carbon heating (e.g., expedite planning approval for district heating networks);
- **Direct power grids and utilities to plan measures** to be able to manage the increases in electricity load and peak that will result from partial or total heating electrification.

Where uncertainties on decarbonization pathways remain, in particular with regards to the appropriate mix of solutions in areas with a pre-existing gas grid, public policy-makers have a choice to make between:

- **Picking one** of the potential cost-effective low-carbon options – most likely between electric resistive, heat pumps, hybrid heat pumps and hydrogen – in the early 2020s to be able to **start investing early** in the deployment of the required in-home equipment, infrastructure and energy provision;
- **Rolling out hybrid heat pumps** combined with gas boilers in the 2020s – supporting both the deployment of heat pumps in homes and the upgrading of the gas network – to **maintain optionality** for a longer period of time, although this might lead to **stranding of some assets** in the following decades.

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