Hydrogen, heat, and the decarbonisation of energy systems

Working Paper

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Contents

1. Sustainable Heating: Implementation of Fossil-Free Technologies (SHIFFT)

SHIFFT is an Interreg 2 Seas project, running from 2019-2022, promoting cross-border cooperation between 4 European countries: The Netherlands, France, Belgium and The United Kingdom. It has been approved under the priority ‘Low Carbon Technologies’.

Space and water heating represent a large fraction of overall energy consumption across the EU Member States, and around one third of carbon emissions. Dependence on fossil fuels has made the heat sector hard to decarbonise in at least three of the four Member States in the 2 Seas region. Further, between 65% and 80% of buildings across these four Member States that will exist in 2050 have already been built, often with fossil fuel heating systems and poor energy efficiency. There is an enormous potential to reduce CO2 emissions in the sector by shifting to low carbon heating alternatives, but there remain many barriers to doing so.

The main objective of the SHIFFT project is to stimulate the adoption of low-carbon heating technologies in existing buildings. It will take multiple routes to achieving this through its three technical work packages (WP).

WP1 develops city strategies for four small to medium municipalities as well as producing general guidance for cities to make their own strategies for the move to low carbon heating. City strategies will be devised for the Belgian cities of Brugge and Mechelen, the Dutch city of Middelburg and the French city of Fourmies, with planning for each led by the cities as full partners in the project. These will inform a document offering guidance to other cities who want to devise their own strategy.

WP2 focuses on developing strategies for the fullest possible inclusion of communities in developing low carbon heating strategies at the local level. This co-creation process will inform the other WPs so that the views of building users are fully incorporated into decision making. We see it as essential to include communities to the fullest possible extent in decisions about the buildings in which they live, work and play. Partners including community facing energy group De Schakelaar (NL) will be working to incorporate communities in this WP.

WP3 concerns delivery of exemplar community low carbon heating projects; one installation of low carbon heating technology will take place in each of the four INTERREG 2 Seas Member States, with each build led by one of our project partners: Places for People (UK), Fourmies (FR), Middelburg (NL) and Woonpunt Mechelen (BE). We will aim to capture learning from these developments and pass it on to the widest possible selection of stakeholders in the sector.

Technical support is provided by two universities, the University of Exeter (UK), acting as project coordinator and Delft University of Technology (NL) and by CD2E (FR). These organisations will support city and other partners as regards technology, policy and co-creation of projects with communities.

The specific and measurable objectives of SHIFFT are to assist in the development of city low carbon heating strategies, both within the project and by demonstrating routes to strategy development for other municipalities, to develop exemplar low carbon retrofit heating projects and to work with others to pass on the lesson learned within the project to maximise the value of the lessons learned.

SHIFFT targets local and regional authorities as a primary target group with the purpose of influencing communities, homeowners, districts, cities, energy consultants, energy service companies and SMEs to consider a wider set of heating solutions than is currently the case.

2. Executive Summary

This working paper examines the role that hydrogen might play in helping to decarbonise heat within the built environment. Global interest in the use of hydrogen to decarbonise energy systems has never been stronger, reflecting some of the key characteristics of hydrogen, which as an energy carrier, could see it provide a wide range of roles across many different areas of the energy sector.

The paper starts from a recognition that to tackle climate change, deep and rapid reductions in global GHG emissions are needed, requiring energy systems and the provision of heating, to largely decarbonise. The opportunities and challenges for enabling this in relation to hydrogen are explored. This starts with some context on current hydrogen production, its supply chain, and projections around its future use (Section 4). Consideration is then given to the role that hydrogen could play in energy system decarbonisation (Section 5), before specifically focusing on the challenges of heat decarbonisation, asking what role hydrogen could and should play within the heat sector (Section 6); conclusions are set out in Section 7.

Hydrogen in context

Hydrogen is a chemical energy carrier, rather than an energy source, that can be produced from a range of resources, using different feedstocks, pathways, and technologies. It can be stored for long periods, transported in a stable way, used within existing infrastructures, and combined with other elements. Collectively these properties make it an appealing proposition for dealing with some of the complexities for decarbonising energy systems.

For pure hydrogen, current global production is around 70 MtH_2/yr and this is mainly used within industry. This production is almost entirely from fossil fuels releasing between 10-19 $kgCO_2eq/kgH_2$ depending on the feedstock which results in around 830 million tonnes of $C0_2$ emissions per year. One route to lower-carbon hydrogen is to add CCUS to the production process to capture CO_2 before it enters the atmosphere, generally referred to as blue hydrogen, this can reduce carbon emissions to between 1-4 $kgCO_2eq/kgH_2$. Hydrogen can also be produced cleanly, through the electrolysis of water using electricity from renewable energy resources, often referred to as green hydrogen this has emissions close to zero.

There are challenges for scaling up both blue and green hydrogen currently. For blue hydrogen, CCUS/CCS needs to be developed, but this has suffered from high cost and project cancellations, with low levels of deployment currently. As this production route is also only low carbon, any significant scaling up of blue hydrogen could lead to ongoing path-dependency and lock-in to natural gas infrastructure, making it hard to reduce emissions in the future and hindering wider energy system decarbonisation. For green hydrogen, production is much more costly currently and there are efficiency losses within the conversion process. Current rates of deployment for both blue and green hydrogen are low, although this is expected to change.

Producing cost-competitive low-carbon hydrogen at scale is recognised as one of the greatest barriers to developing its role within energy systems. Whilst there is an expectation that costs will fall and efficiencies will improve, especially for green hydrogen, the challenge for hydrogen is that it must establish itself in markets that other fuels and technologies currently dominate. For this to happen the whole hydrogen supply chain has to scale up and become resilient by creating supply and demand simultaneously, so that a virtuous circle emerges across production, infrastructure for supply, end-use demand, and the creation of markets. This will require cooperation, coordination, and investment from many different actors across the whole supply chain; and supportive and aligned policies and regulations across different regions and countries.

Many countries already have policies in place to support some areas of hydrogen, mainly in terms of end-uses on the demand side, and several more strategic roadmaps are also emerging. This includes a recent EU plan setting out a framework for building up the supply chain over three phases to 2030 and beyond, with a key goal to build green hydrogen production, although acknowledged that blue hydrogen will be needed in at least the short to medium term. The EU also flag the potential importance of hydrogen valleys where clusters of local production and local demand could develop, enabling dedicated hydrogen infrastructure to emerge that will open up a range of potential end uses across different sectors and help to build wider hydrogen supply chains.

In respect to future levels of demand, several scenarios have been produced at international, regional and local levels. At a global level, the Hydrogen Council suggest that hydrogen could provide 18% of the world's final energy demand, across a range of different sectors and requiring around 545 MtH_2/yr by 2050. Using the same modelling approach, a study focussed on Europe suggests that hydrogen could provide 24% of final energy demand by 2050, requiring around 57 MtH_2/yr.

Hydrogen and energy system decarbonisation

Some of the basic attributes and versatility of hydrogen could enable it to play a role in a wide range of applications within energy systems, as an alternative to current fuels and inputs, or as a complement to the greater use of electricity in these applications. Given the ability for it to be stored and transport, it could also help by providing flexibility and sector-coupling within energy systems opening a range of opportunities to help keep supply and demand in balance, including inter-seasonally.

Hydrogen could also be an enabler of greater renewable energy penetration, particularly from intermittent resources like wind and solar, as excess energy that might otherwise be constrained off the system could be converted to hydrogen to be used to provide power or other end uses, at a later time. This 'renewables plus hydrogen' energy future could provide an important pathway for the widespread decarbonisation of energy systems, although views on the scale of the opportunities are currently mixed, with further research and piloting currently taking place.

Many of the models and scenarios for the supply and demand of hydrogen do not provide clarity on the assumptions taken within them, although they show that it could be used within several different sectors and end uses. For example, it is suggested that hydrogen could play multiple roles within the industrial sector, as well as being used as a clean transport fuel, as a resource for heating buildings, or within power generation and electricity storage. Whilst the potential applications are broad, there does seem to be some consensus that, other than in clusters or hydrogen valleys, the biggest opportunity for hydrogen is to help in those sectors that are proving to be difficult to decarbonise, such as iron and steel production, the chemicals sector, and long-haul transport like shipping and aviation.

Decarbonising heat and the use of hydrogen

Global efforts to decarbonise heating have so far been slow, reflecting several challenges around technologies, costs, and awareness. Regardless of how heat is decarbonised, it is critical to both put energy efficiency first and ensure that people are engaged so that they can give their meaningful consent for change.

There are a range of possible routes to decarbonise heating, with common high-level pathways based on: the electrification of heat; decarbonisation of natural gas; district heating; or more hybrid-based solutions. Each pathway, and the technologies they can utilise, bring different benefits and challenges, and it is apparent that there is no single optimal approach. Heat densities will play an important role in determining potential options, as will wider considerations such as the underlying infrastructure, technologies, fuels, markets, politics, policies, and the supply chains that are in place within a country, as these create a degree of path dependency and lock-in. As well as these high-level issues, the supply and demand of heat will be influenced by a range of local issues, relating to: the age, type, tenure of buildings; energy prices; geography, etc; which collectively result in several different energy sources and technologies co-existing within the heat sector within any country. This all makes the decarbonisation of heat difficult but is also points to a need to develop strategies that consider options on a more place by place basis, as this will help to identify the best options, as well as provide better opportunities to engage end users.

In respect to hydrogen, it currently does not play any significant role in the provision of heat within the built environment, but advocates suggest it could be used in two ways. The first is to blend it into natural gas networks, with a view that by making use of this existing infrastructure, it could help to reduce the costs and risks associated with scaling up hydrogen supply chains. The extent to which hydrogen can be blended without causing problems for the infrastructure or end-use equipment is not clear. Leaving aside the infrastructure, it is suggested that blends of up to 23% by volume are possible without the need for any modification to end-use appliances, but national standards and regulations currently limit blending in many counties to around 2%. Several pilot projects are taking place globally to test hydrogen blending volumes for issues such as safety, efficiency, and environmental performance.

In respect to carbon emissions, a 20% blend of hydrogen will only reduce emissions relative to natural gas by 4-6%, if using blue hydrogen; as such, it cannot be a key strategy for decarbonising heat. Where it might help, is encouraging the more rapid deployment of hybrid-based approaches, but views are mixed, the recent EU roadmap dismissed blending, suggesting that it is an inefficient use of hydrogen that diminishes its value, whilst also potentially risking the fragmentation of cross-border gas markets, if countries adopt different blending standards.

The second option is to use 100% hydrogen to provide heat via dedicated hydrogen boilers or fuel cells. This approach would require significant changes to gas network infrastructure, including retrofitting components or replacing appliances within buildings. Again, if blue hydrogen is used, this is a questionable strategy as it would only reduce emissions relative to natural gas by 60-85%. Using 100% hydrogen for heating would also create significant more demand for hydrogen, requiring much more clean production.

Conclusions

To assess its potential role within the heat sector, there are two key questions. Firstly, how much clean hydrogen can be produced, at what cost, and by when; and then, where within energy systems is it most sensible to use that hydrogen. The answer to the second question is more straightforward, as there seems to be consensus that hydrogen should be used in those areas of the energy system that are proving difficult to decarbonise and where alternatives are not available, this includes iron and steel production, the chemicals sector, and long-haul transport like shipping and aviation.

The answer to the other question is more complicated and speculative, because there are considerable uncertainties, risks, and assumptions based around the development of the hydrogen supply chain, including its clean production. Scenarios for future potential demand, suggest that in respect to heat, Europe might need around 12Mt/H_2/yr by 2050, whilst a central scenario within the UK suggested around 3 Mt/yr would be needed by the same time. How clean that hydrogen would be cannot be easily known, but all the scenarios suggest that blue will have to play a role, at least in the short to medium term. How much the hydrogen will cost is also unknown and that partly relates to the uncertainties around the future cost of gas and CCUS for blue hydrogen, and in the longer term how much costs fall for green hydrogen. In terms of timescales, the existing scenarios seem to suggest that hydrogen will not start to have much of a role until the 2030s or even 2040s; this further complicates cost predictions, but also raises real questions around the use of hydrogen for heating, given the need for rapid and deep cuts in carbon emissions. Things could change, depending on the how quickly green hydrogen is able to ramp up, cost effectively, but currently, in answer to the question, it is not yet clear how much low-carbon hydrogen will be available, at what cost, or by when.

Overall, based on the evidence reviewed for this paper, hydrogen does not currently appear to be a good choice for decarbonising heat, because:

- it can be put to better use in other areas of the energy system, where decarbonisation is proving more difficult and alternative options are not available.
- both of the main options for using hydrogen will require blue hydrogen, which risks locking-in future emissions as any new capacity will remain on the system for decades and create ongoing path dependency around fossil fuels.
- blending is not a good use of hydrogen and will lead to very low reductions in carbon emissions.
- 100% hydrogen comes with big uncertainties over the costs and timescale for its deployment and would only result in the partial decarbonisation of heating, if based on blue hydrogen.

Given these insights, whilst it is seems that hydrogen could play an important role in helping to decarbonise many areas of the energy system, and possible some niche roles within the heat sector, as a strategy for the rapid and deep decarbonisation of heating, the use of hydrogen is highly debateable and not compelling.

3. Introduction

To tackle climate change, carbon emissions from energy systems need to rapidly decrease across heat, power and transport. Global average temperatures have increased by over 1 degree Celsius since the industrial revolution and global greenhouse gas (GHG) emissions continue to rise [1]. The last UN Emissions Gap Report suggests that we need global GHG reductions at a rate of 7.6% per year to stay below 1.5°C [2]. As of 2018, EU greenhouse gas emissions were down by 21% of 1990 levels, although progress in annual reductions have largely plateaued since 2014 [3]. In recent years the EU has progressively looked to increase its efforts to reduce GHG emissions, in line with the Paris Agreement, including plans for a European Green Deal and the objective to be net-zero by 2050 through a new European Climate Law [4,5]. A number of strategies and plans have already been published in support of these, including one on energy system integration, and another on hydrogen [6,7]. Tackling climate change, at the pace needed, will require a complete transformation of energy systems and there is a growing interest in the role that hydrogen might play within this process.

The International Energy Agency (IEA) [8] highlight that globally there has been an historic interest in using hydrogen within the energy sector that has gone through a number of waves, often in response to global issues such as the 1970s oil shocks, concerns over peak oil, and a growing focus on tackling climate change. Despite this, hydrogen has not competitively made it to market within the energy sector, partly because scaling up was dependent on the price of oil and gas and also because early efforts to develop it largely focussed on just the transport sector.

In recent years, interest in hydrogen has come to the fore again, driven by a growing recognition that economies and the energy systems that drive them, will have to be decarbonised in order to reach the increased ambitions under the Paris Agreement. This has led to unprecedented business and political interest and support globally to develop the role of hydrogen in energy system decarbonisation [8]; reflecting the fact it could play an important role in many different areas of energy systems, including those that are providing difficult to decarbonise [7–9].

However, there remain a range of challenges facing the widespread development and use of hydrogen in energy transitions, including: how cleanly it can be produced, its cost, the infrastructure to support it, as well as a need for supportive and coordinated policies and regulations [8]. There are also considerable differences in where actors think hydrogen will and won't play a role in energy system decarbonisation. Whether a hydrogen economy will emerge this time around, remains to be seen; as a recent academic review put it [10], the majority of the literature still shows that a full hydrogen dependent economy is highly debatable and not yet realisable, although it is starting to show potential.

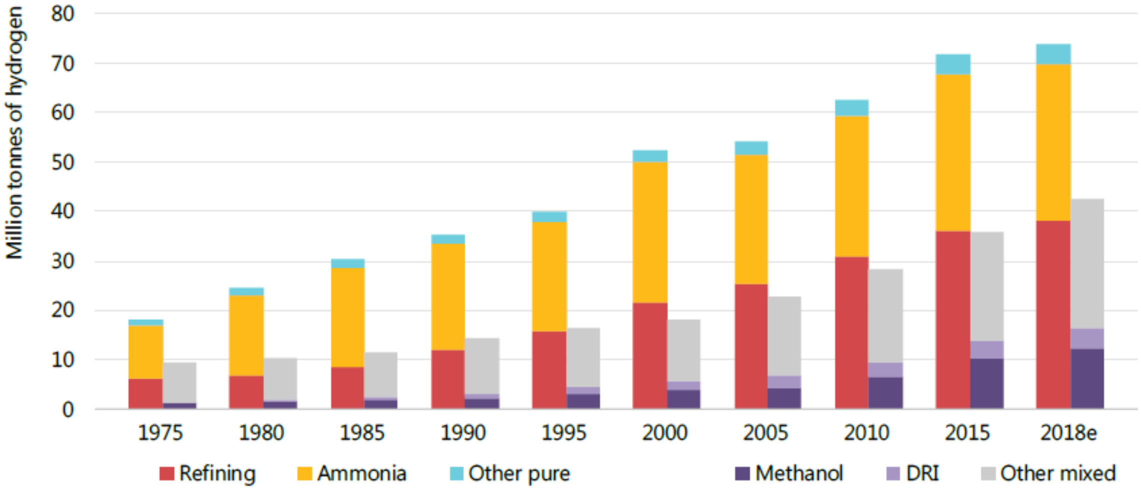
This paper provides some background context on hydrogen, its potential role in energy system transformations, before focussing specifically on what role it could or should play in decarbonising heat within the built environment.

4. Hydrogen in Context

Like electricity, hydrogen is an energy carrier, rather than an energy source, albeit a chemical energy carrier composed of molecules (compared to electrons in electricity) [8]. As the IEA highlight, chemical energy, in common with other fossil fuels, is attractive because it can be stored for long periods, transported in a stable way, be used within existing infrastructures, and be combined with other elements increasing the range of applications it can have [8]. Hydrogen can also be produced from a wide range of resources, using different feedstocks, pathways and technologies [10]. These properties help make hydrogen an attractive proposition in dealing with the complexity of decarbonisation and in part explain the growing interest in its potential role within energy systems.

4.1. Hydrogen demand and production

Much of the current interest is around pure hydrogen, which only contains small levels of additives or contaminants which many applications require. Based on recent IEA data [8], global demand for pure hydrogen has increased from around 18 million tonnes per year (MtH_2/yr) in 1970 to 70 MtH_2/yr in 2018, and is used largely in oil refining and ammonia production (mainly for fertilisers). The IEA also highlight that there is an additional demand of 45 MtH_2/yr for hydrogen as part of a mixture of gases, with uses in methanol production and steel production – see Figure 1 and Figure 2.



Notes: DRI = direct reduced iron steel production. Refining, ammonia and "other pure" represent demand for specific applications that require hydrogen with only small levels of additives or contaminants tolerated. Methanol, DRI and "other mixed" represent demand for applications that use hydrogen as part of a mixture of gases, such as synthesis gas, for fuel or feedstock.

Figure 1: Global annual demand for hydrogen since 1975 (Source: IEA (2019) [8:p18]**)**

The most common form of production currently is steam reforming of natural gas, which creates a synthetic gas that can be converted to hydrogen and CO_2 for pure hydrogen applications [11]. Other methods include gasification and the electrolysis of water and there are also a range of emerging technologies [8]. The IEA suggest that around 60% of hydrogen production comes from facilities that are specifically designed to produced hydrogen, whilst a further third comes as a by-product from other processes (Figure 2); currently most of this production occurs near to its end use, using resources that are extracted in the same country, rather than it being produced and sold through international markets [8].

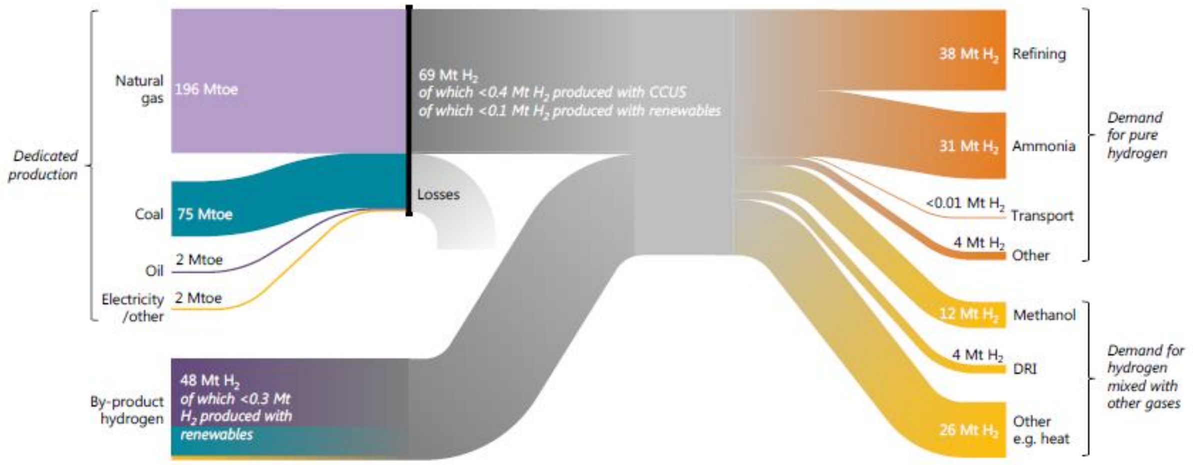


Figure 2: Current hydrogen value chains (Source: IEA (2019) [8:p32]**)**

The technology, feedstock and energy resources used to produce hydrogen directly impact the emissions associated with it, as well as its costs and material requirements [7]. As is obvious from Figure 2, currently production is almost entirely through fossil fuels. The IEA [8] estimate that this production accounts for around 2% of total global energy demand, and is mainly from natural gas, equating to approximately 6% of total global gas demand. Hydrogen is also produced from coal and to a much lesser extent oil and electricity. There is also a growing global interest in the use of electrolysis, whilst the currently market share is tiny, with less than 0.1% of dedicated hydrogen production produced through this route [8], the global project pipeline is rapidly increasing [12].

4.2. Clean hydrogen production

Whilst hydrogen is a zero-emission energy resource at the point of end use, how the hydrogen is made dictates how clean it actually is and therefore the extent to which it can play a meaningful role in energy system decarbonisation. With multiple routes to production, a range of different terminology is used to describe the type of hydrogen production, e.g. the recent EU hydrogen strategy described seven different routes [7]. A shorthand that is widely used to describe the cleanliness of hydrogen is based on colour. There are a number of different colours in use [8,10], but three of the more common are: grey (hydrogen produced from fossil fuels and considered to be polluting); blue (produced from fossil fuels, but with carbon capture, utilisation and storage (CCUS) which is cleaner); and green (produced from 100% renewable resources, which is the cleanest) [8,10].

The issue currently, is nearly all production is grey, relying on fossil fuels that lead to a significant carbon impact. Actual emissions depend on the feedstock used and the conversion efficiency of the process, but the IEA [8] suggest that production using natural gas creates around 10 tonnes of carbon dioxide per tonne of hydrogen (tCO_2/tH_2), increasing to around 19 tCO_2/tH_2 if it is produced from coal. Most of this carbon dioxide is emitted to the atmosphere, resulting in the release of around 830 million tonnes of $C0_2$ per year, equivalent to the combined annual CO_2 emissions of the UK and Indonesia [8]. It is not only the production of hydrogen that results in emissions, its purification, compression, storage and distribution, which will all play a role in its future utilisation potential, also involve energy consumption and emissions [10].

Hydrogen's future in energy system decarbonisation, therefore, depends on a radical and quick shift away from current grey production methods. If produced from fossil fuels, it can only be considered low carbon if the process is combined with CCUS[1] i.e. blue routes. Similarly, to be considered green, hydrogen produced using the electrolysis of water can only be low carbon if the source of electricity used for that production is emissions free, i.e. from renewables.

4.2.1. Blue hydrogen

For blue hydrogen to scale up, CCUS is needed. This is a catch all term for a number of different ways for dealing with CO_2 emissions, the IEA [8] describe it in terms of the capture of CO_2 before it can be emitted to the atmosphere and its subsequent permanent geological storage or use in other process that can deliver equivalent emissions reductions. There are a number of potential barriers to the scaling up of CCUS, including costs which are discussed in the next section.

A key issue for CCUS is the current availability and rate of deployment. Looking at just the power sector, whilst there are a number of demonstration projects and twenty CCUS projects reportedly under development, there are currently just two large-scale CCUS power projects in operation globally, with a combined capture capacity of 2.4 $MtCO_2$ per year [13]. To put that into perspective, global $C0_2$ emissions from the power sector in 2018 were estimated at 33,100 Mt CO_2 [14]. There are a further 19 CCUS projects in operation across industry and fuel transformation, including in hydrogen production, which have a combined potential to capture 34 $MtCO_2$ per year [15]. So currently the global capacity is tiny and it remains commercially and technically unproven in some countries, being plagued by high costs and project cancellations [12,16]. This could be further impacted by Covid-19, which has resulted in momentum for CCUS disappearing with the technology now facing considerable investment challenges [17]. With low rates of deployment globally, a view from some, that there has been a lost decade for CCUS [18], and now with new challenges for investment, a key issue facing the widespread development of blue hydrogen is that CCUS may not emerge.

A further consideration for CCUS is that the effectiveness of carbon capture varies. The recent EU hydrogen strategy [7], using IEA figures for gas steam reformation, suggest that at a potential maximum capture rate of 90%, the well-to-gate emissions of hydrogen production would be 1 $kgCO_2eq/kgH_2$, if the capture rates fall to 56%, emissions increase to 4 $kgCO_2eq/kgH_2$. So, whilst blue hydrogen is an improvement compared to grey hydrogen (at around 10 $kgCO_2eq/kgH_2$), it is not a carbon free, even at high capture rates. The risk, from a whole system perspective, is that any significantly scaling up of blue hydrogen production facilities will lead to decadal lock-in to natural gas infrastructure and the price volatility and geopolitics that come with gas [19,20], which may make it harder to reduce emissions in the future. There is also risk, as has been seen in the power sector, that planning permits can be provided for new plant on the basis that they are 'carbon capture ready' [21], even if the ability to capture that carbon then does not materialise.

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[1] Carbon capture and storage (CCS) is also widely discussed. As the name suggests, this just covers routes to capture and permanently store the carbon, rather than making use of any CO_2 that is captured.

4.2.2. Green hydrogen

The second option for producing clean hydrogen at scale is through electrolysis, an electrochemical process that uses electricity to split water into hydrogen and oxygen, often referred to as power-to-gas [8]. Electrolysers are a modular technology making them suitable for small-scale on-site hydrogen production, although they can also be stacked to make much larger production facilities [9]. Unit sizes up to 10 MW are available and examples of recent plants include projects of 30-100 MW in scale [22,23].

Providing that the source of electricity is low carbon, this is a clean route to hydrogen production, for example if from renewable energy resources, the well-to-gate emissions are estimated to be close to zero [7]. There are three main electrolyser technologies in use today, with different technical and economic characteristics, plus others in development which could lead to significant performance improvements [8,9]. The EU hydrogen strategy is largely focussed on ramping up this method of production, although it also highlights that renewable hydrogen could also be produced through reformation of biogas instead of using natural gas [7][2].

Potential issues for the scaling up electrolysis include sufficient access to cheap, clean electricity. The IEA suggest that if the current global demand for hydrogen was produced via electrolysis it would require 3,600 TWh of electricity, which is more than the current annual electricity generation of the EU [8]. This production route also needs access to water, with the IEA suggesting that around 9 litres are needed to produce 1 kgH_2 (although water is also required for gas reformation, albeit 50% less).

Despite these issues, recent analysis suggests that the global pipeline for the development of electrolysis is between 8–15 GW currently [12,24]. It is suggested that around 22 100MW+ green hydrogen projects have been announced since October 2019, with two 1GW manufacturing facilities under construction and another recently announced [12]. Competition between China and the EU on green hydrogen technologies could transform the sector and rapidly drive down costs [25].

4.3. Costs and efficiency

Assuming hydrogen can be produced cleanly, understanding the extent to which can it could have a role within energy systems, will also need to take account of its production costs, and in part linked to this the efficiency by which it can be produced.

Considering costs first, the cost of producing grey hydrogen from fossil fuels will depend on the costs of those feedstocks as well as wider local circumstances linked to its production. Estimates for gas reformation put global average prices at around 1.5 $/€ per kg [7]. As highlighted above, to produce blue hydrogen CCUS has to be added to the production pathway and based on gas reformation, this can add as much as 50% to CAPEX costs, a doubling of OPEX costs, and increase total fuel costs by 10% [8]. This addition of CCUS results in cost estimated for blue hydrogen of around 2-3 $/€ per kg, whilst for green hydrogen through electrolysis costs are higher still, ranging from 2.5-5.5 $/€ per kg [7,26] - Figure 3.

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[2] There are a range of issues around the sustainability of bio-energy globally, including land use change, availability, and emissions, which means it cannot just be assumed to be low carbon [27,91,92].

Whilst forecasting future costs is far from accurate, Figure 3 shows a range of projected costs for blue and green hydrogen through to 2030 and 2050 from Bloomberg New Energy Finance. Notable in their forecasts, the cost of blue hydrogen remains almost static, whilst the costs of green hydrogen are expected to significantly reduce. This upbeat prediction matches wider analysis, including from the EU, which looking at cost estimates from a range of international energy agencies, suggests that electrolyser costs have already reduced by 60% over the last 10 years with an expectation that they will halve again by 2030 [7]. Operating costs are also expected to decline for electrolysis, if using electricity from renewable resources because of the ongoing global reductions in the cost of power from wind and solar generation [26].

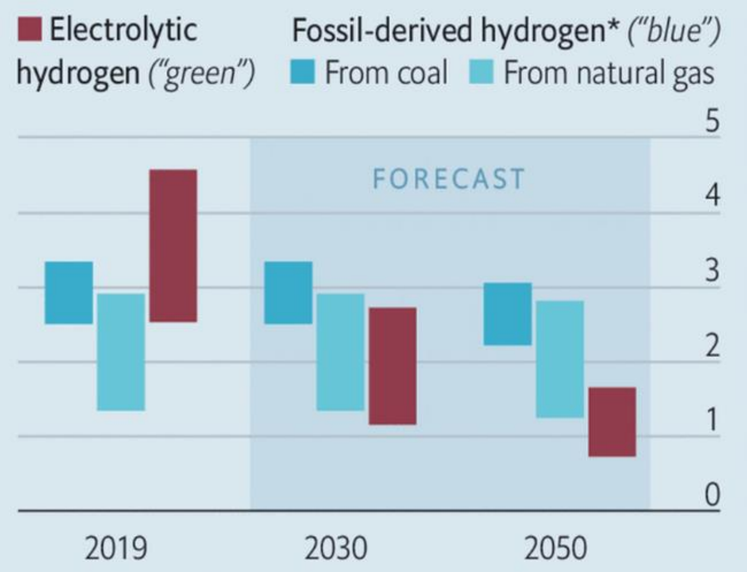
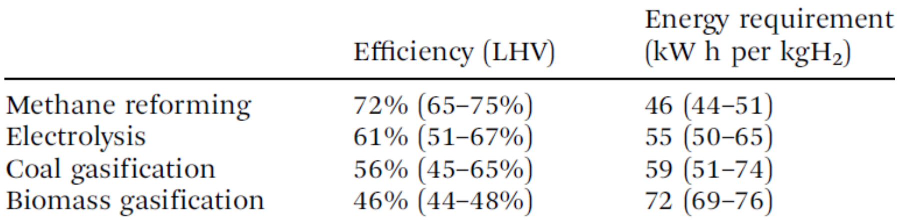


Figure 3: Estimated costs of global hydrogen production $ per kg, 2019 prices (Source: BloombergNEF in Economist (2020) [26]**)**

How the economics of low carbon hydrogen production develop in coming decades will be influenced by a range of factors. Currently most applications for low carbon hydrogen are not cost-competitive without government support [8] and many of the models on future costs assume significant subsidies will be made available, for example BNEF analysis assumes that as much as $150bn will be needed over the next 10 years [26]. Price differentiation across different end-use technologies and fuels will also influence deployment rates. Increases in gas prices from global market dynamics or through changes in taxation to reflect their carbon impact, which are being called for [27] and considered by the EU for example [6], will push up costs for blue hydrogen without additional policy adjustments. Some analysists suggest that forecasted increases in natural gas prices will lead to significant costs rises for blue hydrogen in most countries, perhaps by as much as 59% by 2040 [12]. Equally, falling costs for electricity from renewables will make green hydrogen more competitive, but the lower cost for this electricity will also make the use of the electricity in other end-use sectors more financially attractive, reducing the potential availability for its use in hydrogen production.

Producing cost-competitive low carbon hydrogen is recognised as one of the greatest barriers to developing its role within energy systems [18]. A wide range of technical and economic factors will impact on the cost of hydrogen production which, as well as some of the considerations above, includes the conversion efficiency of different production routes [8]. A key issue is, hydrogen requires energy to produce it, and because of the laws of thermodynamics, the energy input needed to be produce it will always be greater than the energy output it can provide [10]. If you consider this inbuilt efficiency it has led some to question why not simply power the end-use with electricity, rather than using hydrogen as an intermediary [26,27]. Figure 4 gives an indication of the efficiency of different production methods and their energy requirement. Assuming that end-use efficiencies are similar, it is clear that hydrogen production will always face an energy penalty relative to the direct use of fossils fuels [9].



	Efficiency (LHV)	Energy requirement (kW h per kgH_2)
Methane reforming	72% (65–75%)	46 (44–51)
Electrolysis	61% (51–67%)	55 (50–65)
Coal gasification	56% (45–65%)	59 (51–74)
Biomass gasification	46% (44–48%)	72 (69–76)

Figure 4: Efficiency and energy consumption of hydrogen production pathways (Source: Staffan et al (2019) [18]**)**

4.4. Storage, transmission and distribution

Sitting between the production and end use of hydrogen are considerations for how it can be stored and moved. Currently, most hydrogen is stored and delivered as a compressed gas or in liquid form and globally around 85% of hydrogen is produced and consumed on-site, with the remaining 15% transported in trucks or pipelines [8]. Some of the options for storing and moving hydrogen are set out within Figure 5.

Note: LOHC = liquid organic hydrogen carrier.

Figure 5: storage, transmission and distribution of hydrogen (Source: IEA (2019) [8: p68]**)**

For storage, a range of options are available including in natural gas or in other forms, such as hydrogen-based fuels such as synthetic methane, synthetic liquid fuels, or ammonia. The IEA [8] suggest that most appropriate form of storage will be depend on a range of factors such as: the volume to be stored; how long it needs to be stored for; the required speed of discharge; and the geographic availability of different options. Their view is that geological storage, such as salt cavern or depleted fossil fuel reservoirs, will be the best option for large-scale and long-term storage, while storage tanks will be more appropriate for short-term and small-scale storage. Importantly in the IEA's view, the successful development and operation of intercontinental hydrogen value chains will depend on the availability of adequate storage capacity and functionality.

In respect to transmission and distribution the IEA highlight [8] that as hydrogen has a low energy density by volume, that in comparison to other fuels, larger volumes will be needed to meet identical energy demands. To overcome this, the IEA suggest that hydrogen can be compressed, liquified or combined with larger molecules that are more readily transported. As well as moving it via trucks and shipping, other options include new dedicated larger or faster flowing pipelines or blending it into methane within existing gas networks. It is suggested that pipelines will probably be most cost-effective for local hydrogen distribution if there is sufficient localised demand; whereas for longer distances over 1500km shipping may be a better option. As with storage, the IEA suggest that the best and most cost-effective solution, will depend upon a range of factors, such as geography, distance, scale, and the end-use market of the hydrogen.

Whilst the ability for hydrogen to be stored and transported between production and end-use offers a range of benefits, it also creates additional challenges for cost competitiveness. All these supply chain aspects bring additional financial costs and come with an efficiency cost, as there will be losses during the various conversion and reconversion processes highlighted in the above figure. The IEA suggest, that unless hydrogen is used near to the point of production, it has to be stored and/or transported to the point of end use and these processes add to costs, with a suggestion that costs can be as much as three times higher than the cost of it production, if the hydrogen has to be moved a long distance [8].

4.5. Market development and policy support

For hydrogen to play a central role within energy systems, its whole supply chain has to scale up and begin to establish itself in markets that other fuels and technologies currently dominate [8]. This is not only about the emergence of clean production, but also the wider transmission, distribution, storage, and end-use infrastructure, that connects supply to demand. A central challenge is the need for both supply and demand to be created simultaneously; there is no point production ramping up if there is no demand to use it, and there is no point developing an end-use if there is no hydrogen supply available [28]. This need to stimulate supply and demand at national and international levels, is a central theme in the IEA's recent advice to the G20 and it is clear that in addition to government policy and support, it will require co-ordinated investment by many different market participants across the whole supply chain [8]. This will also be necessary to help overcome a number of key barriers for the use of hydrogen within energy systems relating to: costs, policy and technology uncertainties; ongoing R&D needs; clean product routes; supply chain complexity; standards and regulations; safety; infrastructure needs; and end-user and public acceptance [7–9,27]. In their advice to the G20, the IEA put forward seven key recommendations to help address these issues, including: establishing a role for hydrogen in long-term energy strategies; stimulating commercial demand for clean hydrogen; addressing the investment risks of first-movers; supporting R&D to bring down costs; eliminating unnecessary regulatory barriers and harmonising standards; engaging internationally and tracking progress; focussing on key opportunities to further increase momentum over the next decade.

Looking at the international picture, the IEA [8] provided a range of examples of recent regional and national level government announcements, suggesting that by mid-2019 there were around 50 targets, mandates, and policy incentives in place globally to support the development of hydrogen. They also highlighted the creation of the Hydrogen Council in 2017, comprising private sector actors who are working to implement projects and develop markets [7,8,29].

From a regional perspective, the European Green Deal highlighted hydrogen as one of the priority areas [5], and the subsequent hydrogen roadmap recognised the need to create a virtuous circle across production, infrastructure for supply, end-use demand, and the creation of markets [7]. This included an announcement of a new European Clean Hydrogen Alliance, made up of public authorities, industry and civil society to develop an investment agenda and a pipeline of hydrogen projects [7]. The EU envisions 25% of energy coming from hydrogen by 2050 [28], with a priority on the development of green hydrogen, although using blue hydrogen in the short to medium term. To help promote the development of hydrogen, the roadmap considers how to stimulate the creation of the supply chain and boost demand for clean hydrogen by creating supportive frameworks, well-functioning markets, clear rules, and dedicated infrastructure and logistical networks. They also highlight the importance of promoting research and innovation in clean hydrogen technologies. The roadmap sets out a strategy for hydrogen based on three phases:

- To 2024 the aim is to support the installation of at least 6GW of green hydrogen electrolysers to produce up to 1 million tonnes of hydrogen.
- From 2025 to 2030 the focus is on hydrogen becoming an intrinsic part of an integrated energy system, with at least 40GW of green hydrogen from electrolysers and a target to produce 10 million tonnes of hydrogen in the EU.
- From 2030 onwards, the anticipation is that hydrogen will be deployed at scale across all hard to decarbonise sectors.

Echoing the view of the IEA, the EU approach recognises that all actors, public and private, at national and regional levels, within Member States and in countries outside of the EU, will have to work together, across the entire value chain, in order for hydrogen to develop a meaningful role within Europe. Whist the EU roadmap makes a positive case for the future of hydrogen, it also highlights there are lots of unresolved issues that will need to addressed, including around infrastructure, transport and a functioning market [30].

National policies will also play a key role by helping to create clear visions, supportive frameworks, and industry confidence [8]. Some countries have already produced national hydrogen plans, such as Germany, The Netherlands, Portugal, Spain, Norway and Japan [8,12,31], with some linking these to specific industrial and economy wide strategies, such as Germany's recent €9bn investment plan to adopt hydrogen and make the country a leader in the field of hydrogen technologies; and France's play to invest €7bn by 2030, including 2 billion in 2021/2 as part of its Covid-19 recovery plans [32]. Other countries do not have a coherent strategy for hydrogen [28], although many face increasing calls for a clear strategy to be developed [31,33].

4.6. Future demand projections

There are a range of projections from different organisations about what the level of demand might be for hydrogen across different end-use sectors. An early assessment was produced by the global industry-led Hydrogen Council who worked with McKinsey to develop a hydrogen roadmap to 2050 suggesting that by then, hydrogen could provide 18% of the world's final energy demand [34]. They estimated this would need around 545 MtH_2/yr of hydrogen by 2050, with around: 28% used for transportation; 21% used by industry; 14% use for heat and power in buildings; 12% used for power generation; and remainder used for feedstocks.

A more recent assessment at a European level was produced in 2019 by the Fuel Cells and Hydrogen Joint Undertaking, an EU based public private partnership [35]. Again, working with McKinsey and adapting the Hydrogen Council roadmap above, this work considered a business as usual scenario and an ambitious scenario (based on meeting a 2-degree Celsius pathway). This assessment suggested that around 24% of final energy demand in Europe could come from hydrogen by 2050, which would require around 57 MtH_2/yr [3] by 2050 (2,251 TWh) and 17 MtH_2/yr by 2030. Again, an assessment of the amount that different end sectors might need was provided, with transport (30%), feedstocks (29%), and heat and power for buildings (26%) having the largest demands – Figure 6.

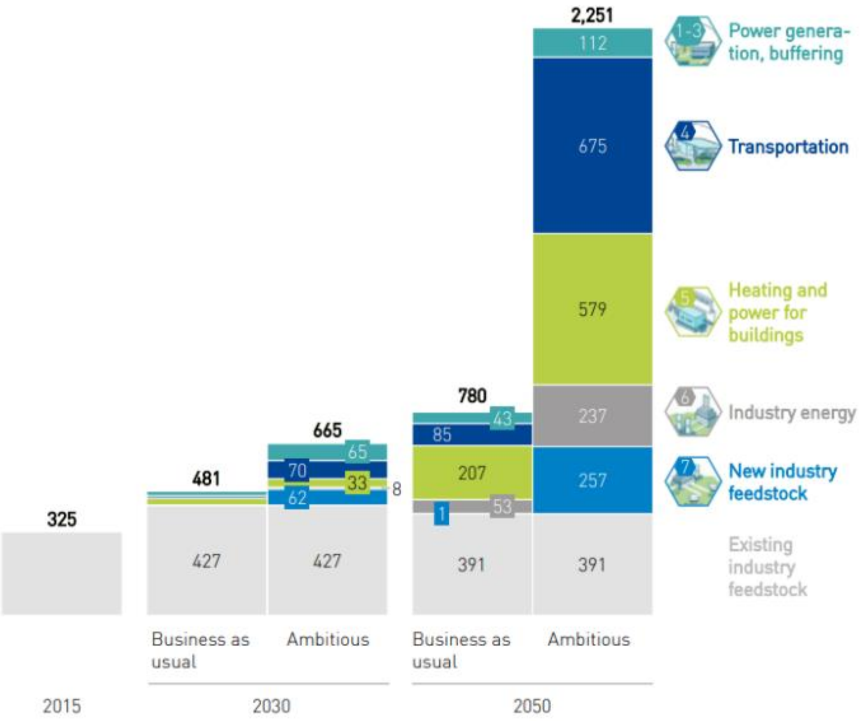


Figure 6: Scenarios for hydrogen use within Europe (Source: Fuel Cells and Hydrogen JU (2019) [35: p8]

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[3] 1 Mt/H_2 is equivalent to around 39 TWh

There are also country specific scenarios and modelling, and assessments below the national level. In the UK, the independent national climate advisor (Committee on Climate Change (CCC)), review of hydrogen in 2018 [9] considered three separate illustrative scenarios[4]:

- a full hydrogen scenario where gas networks are repurposed to supply hydrogen relatively quickly.
- a hybrid hydrogen scenario which sees gas networks being repurposed, but at a later date.
- and niche hydrogen where gas networks are not switched to hydrogen, with its use mainly in areas where it will bring the most value.

The potential level of total demand across these scenarios, for different sectors, is shown in Figure 7, it ranges from around 18 MtH_2/yr (700 TWh) by 2050 in the full hydrogen scenario to around 2 MtH_2/yr in the niche scenario. For context, the CCC suggest that current hydrogen production in the UK is around 0.7 Mt [9].

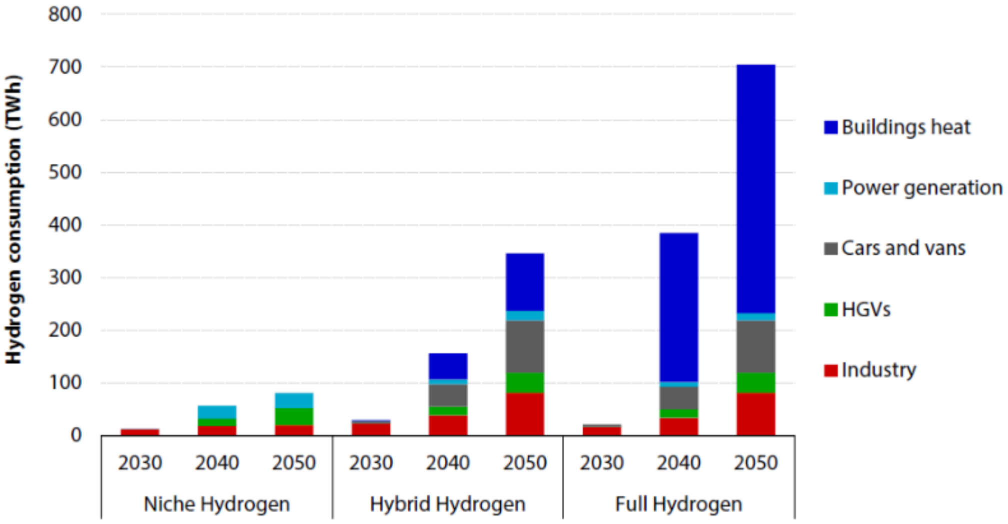

Figure 7: CCC hydrogen scenarios 2030 to 2050 (Source CCC (2018) [9: p97]

There are then, a range of different policy assessments and scenarios for scaling up the use of hydrogen with economies at the global, regional, and national level. The next section specifically considers what roles hydrogen could play within energy systems.

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[4] These scenarios are based around a key decision of whether to repurpose gas networks to deliver hydrogen and the analysis also assumes that demand is provided through hydrogen produced domestically, rather than relying on imports.

5. Hydrogen and Energy System Decarbonisation

It is clear in the discussions above that there are a wide range of potential benefits, as well as several challenges, facing the widespread development and deployment of clean hydrogen. However, as the IEA and others highlight, the renewed global interest in the use of hydrogen reflects some of its basic attributes, such as: it is light; storable; reactive; has a high energy content per unit of mass (although not volume); can be produced at an industrial scale using a range of technologies, feedstocks and energy sources; is clean at the point of end use [8,11,18,26]. This gives hydrogen considerable versatility across its supply chain and opens up a range of opportunities for is use beyond current industrial applications, including within energy systems.

The IEA [8] highlight that hydrogen can support some of the key challenges facing the transformation of energy systems, including its ability to: reduce GHG emissions and therefore contribute to efforts to tackle climate change (if produced cleanly); reduce air pollution; and support energy security. They suggest that hydrogen's potential contribution to a resilient, sustainable energy future broadly fall under two areas. Firstly, existing applications using hydrogen can be made low carbon by moving to cleaner production methods. Secondly, it can be used in new applications as an alternative to current fuels and inputs, or as a complement to the greater use of electricity in these applications. This can include hydrogen in its pure form, but also through conversion to hydrogen-based synthetic fuels, ammonia, and methanol.

5.1. System wide benefits

The use of hydrogen within energy systems could bring several wider system benefits. Key amongst these are the ways that it could provide flexibility and sector-coupling within energy systems [36]. This relates to its ability to be stored and transported to where (and when) it is needed, which opens up new possibilities to help keep energy supply and demand in balance, including inter-seasonally [28], which is a key issue for some sectors, such as heating.

The potential to produce and store hydrogen could also be an enabler for greater renewable energy penetration, particularly from intermittent resources like wind and solar. At times when these renewables are producing more power than the level of demand, in the absence of storage, they would normally be constrained off the system. This excess renewable power could be used to produce hydrogen (power-to-gas), which would both avoid constraints (and the costs associated with this), and potentially enable more renewable electricity projects to be developed. That stored hydrogen could then be converted back to electricity (gas-to-power) at times of high demand [37], or be used across a range of different end-uses and sectors. Although there will be efficiency losses in all these conversions, this potential to enable a greater use of renewables could play an important role in the long-term decarbonisation of energy systems. There are already a number of large-scale experiments and commercial projects in Europe and elsewhere exploring the potential for a 'renewables plus hydrogen' energy future [38]. However, the idea that there might be lots of surplus renewable electricity to support hydrogen production in this way has also be questioned by some [9]. Power-to-gas projects could also be an enabler of production in countries that have good renewable resources, but low energy demand – creating new economic opportunities in a global energy system [39], albeit, as discussed above, if using electrolysers these areas would also need access to a plentiful supply of water.

Given these system wide benefits, alongside the variety of roles that hydrogen might play, it is understandable why there is so much interest and momentum around its potential use for helping to develop a whole-systems approach to energy system decarbonisation [40–42]. Figure 8 brings together an overview of the potential hydrogen production and usage pathways within energy systems, with these possible end uses explored in more detail below.

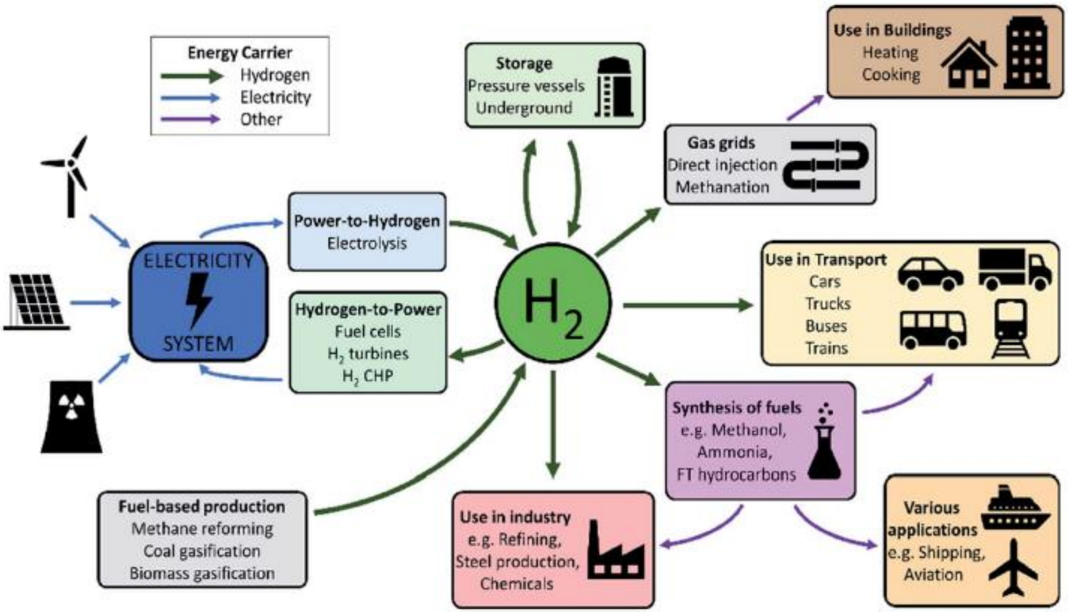

Figure 8 – Production and usage pathways for hydrogen (Source: Quarton et al (2020) [21:81]

5.2. Sector and end-use perspectives

Whilst the opportunities are broad and perhaps because they are, there are many differing perspectives about where hydrogen could or should play a role in decarbonising energy systems. This varies between organisations, regions, and individual countries, and within much of the modelling and scenarios used to underpin the narratives for hydrogen development.

Recent academic studies that have reviewed the literature on the potential roles of hydrogen show there is a general consensus that it could play a role across multiple sectors, including heat, power, transport, and industry [36]. However, a recent review looking at integrated energy system models, which shape scenarios that help to inform policy decisions, found that there is often uncertainty about the role of hydrogen because it is difficult to represent hydrogen technologies and systems within the models [43]. In another review, it was also highlighted that within many of the models and scenarios that consider hydrogen, not only is there considerable variation about its potential role, but there is a tendency to not provide much detail on the assumptions that have been taken for hydrogen [36]. This makes clear and definitive statements about the role that hydrogen could play within energy systems difficult, but subject to this caveat, there is value in understanding the views that exist within wider energy and policy circles about the possible roles for hydrogen.

Starting from a global perspective, the IEA's report to the G20 in 2019 set out a wide range of applications for hydrogen [8]. They highlight that hydrogen could play a key role in tackling some critical energy challenges where it is proving hard to reduce emissions, like long-haul transport, chemical, and iron and steel production. However, they also make the case that it can be used much more widely and that it should be adopted in sectors such as transport, building and power generation. The IEA suggest that the long-term potential of hydrogen really depends on it moving beyond its existing industrial uses into these wider sectors, with some of the opportunities for its use within other sectors including:

- As a clean transport fuel – such as pure hydrogen for use in fuel cell electric vehicles or as a synthetic fuel for wider applications. Possible end uses could include light-duty vehicles, heavy-duty vehicles, the maritime sector, rail, and aviation.
- As a fuel of heating buildings – including blending hydrogen into natural gas or the use of 100% hydrogen in boilers and fuel cells, for individual buildings or within heat networks.
- For use in power generation and electricity storage – including the possibility for co-firing within conventional plant or using it within dedicated hydrogen gas turbines. In addition, they highlighted that stored hydrogen could be used to help balance electricity demand on short to long timescales, enabled through power-to-gas and gas-to-power.

The IEA report also provides a useful snapshot of national level policies to support the development of hydrogen (as of May 2019), giving a crude indication of where some of the interest currently sits in respect to end-use markets – Figure 9.

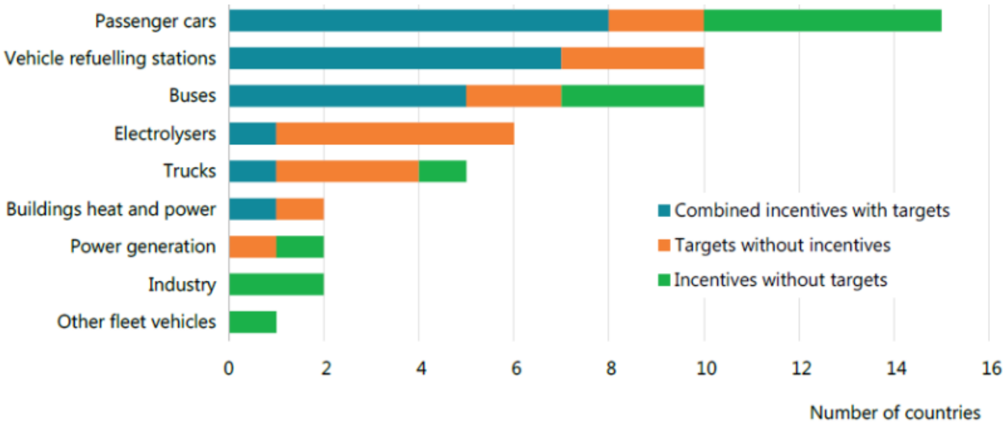

Figure 9: policies directly supporting hydrogen deployment by target application (Source: IEA (2019) [8: p20]

Taking a more regional perspective, the EU's recent hydrogen roadmap [7] also set out a range of possible uses for hydrogen across different applications and sectors. These potential end uses reflect the phases of development the EU see for hydrogen (see section 4.5 above). In the first phase, the priority is seen as decarbonising hydrogen production in existing industrial sectors. As hydrogen becomes more cost-competitive, the expectation is it will be used in new applications such as steelmaking, trucks, rail and some maritime and other transport modes. Beyond 2030, the hope is that hydrogen and hydrogen-derived synthetic fuels will be used across a wide range of sectors, like aviation, shipping and hard-to-decarbonise industrial and commercial buildings. The overall emphasis in the EU approach is largely based on hard-to-decarbonise sectors like steel and chemicals, and forms of transport where electrification is not currently feasible [44].

The EU roadmap also anticipates that local hydrogen clusters could emerge (hydrogen valleys) that will link local production using renewable resources, with local demand, enabling dedicated hydrogen infrastructure to emerge that will open up a wider range of potential end uses across different sectors, such as: industrial and transport applications, electricity balancing, and heat provision in buildings [7]. These local hydrogen hotspots could later be joined to start to build a the backbone of a European wide hydrogen infrastructure [25].

At national levels, approaches can become more divergent, reflecting local circumstances in terms of the energy mix and infrastructures, government policy, industrial strategies, as well as the incumbent actors in any country. As highlighted above, many countries already have supportive policies in place for various parts of the hydrogen supply chain. Taking the UK as an example, despite the lack of a national strategy around hydrogen, there are a wide range of assessments, research funding, trials and pilots, looking at the potential role of hydrogen across different end-use sectors [45–52]; as well as independent advice from the CCC [9]. In July 2020, the UK also launched the Hydrogen Advisory Council to help inform the development of hydrogen, including its possible roles in energy decarbonisation [53].

Looking at the advice from the CCC, they take a model-based approach to examine how the UK can cost-effectively hit its legal obligations to become net zero by 2050, which is mandated in law [54]. In a 2018 review on the potential role of hydrogen with a low carbon economy, the CCC, amongst other things, considered which areas of the energy system hydrogen could play a role [9]. Within the key messages of the report, the CCC conclude that hydrogen will be best used selectively where it adds most value, with a view that whilst generally less efficient than electrification, the ability to store it means it could play an important role in replacing gas and possibly oil, where electrification is either difficult, disruptive, and or expensive. Their assessment included the following sectors and end uses:

- Industry – for providing industrial heat in furnaces and kilns, as well as within areas where decarbonisation is more difficult because of their distributed nature, e.g. food and drink sector.
- Buildings – where it could help with heat decarbonisation using hydrogen boilers as part of a hybrid approach combined with electric heat-pumps, to help manage peak heating demands.
- Power – where it could be used in peak power plants, replacing natural gas.
- Transport – for areas where electrification based on batteries may struggle, such as, long journeys in light vehicles, and heavy-duty vehicles like buses, trains, lorries, and for shipping.

In their annual progress report to the UK parliament in 2020, the CCC called on the UK government to develop a strategy for low carbon hydrogen, suggesting largescale hydrogen trials should begin in the early 2020s [33]. As within the EU hydrogen roadmap, there is also considerable interest within the UK for creating regional industrial clusters or hubs where production and use are more closely linked, such as former industrial regions on the North Sea coastline [28,33].

It is clear from literature, and the various strategies and guidance at the global, regional, and national level, that hydrogen could make a contribution across a wide range of sectors and end uses and therefore play an important role in energy system decarbonisation. Where the use of hydrogen is most appropriate is more contested and it seems this often depends on a range of local factors across the hydrogen supply chain. The next section considers the role that hydrogen might play within the heat sector of energy systems.

6. Hydrogen and Heat Decarbonisation

Global efforts to decarbonise energy systems so far have largely focussed on reducing emissions in the electricity sector, with less progress being made to reduce emissions associated with heat and transport [55]. Current estimates suggest that globally, the built environment accounts for 30% of final energy use, of which 75% is for heating, and of this demand around 50% is provided by fossil fuels, with only 10% coming from modern renewables[5] [8,56]. At the EU level, it is estimated that heating and cooling represents around half of all energy use and is responsible for around one third of carbon emissions [55,57]. Primary energy supply in the EU-28, just for residential heating, is dominated by fossil fuels, predominantly natural gas and to a lesser extent coal and oil; although there is considerable diversity between Member States in terms of the fuel mix (Figure 10) [58]. This divergence at national levels means a range of factors will influence the options for decarbonising heat in any particular country. Taking the UK as an example, heating accounts for around 40% of total energy consumption and this is mainly provided by natural gas, with around 85% of households and 65% of non-domestic buildings connected to a national gas grid; overall meeting this heating demand accounts for around a fifth of the UKs GHG emissions [59,60]. Whichever country is looked at, what is clear, is that to tackle climate change and meet the commitments under the Paris Agreement the way this heat is provided will have to change and urgent action is needed [27,61]. This will require a reduction in the energy demand for heating whilst also shifting the remaining supply of heat away from fossil fuels to low carbon sources.

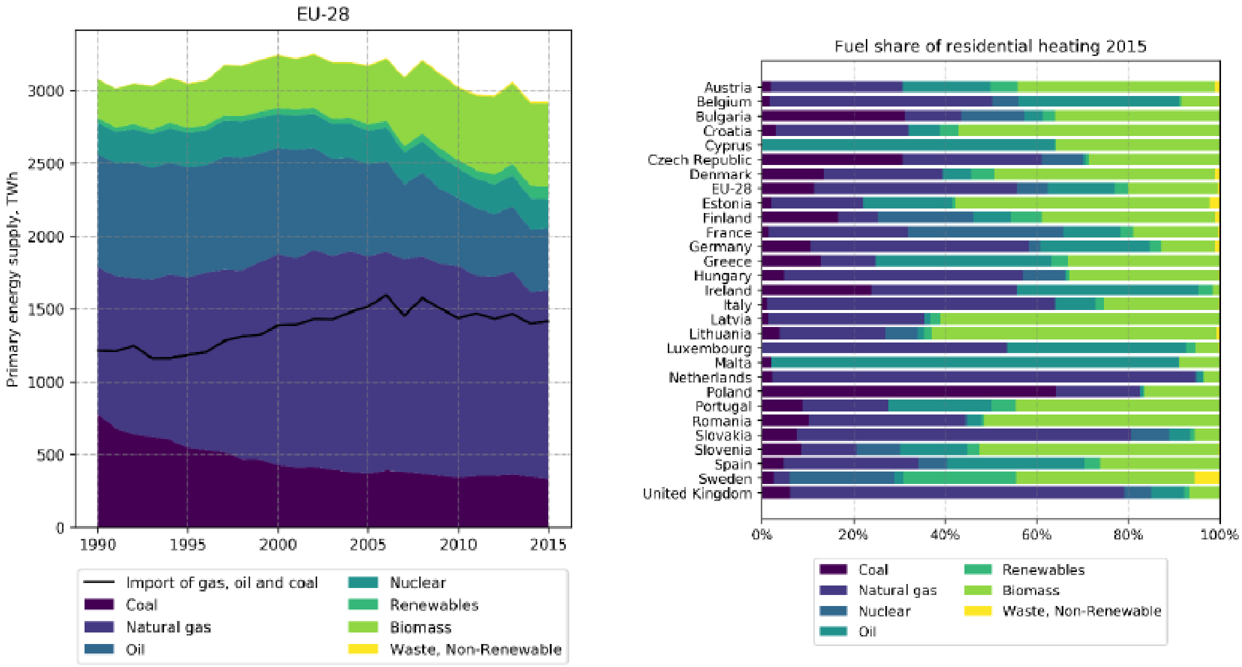

Figure 10: Primary energy supply for residential heating in the EU-28 (1990 to 2015) and fuel share by country (2015) (Source: Bertelsen & Mathiesen (2020) [58]**:8**

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[5] Modern renewables cover technologies such as hydropower, solar, wind, geothermal and modern biofuel production (including modern forms of waste-to-biomass conversion), they exclude traditional biomass [93]

6.1. Energy efficiency

Before moving on to consider heat decarbonisation in more detail, the central role of energy efficiency in heat decarbonisation needs to be acknowledged. This paper does not consider this in detail, but from a whole systems perspective, energy efficiency can be seen as the 'first fuel', which can deliver a wide range of multiple benefits [62]. The principles and benefits of 'efficiency first' are well established and widely recognised to be a key enabler of heat decarbonisation [9,16,27,63]. Energy efficiency can cover a wide range of measures, from the fabric improvements of building, through to numerous technology options, all of which are further shaped by the habits and behaviours of people that use the buildings [40].

In respect to heating, energy efficiency reduces the level of heat demand in a building, which in turn reduces costs for heat decarbonisation, both in terms of the size and therefore investment costs needed for a low carbon heating technology, but also its ongoing running costs [27,61]. Efficiency also makes buildings more comfortable and easier to control, improving the experience for the people that use or occupy the building. Importantly, from a whole-systems perspective, energy efficient buildings open up the possibility to provide flexibility, by acting as thermal stores, in terms of the fabric of the building and hot water storage if present. This can enable heat loads to be shifted over the course of a day, whilst maintaining comfort, thereby providing wider energy system flexibility and the avoidance of peak loads. This flexibility has been demonstrated in a number of countries and can range from a few hours to more than ten hours, depending on the level of insulation and outside temperatures [27,63].

6.2. The role of people

Another important consideration which is central to the challenge of heat decarbonisation, is the role of people. Heating is a fundamental aspect of human need that reaches far into people's homes, workplaces, and private lives, involving everyday habits and behaviours, which are not just linked to technologies, but far wider social, cultural, economic, and psychological phenomenon [55]. This means any transition to low carbon heating has to see people, homeowners, local communities as essential parts of the system, which is why many highlight the need to put people into the heart of the energy system [55,64]; they need to be actively involved in the co-creation of low carbon heating solutions [65].

There is emerging evidence which shows that people are predominantly interested about their heat experience, rather than the specific technology that keeps them warm, which means they may accept alternative heating technologies, as long as they provide an as good or better experience than the technology it replaces [66]. This can help inform solutions, although it is also clear that wider generalisations around people and heating are difficult, as preferences can be shaped by a wide range of factors [67]. Different consumers will also value different things, some will prioritise cost effectiveness, others will put comfort before cost, others need heat for health reasons, some won't be interested at all [66]. There is also evidence that shows many people have a lack of awareness and knowledge of low carbon heating and the benefits it can offer, and there can be a lack of incentives to encourage those that do have knowledge, to make a switch [68]. A final consideration and key issue for people, is the initial, up-front investment costs for sustainable heating installations are often high, compared to conventional technologies and therefore a wide range of actions will be needed to help raise awareness, remove barriers and create financial incentives for the transition to sustainable heating [55]. All these considerations need to be taken into account when navigating pathways towards low carbon heat and they represent one of many challenges for decarbonising heat.

6.3. Challenges for heat decarbonisation

Energy efficiency and engaged people are both critical for the transition to low carbon heating, regardless of the technology that is adopted to provide the heat [27]. Assuming efficiency first principles are followed and mechanisms are used to engage people, there are then a number of system-wide considerations for heat decarbonisation, covering technical and social components, across the supply, distribution, and the demand side [55]. This will partly reflect the historical context in any country, in terms of the infrastructure and fuels that have shaped the energy system and the provision of heat. Throughout this process, over many decades, there will have been multiple co-evolving innovations - socially, politically, institutionally and technically [69], which include all the actors along energy supply chains, and the way in which they interact with each other and the system; as well as the wider institutional and political structures that govern the system [70–72]. The combination of all these factors has led to energy systems which are mature, highly interconnected and complex, making them prone to inertia and lock-in [73,74]. This makes change difficult, including within the heating sector.

Research at the EU level by Bertelsen & Mathiesen [57] shows how the infrastructure and fuels around heat supply and demand create clear path dependency and lock-in. As the authors highlight, as well as the historical developments around fuels (Figure 10), the wider infrastructure that is built around these fuels also has a large impact. This includes large-scale collective infrastructures, such as gas grids, electricity networks, or district heating; and more loosely coupled systems that use individual boilers/stoves, based on more diverse distribution networks, such as solid or liquid fuels that are easy to transport without dedicated infrastructures, like coal, oil, and biomass. These types of infrastructures are based on very different technologies and very different supply chains which add further complexity for decarbonising heat because of economies of scale, network effects, knowledge and preferences of end users, actors and decisions makers, that will exist across their supply chains.

As well as these high-level issues around fuels and infrastructures, there are also much more granular, local considerations at the national and sub-national level for decarbonising heat. These, in part, reflect the physical properties of heat which make it hard to distributed, sell, or exchanged over long distances, which leads to heat markets (for fuels and technologies) being local and contextualised [57]. In addition, the supply and demand of heat will be influenced by building types, tenure, location, customer preferences, equipment costs, energy prices and overall convenience [8]. This means there is unlikely to be a one size fits all solution for low carbon heat, instead several different energy sources and technologies are likely to co-exist within any particular country [8,59]. This reinforces the importance of locality, as the best potential heating solution will vary depending on local circumstances. So, although national strategies and policies will be important for helping to shape the framework for action at a sub-national and local level, there is evidence to show that options and delivery methods are best decided on a more local, place by place basis [16,68].

6.4. Pathways to decarbonise heat

There is a plethora of resources that assess the possible options for decarbonising heat in residential and non-residential buildings. The options can include individual or combined approaches based on: combined heat and power (CHP); district heating and heat networks; the electrification of heating and use of heat pumps; repurposing gas networks to carry 'green' gases; as well as hybrid based systems, such as heat pumps operating in combination with a gas or hydrogen boiler [8,60,75]. Some of these individual and collective solutions are highlighted in Figure 11, along with the potential range of energy carriers and resources that could be used. When looking at international experiences of promoting the uptake of low carbon heat, to date, heat pumps and district heating have been most widely deployed [75].

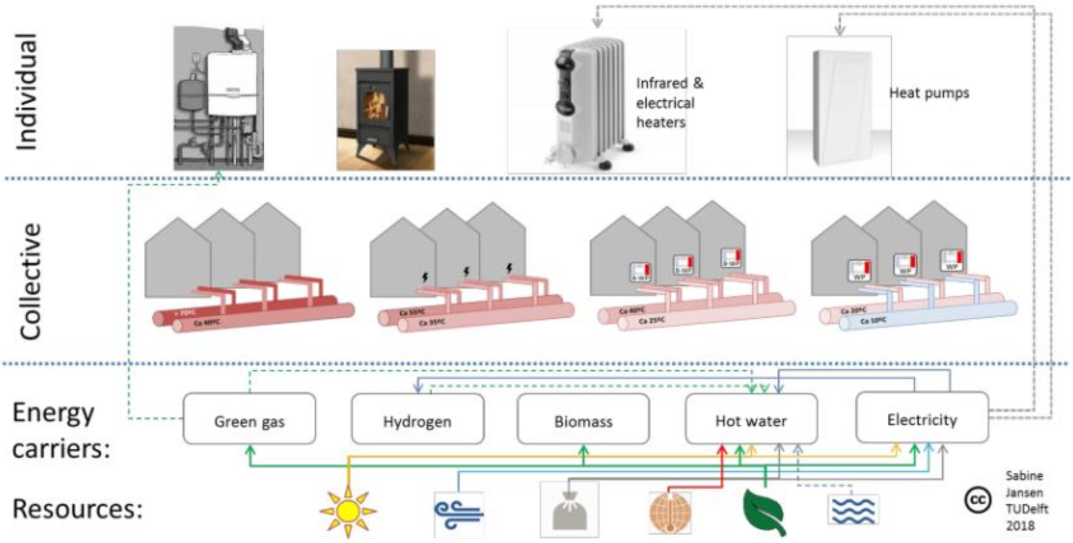


Figure 11: Alternative heating solutions for the built environment (Source: Jansen (2018) [76])

Whilst there is divergence in terms of technologies, energy carriers and resources, there is some consensus that heat densities play a central role in determining potential pathways for heat decarbonisation. In areas with a high heat density, such as built up urban areas, there are good opportunities for an approach based on district heating/heat networks; whilst for lower heat densities, such as rural areas, there are likely to be good opportunities for rolling out electric heating using heat pumps [57]. Whilst sitting between these high and low heat density areas, a range of different approaches might be more appropriate, reflecting the underlying infrastructures that are in place [60].

More broadly in terms of high-level pathways, possible solutions tend to fall under one or more of the following narratives: the electrification of heat; decarbonisation of gas; district heating, or more hybrid-based solutions. There is no silver bullet in any of these approaches and viewpoints vary depending on the type of actor asked, and as discussed above, the underlying infrastructure, technologies, markets, politics, policies, and the supply chains that are in place [77,78]. These possible high-level pathways are also not fixed, the debate changes with time as new options or insights emerge, lobbies evolve or are created, technology and fuel economics alter, supply chains improve, and new research takes place, etc [8,16,52]. This is particularly true for hydrogen that has come back into discussions on heat decarbonisation only over the last decade or so. Some of these high-level pathways are set out in more detail below.

Whilst many countries have strategies and policies in place for decarbonising heat, others continue to struggle to set a clear direction [37,52,75,78]. To help identify possible pathways, there are a growing number of resources available that can assess and evaluate possible options, such as heat mapping and tools to consider potential options at the city, district, neighbourhood and building levels [55]. These can help identify which of the possible pathways, or what combination of them, might best be suited. As discussed above, given that heat is largely a local issue, that needs to take account of local circumstances, and involve local communities, the transition to sustainable heating can also be facilitated by the development of sustainable heating strategies at the city, municipality or local authority level [55,65].

6.4.1. Electrification and heat pumps

Ground, air, and water source heat pumps widely feature as a solution to heat decarbonisation. They are central to the options for the electrification of heat and are often seen as a key solution for areas with low heat densities and/or without access to natural gas infrastructure. As electricity systems have continued to decarbonise, its use to provide heat can provide an effective and quick route to heat decarbonisation. The carbon impact of a heat pump will vary based on a range of factors, including the carbon intensity of grid electricity, but studies consistently show they have a significantly lower carbon footprint than gas-based or direct electric technologies [79,80]. This is because heat pumps are very efficient, producing several units of heat for each unit of electricity used. Ratios of heat out, to electricity in, typically fall within a range of 2 to 4 for air source heat pumps and up to 8 for ground source heat pumps [9]. Heat pumps can be scaled to the size of a room, building and large-scale heat pumps can be integrated into collective systems based on district heating networks [63]. They are already widely used in many countries, reaching high levels of market penetration in some e.g. France, Sweden, Estonia, Finland, Norway [27,81,82].

One common concern that is raised over the widespread adoption of heat pumps, is that their unmanaged deployment and use will impact electricity systems because the energy demand for heat can be 2 to 4 times larger than current electricity demands [57]. The implication of this is that additional generation capacity will be needed, which will need to be clean to help maintain a low carbon intensity for grid electricity. In addition, significant new demands for heat from electricity could create capacity issues at the distribution level, requiring costly reinforcement and network upgrades, with a particular concern around the coldest days of the year [9,16,61]. However, these impacts can be minimised, in efficient buildings, heat pumps can operate flexibly, allowing for intra-day load management, so it is possible to manage peak demands on the system to some degree, potentially through automated approaches, based on smart heat principles [27,61,63]. Heat pumps within district heating are less problematic because of the inbuilt flexibility from the storage that exists within these larger networks. Inter-seasonal flexibility is a bigger challenge for heat pumps and the widespread electrification of heat, for which there is not yet an easy, cost effective solution, particularly for individual building systems, and for this reason there is a growing interest in some countries around the use of hybrid systems (section 6.4.4). There is also an emerging body of research on the development of electrification based on smart, flexible principles and policy [27,61,63]. It is also worth noting that developments in smart thermal storage could play an important role in supporting the electrification of heat, with a range of technologies already available that that could enable the cost-effective delivery of flexible low-carbon electric heating, although more modelling and analysis is needed [63].

6.4.2. District heating/heat networks

Communal heating can be provided to multiple buildings at a range of scales, very efficiently and at low cost [16]. It is an effective solution in high heat density areas and is well suited to providing heat in mixed use areas. As a route to heat decarbonisation, the fuel source used to generate the heat will dictate how clean it is, with possible low carbon options including biomass (if sustainably sourced), geothermal, heat recovery (from industrial processes, waste incineration, data centres, subways, etc) and large-scale heat pumps [16,81]. The share of renewable energy within district heating networks varies from country to country from around 70% in Sweden to less 2% in the UK, with the IEA suggesting that the carbon intensity of district heating in the EU ranges from 150 – 300 gCO_2/kWh [78]. District heating is firmly established in many European countries, providing around 8% of total heat demand, with high levels of market penetration in Finland, Denmark, Sweden and Baltic countries [83].

New district heating schemes can make use of waste heat and other low carbon fuels from the start, but in existing district heating schemes, fossil fuels are currently widely used. For these existing projects, it is possible to change the fuel supply to exploit low carbon resources without significant impact to the wider heat network infrastructure [57]. This offers one of the easiest routes to decarbonise existing district heating networks, but there are also a number of other ways to reduce demand and increase efficiency, at the network and building level [84]. For new developments, it is clear that with each evolution of district heating, supply temperatures are reducing and efficiencies are increasing, e.g. systems in 1980 were supplying heat at around 90°C with efficiencies of 83%, but by 2020 systems are supplying heat nearer to 50°C and with efficiencies of around 91% [84]. As efficiency increases, within buildings and the networks, the possibility for using low carbon resources such as waste heat increases, the challenge therefore for existing district heating is to increase efficiencies and lower the supply temperatures [57].

6.4.3. Gas decarbonisation

The gas decarbonisation pathway is based on replacing, or mixing, low carbon gases into existing natural gas infrastructure. Much of the initial interest for this approach was based on injecting biomethane into natural gas networks, but more recently the focus has been on hydrogen [16]. As well as being able to make use of existing infrastructure, another reason these options are attractive to policy makers is they provide a non-distributive route towards heat decarbonisation, requiring very little change from consumers [9,37,52,85], although this may be short-sighted in terms of the need to active engage and seek the consent of people for energy system change [64,65]. It is not yet clear what the overall potential is for decarbonising gas in these ways [57], and it is likely to be country specific for both resources.

Biomethane is a near-pure source of methane that is largely indistinguishable from natural gas, so it can be used without changes to end-user equipment or to existing gas transmission and distribution infrastructure. The IEA suggest it is relatively expensive compared to natural gas and that globally around 2.5 million tonnes of oil equivalent (Mtoe) of biomethane are produced annually either by upgrading biogas (from biodigesters, landfill recovery or waste water treatment plants) or through the gasification of solid biomass followed by methanation [85]. The availability of biomethane is country specific, for example in the UK it is suggested that only around 5% of gas consumption could be provided from biomethane, due to the availability of the resource and its potential value for other end uses in the energy system [9]. Looking more widely at Europe, Germany has the largest biogas capacity, and it has been actively promoted in Denmark, France, Italy and the Netherlands [85]. Looking to the future, the IEA's assessment suggests based, on sustainable technical potentials and costs, biomethane supply could meet over 20% of current annual global natural gas demand, with around 16% of that coming from Europe [85].

The other option for decarbonising gas is to use hydrogen. How much this can decarbonise the gas network will depend on how clean the production process for the hydrogen is and then what percentage it is used at. As the properties of hydrogen are different from methane it can only be blended up to a certain percentage without having an impact on the current gas value chain, although with changes to gas networks and end-use equipment it is theoretically possible to use 100% hydrogen [8], either in dedicated hydrogen boilers or with fuel cells to provide CHP. The use of hydrogen for decarbonising gas and for wider roles within the heating sector is discussed in detail in the section 6.5 below, again the potential to use hydrogen in this way will be country specific, reflecting the development of local hydrogen supply chains and wider markets.

6.4.4. Hybrid solutions

Hybrid heating systems can combine a small heat pump with a gas boiler as back-up. As well as making use of gas grids, which are an existing infrastructure with largely sunk costs, the interest in hybrid approaches also reflects the opportunity they offer to overcome the inter-seasonal heat challenge. A hybrid system is sized and run in such a way that it mainly provides low carbon heat using electricity with the heat pump, but on cold winter days the gas boiler is used, so that peaks on electricity systems can be managed and the costs of reinforcing distribution networks can be avoided [81]. It is possible that one integrated system can be used, although a bivalent system that uses a separate heat pump and an existing gas boiler are more widely discussed [16,27]. Whilst this approach can necessitate having two technologies in a building, if retrofitting into a building with existing gas boiler, the additional costs are similar to fitting a fully sized air source heat pump solution [81]. There is also a possibility in the future, instead of a natural gas boiler, a hydrogen boiler is used alongside the heat pump.

Views on hybrid systems will be country specific, with those countries with significant natural gas networks likely to lead the way. Some suggest that hybrid systems may only play a bridging role in helping to decarbonise the heat sector, as whenever the heating is running in gas mode, there will be associated carbon emissions [16], although if hydrogen (or biomethane) is used in blends or at 100% then emissions could be lower, depending on how those fuels are produced [9]. Looking at the UK as an example, the potential role hybrid system might play is evolving, with the country's climate advisors in 2016 initially seeing them as having a possible role until the early 2030s [81], but more recently suggesting they could play a role out to 2050, depending on how things progress with clean hydrogen production and energy efficiency deployment [9,33]. A recent successful small scale trial in the UK, has shown that hybrid systems do mainly run in heat pump mode, successfully meeting comfort levels within a range of household types, without adverse effects on electricity networks [9].

6.4.5. Other options

Although the main high-level pathways for heat decarbonisation are set out above, there are other options, and these could easily play a role in some countries. This can include the direct use of electricity to provide heating, although this is probably only economic in well insulated buildings [16] and is less energy efficient than the use of heat pumps [63]. In countries with low heat demands and high solar irradiation, solar thermal can be a key resource, although its use can be limited by their ability to produce heat on-demand [27,63]. Whilst biomass already plays a significant role within many countries (Figure 10), there are two issues facing its large-scale use. The first is around its sustainability relating to land-use, land-use change and forestry, and the emissions that are associated with these, which make actual CO_2 emissions savings from the use of biomass unclear [16,57]. The second issue is around air quality concerns from the release of particulates and nitrogen oxides when the biomass is burnt [27,81]. Given these concerns there is a view that the further uptake of biomass for heat decarbonisation may be limited, although approaches will be very country specific. One other option, which is discussed in more detail below, is the use of fuel cells and micro-CHP.

6.5. Hydrogen and heating

As highlighted above, hydrogen could play a role in some of the pathways for decarbonising heat. Within this section, these options are explored in more detail from two different perspectives. Firstly, consideration is given to what the literature says about the roles that hydrogen could play in decarbonising heat, in respect to the options available and the potential benefits it could bring. Secondly, consideration is given to what role hydrogen should play within the heat sector. Whilst this second discussion is more speculative, it is important because it is apparent from the literature that there are many divergent views about the use of hydrogen for heat decarbonisation that make simple assessments of its suitability difficult.

The primary focus in this section is on the use of hydrogen for meeting heating demands within the built environment, rather than process heat in industry, where there is clear consensus on the potential value of hydrogen [7–9,78].

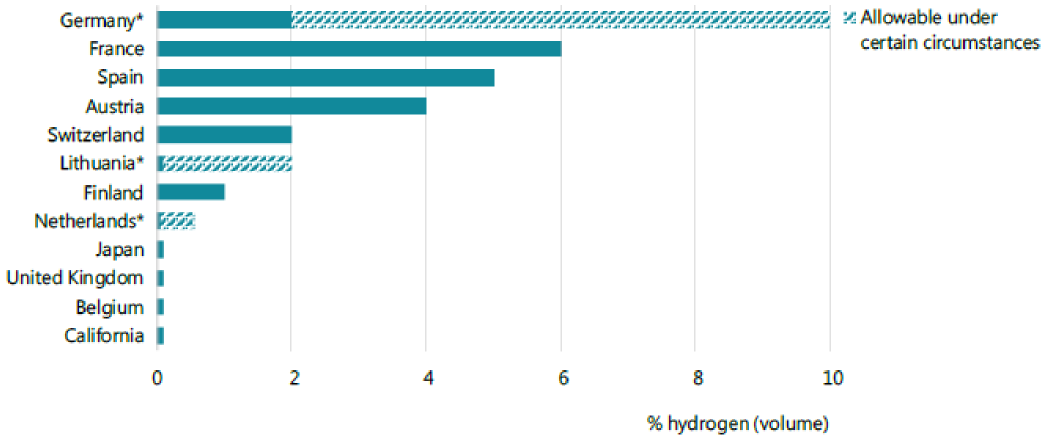
6.5.1. What role could hydrogen play in heat decarbonisation?

In the IEA's 2018 assessment [8], they highlight that currently hydrogen is hardly used to provide heat in the global buildings sector, but in their view there are two main opportunities for its future use. The first is blending hydrogen into existing natural gas networks and the second is using it to heat buildings either directly with end-use technologies within the building or indirectly via collective systems like district heating networks. Several trials are taking place around the world for both these approaches.

Blending hydrogen

Blending hydrogen into natural gas networks could help reduce emissions for heating to some degree, if the hydrogen is produced cleanly. Although, the main drivers behind this approach appear to be largely based on making use of an existing infrastructure, reducing risks and costs for using hydrogen, whilst also helping to increase demand and therefore supporting the development of new hydrogen supply chains [7–9].

The extent to which hydrogen blending can take place will depend on the tolerance of existing components along the whole natural gas value chain, with the IEA [8] suggesting that in many countries the maximum level of blending allowed is just 2%; although these limits, which are set out in national standards and regulations, do vary from country to country (Figure 12). Despite these low levels, it is reported that many appliances in Europe can run on hydrogen blends of up to 23% (by volume) without any modification [8,9,26]. There are a number of pilot projects around the world testing hydrogen blending for issues such as safety, efficiency and environmental performance and calls for further trials to take place [8,59].



* Higher limit for Germany applies if there are no CNG filling stations connected to the network; higher limit for the Netherlands applies to high-calorific gas; higher limit for Lithuania applies when pipeline pressure is greater than 16 bar pressure.

Figure 12: Current limits on hydrogen blending in natural gas networks (Source: IEA (2019) [8: p73]**)**

Direct hydrogen use

The other main, longer-term prospect for using hydrogen in the heat sector is its direct use in either hydrogen boilers or fuel cells [8]. This pathway is based on the repurposing of gas distribution networks so that they carry 100% hydrogen, an approach that will require adjustments to gas network infrastructure, retrofitting components or replacing appliances within buildings, and possibly changing pipework within buildings [9,18]. From a cost perspective it is suggested that this would be most suitable for areas with large commercial buildings, building complexes or district heating networks [8].

Considering hydrogen boilers, research in the UK suggests that the transition from natural gas to hydrogen could take up to 20 years, as appliances in every building would need to be converted or replaced, whilst also ensuring continuity of supply [18]. A possible enabler of this approach would be the installation of 'hydrogen-ready' boilers that can easily be switched from natural gas to hydrogen, with protypes already being developed and promoted by some gas boiler companies [26,59]. Whilst hydrogen boilers are expected to be comparable in costs to a gas boiler, the expectation is that energy costs will be higher because of the wider economics associated with the infrastructure and development of the hydrogen supply chain [9].

Hydrogen can also be directly used in fuel cells to co-produce electricity and heat, at high efficiencies, with the ratio between heat and power depending on the type of technology [18]. These can be used within individual buildings and be incorporated into district heating networks. Analysis in the UK suggests that fuel cells will struggle to compete economically with hydrogen boilers [9], with others suggesting that whilst it may take time for them to be cost competitive for housing, their use in commercial buildings, especially if they are combined with storage capacity, will be more economic [8,18]. One consideration with the wide spread use of fuel cells for heating is they would use greater levels of hydrogen than hydrogen boilers, which will require even greater levels of clean hydrogen production [9].

As well as the idea for repurposing gas networks, there are also emerging proposals for dedicated hydrogen pipelines, although these may also involve some repurposing of existing pipelines, on the assumption that they will become available as demand for natural gas decreases. One proposal in Germany from a group of pipeline operators suggests creating a 1,200km hydrogen grid by 2030, at a cost of €660m [26]. Another example from a group of 11 European gas infrastructure companies from nine different countries is based on creating a dedicated hydrogen pipeline of around 23,000 km to connect future hydrogen supply and demand centres across Europe, such as industrial clusters, CCS locations and large scale renewable electricity production sites, at an estimated cost of €27 to €64 billion [86].

6.5.2. What role should hydrogen play in the heat sector?

The range of reasons put forward for considering hydrogen within heat decarbonisation include: the ability to carry on using existing infrastructure; the opportunities to use it across industry, businesses and homes; the potential to produce it in large volumes; a view that it compares well to other low carbon heat options; a view that consumers would not notice any difference in the way they get their heat; as a way to build hydrogen supply chains; and as a route to start decarbonising heating quickly and cost effectively [8,9,37,87]. However, whilst the global, regional and national analysis used in this paper all highlight that hydrogen could play a role in helping to decarbonise heating, there is not a strong narrative or clear consensus over the role that hydrogen should play.

For approaches based on blending hydrogen into natural gas networks, there is agreement that this could help support the development of the hydrogen supply chain, without the need for investment costs or risks for developing new infrastructure for hydrogen distribution [7–9]. If the hydrogen used for blending comes from low carbon sources, then this approach could provide a near-term route to reduce emissions in the built environment, particularly in areas where electrification is difficult [8]. The EU is cautious on the value of blending, suggesting that it is not an efficient use of hydrogen and it diminishes its value [7]. Given that it changes the quality of gas within networks, the EU roadmap also highlights that there is a risk it could fragment internal cross-border gas markets, if different countries adopt different blending standards. Whilst in the UK, the CCC suggests that blending could be of limited potential, perhaps helping to overcome the current inaction around developing a role for hydrogen within the energy system [9]. Although, they also suggest, in respect to achieving targets, that electrification using hybrid heat pumps could reach higher penetration levels if the gas used for peak heating loads is decarbonised with hydrogen or biomethane.

When looking at emissions reductions, it is apparent that hydrogen blending will not achieve any deep decarbonisation of gas networks or the heating sector [18]. This is because, even at higher levels of blending, up to 20% (by volume), it will only reduce the carbon footprint of natural gas by 4-6% if using blue hydrogen from gas reforming, with potentially slightly greater savings if the hydrogen comes from electrolysis using low carbon electricity [9].

A further policy challenge for blending is the potential impact any mandates or incentives to support blending will have on costs and therefore fuel switching. The IEA [8] give an example of using a 3% by volume hydrogen blend within current global natural gas demand, which would require around 12 MtH_2/yr of clean hydrogen. At this level of demand, the IEA estimate that the scaling up in gas use within the hydrogen supply chain could add up to 15% to natural gas supply costs, which could result in customers moving away from gas for heating into electricity; which is already a risk as the price differential between gas and electricity is already close in many markets. Costs could be further exacerbated through blending as a greater volume of gas will need to be purchased to meet a given energy demand. This is because the energy density of hydrogen is around a third that of methane, so hydrogen blending reduces the energy content of the delivered gas, so more gas is needed e.g. the IEA, citing (Haeseldonckx and D'haeseleer, 2007), suggest a 3% hydrogen blend reduced the energy content of the gas in that pipeline by around 2% [8].

For the more direct applications of hydrogen in boilers or fuel cells, the IEA highlight its potential will depend on infrastructure updates, routes to address safety concerns from consumers, and critically the upfront capital cost for the technologies and their ongoing running costs [8]. At the EU level, the 2020 roadmap only mentions heating twice and does not mention 100% hydrogen for heat in buildings, although it could be implied as part of the thinking around 'hydrogen valleys' where local production and a variety of demand side applications might open up [7]. Whilst in the UK, it is suggested that 100% hydrogen pathway would create a very large demand, requiring a considerable ramping up of green hydrogen, but also inevitably requiring more blue hydrogen which will create its own challenges because of the availability of CCS and a requirement to increase gas imports [9]. The CCC also highlight that it is not clear if a strategy to switch to 100% hydrogen would be possible at the pace need to meet the UK's 2050 climate targets.

Research for the CCC in the UK, suggests that for those countries with extensive gas grids, it is not necessarily more cost effective to try and decarbonise heating through their continued use. Even when taking account of the sunk costs associated with these networks, switching them to hydrogen will have similar costs to other heat decarbonisation pathways, including those which result in a reduced role or the decommissioning of the gas grid [9]. Also related to costs for heat decarbonisation, another UK study suggests that top-down large-scale solutions like 100% hydrogen (or an all-electric approach) are two to three and half times more expensive than bottom-up solutions that choose the best options on a place by place basis [68].

There are growing number of reports that consider the role of hydrogen in heating, beyond the main ones cited within this working paper. Recent analysis in Germany concluded that hydrogen is the worst energy carrier for building heating in terms of its efficiency and associated infrastructure requirements [39]. Whilst others make the case for electrification and heat pumps as the most sensible approach, as it is ready to go and highly efficient, and as such hydrogen should only have a niche role [27,37]. What does seem to be apparent is that interest in using hydrogen to decarbonise heating in the built environment has only really emerged in the last five or so years and that much of this has been has been driven by the gas industry, who clearly have an interest in maintaining a role for gas into the future [37]. This particularly appears to include incumbent companies, associated with gas networks and appliance manufacturing, who have been shown to engage in lobbying activity, and within innovation, research and development projects to promote and support a pathway which maintains the gas system and converts it to hydrogen [51,52]. Although clearly, it is also likely that those companies with an interest in heat pumps and electricity systems will actively be lobbying and promoting those pathways over hydrogen.

There are perhaps two key questions for assessing what role hydrogen should play in heating. The first is how much clean hydrogen can be produced and at what cost and then, where within the energy system should that hydrogen should be best put to use, the answers to which are currently not known [59,88]. Looking at some of the scenarios for using hydrogen, just in respect to heat for buildings, the assessment in Europe (Section 4.6) indicated that around 12Mt/H_2/yr would be need by 2050 [35], whilst in the UK, the mid scenario suggested around 3 Mt/H_2/yr would be needed [9]. In both of these scenarios, blue hydrogen produced by gas reforming with CCS is needed, which can only reduce emissions relative to unabated natural gas use by around 60-85%[6] [9]. As such, these approaches will only help to some degree to reduce the carbon emissions from the heating sector, until such a time that green hydrogen can scale up cost effectively.

These insights come full circle back to the challenges of decarbonising heat discussed at the start of this section and the reality that there is no one silver bullet, with the optimal solution varying between countries and within countries, often reflecting locality specific issues, including the views of people and the costs for different options. It points to a need for clear policies around heat at national levels, which can shape and help drive change at more local levels. Heat decarbonisation is a transformative challenge that requires clear signals and well-coordinated approaches across building, policies, people, supply chains, and technologies [9,27,55], and this should include any possible role for hydrogen.

All the issues discussed within this section also highlight this need for whole-system thinking around energy system decarbonisation. In the case of hydrogen, its use within the heat sector will have knock on impacts for other sectors, given the need for energy and feedstocks to produce it, but also because hydrogen could be used in many different end-use sectors and applications. The same is true for a strategy based on the electrification of heat, which will have impacts on the power sector in terms of generation, supply, and network management, as well as other sectors where it could play a major role, such as transport. These sorts of issues can only be addressed at a whole-system level, but it is widely recognised that energy decarbonisation is often looked at in a very siloed way, with different bodies working to different objectives in different areas of the energy system [89,90]. This largely comes down to poor governance[7], and it can result in lack of direction-setting; a dominance from established industry players; confused signals for market participants; and a lack of clear responsibilities for energy system decarbonisation and integration [89]. The recent EU strategy to consider system integration is a welcome departure from these problems [6], and is clear that many countries could benefit from independent organisations that can help oversee direction-setting processes and co-ordinate actors to enable transformations to take place [89]. This seems particularly true for any efforts to try and scale up a new energy carrier like hydrogen, given the implications it will have across energy systems.

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[6] This is due to uncaptured CO_2 in the CCS process and upstream emissions from the gas supply chain.

[7] Governance can be described as the policies, institutions, rules and incentives related to the energy system, and the underlying decision-making process which establishes those rules and incentives [89].

7. Conclusions

Global interest in the use of hydrogen to decarbonise energy systems has never been stronger, with many industry actors, companies, researchers, and governments seeing it potentially playing a key role in helping to meet targets for climate change. As an energy carrier, and given its ability to be stored, transported, and combined with other elements, hydrogen could provide a wide range of opportunities and benefits for decarbonising many different areas of energy systems.

However, it is apparent, within the literature, that there are conflicting messages on where it could and should be used within energy systems. Assumptions differ, and views vary, largely depending on the type of actor and the underlying fuels and infrastructures that are in place within different countries. Based on the evidence reviewed for this paper, the case for hydrogen playing a significant role in decarbonising heating is currently not convincing. This conclusion specifically relates to the ability to produce it cleanly and the assessments of where it will add most value for decarbonising the energy sector.

7.1. Clean hydrogen production

A key challenge for the future of hydrogen in any low carbon world, is around the ability to scale up its production cleanly and cost effectively. Current global hydrogen production is around 70 MtH_2/yr and this is mainly from unabated fossil fuels, creating around 10-19 tCO_2/tH_2. Scenarios for future hydrogen demand by 2050, suggest that globally this may rise to 545 MtH_2/yr, whilst within Europe demand could be around 57 MtH_2/yr. The challenge is, therefore, to ensure that any new demand is met through low-carbon routes. Ideally, this should come from green hydrogen production which has estimated well-to-wheel emissions close to zero, but electrolysis technologies need to scale up and reduce in cost to enable this to happen. The alternative is blue hydrogen, which relies on fossil fuels but with the addition of CCUS has estimated well-to-wheel emissions of around 1-4 $tCO_2/tH_{2,}$ depending on the production process and the effectiveness of CO_2 capture. Whilst production for these alternatives to grey hydrogen are ramping up globally, levels are still very low, so it is not yet possible to say with confidence how much low carbon hydrogen will become available, or by when.

In all the scenarios for scaling up hydrogen over the coming decades, blue hydrogen is expected to be required, to help enable supply and demand to build up, until such a time that electrolysis costs significantly fall. There are inherent risks associated with this relating to lock-in and path-dependency, for both emissions and energy system change. In respect to emissions, blue hydrogen is only low-carbon, and once built it could remain on the system for decades locking-in future global GHG emissions, unless policy or rising natural gas prices make it uneconomic. Also, given the problems and costs associated with CCUS it is not impossible that if global demand for hydrogen starts to increase and sufficient blue hydrogen is not available, then either, a global hydrogen pathway will falter, or worse, grey hydrogen production could increase to fill the gap. As blue hydrogen also relies on fossil fuels and the infrastructures built around them, from a system change perspective, its development will continue to support and maintain a role for fossil fuels and their supply chains, potentially slowing down the pace of energy system change and hindering alternative low carbon pathways.

7.2. Hydrogen, energy systems, and heat

If resilient low-carbon hydrogen supply chains do develop at scale, the next consideration is where should that hydrogen best be deployed to help decarbonise energy systems. Whilst hydrogen could be used in many sectors, there is some consensus that its optimal use will be within those areas where it is proving hardest to reduce emissions, such as iron and steel production, the chemicals sector, and long-haul transport like shipping and aviation. The potential exception to this, is in those clusters or hydrogen valleys where the proximity of supply and demand create a rationale for its use across several different end uses.

This consensus on sectors, starts to raise questions for the use of hydrogen to help decarbonise heat within the built environment. Hydrogen is also just one of many possible pathways to decarbonise heat and of the options available it is one of the least developed, with most studies not seeing it having any significant role in the short to medium term. There is therefore a risk, in pursuing the use of hydrogen for heating, that it could delay decisions, or stop progress on alternative heat pathways, which can be deployed now, such as electrification using heat pumps or district heating. Given the need for rapid emission reductions and the lack of progress in decarbonising heat to date, this would not be a good outcome.

If hydrogen was used within the heat sector, there are currently two main options, blending it into natural gas networks, or using 100% hydrogen. For blending, the case is not strong, given that the potential emissions savings, even at a 20% blend, would only result in savings of 4 to 6% relative to natural gas, if using blue hydrogen, which is likely to be the only source available in the short to medium term. Other than the gas industry, most assessments tend to see blending primarily as just a route to help kick start demand for hydrogen and therefore help to build its supply chain, rather than a strategic strategy for heat decarbonisation. One exception could be its use within countries where natural gas dominates the heat sector, where blending could speed up the electrification of heating, through the more rapid and widespread use of hybrid heat pumps.

Another concern around blending is that its widespread use could result in the development of blue hydrogen production that might not otherwise be needed. If green hydrogen were used emissions would be lower, but the costs and potential value of this clean hydrogen in the short to medium term, would make its use for decarbonising natural gas hard to reconcile. Given these insights, there does not appear to be a strong rationale for actively encouraging the use of blending until there is more clarity and understanding on the potential to scale up and reduce costs for green hydrogen, and greater understanding of where that should best be used.

For pathways based on the use of 100% hydrogen the uncertainties seem even greater. If from blue hydrogen production, the direct use of hydrogen would only reduce emissions relative to natural gas by 60-85% because of the upstream emissions from natural gas and the efficiency of emissions capture through CCUS. So again, as a strategy for heat decarbonisation, it could only play a partial role. This pathway would also require significant updates to infrastructure, including within every building on a 100% network, which in addition to concerns over costs, could also mean that the pace of change to enable this route to scale up will not be compatible with meeting climate change targets. Using 100% hydrogen for heating will also create much more significant levels of demand, creating bigger challenges for the clean production of hydrogen. As such, it is hard to see this is as a sensible strategy for decarbonising heat within the built environment, if alternatives are available.

7.3. Final considerations

The science surrounding the climate is clear, deep and rapid reductions in global GHG emissions are needed right across economies and the energy systems that drive them, in order to have any chance of limiting average global temperature increases to below 2 degrees Celsius. Energy systems and the supply of heat account for a large proportion of these global emissions, because of the dominance of fossil fuels within them. Given its properties, hydrogen could clearly help with global efforts to decarbonises energy systems, providing it can be produced cleanly, but its use in the heat sector where rapid progress is needed, is less clear, given that most scenarios do not see hydrogen being able to play any sort of significant role until the 2030s, perhaps even the 2040s.

Decarbonising heat is challenging, none of the solutions are easy, and they will be shaped in any country by the underlying fuels, infrastructures, actors, governance, as well as the economics of different options, and the views of people and communities. Putting energy efficiency first and ensuring there are mechanisms by which people are meaningfully engaged to give their consent for change, will be vital, whichever heat decarbonisation pathway is followed. It then seems that identifying the optimal solutions will require a much more locality-based approach, at the level of cities, towns, neighbourhoods, etc where opportunities and barriers are easier to identify and where the opportunities to work with people and wider stakeholders are greater. Except for a few areas like hydrogen valleys, where a range of options might emerge, or some niche uses where there are not alternatives for decarbonising heat, it is hard to see how hydrogen fits with this sort of approach.

Given all the insights within this paper, as a strategy for the rapid and deep decarbonisation of heating within the built environment, the use of hydrogen is currently highly debatable and not compelling.

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