Written Evidence Submitted by Gordon Taylor
(HNZ0054)

This Submission has three parts:

The Role of Hydrogen in Achieving Net Zero – Summary

1. The suitability of the Government's announced plans for "Driving the Growth of Low Carbon Hydrogen", including:

- *the focus, scale and timescales of the proposed measures;*
  The first step in decarbonising should be to reduce the energy demand and carbon emissions – as the most sustainable option. For example, Neoline is building wind assisted ocean-going freighters offering carbon savings of 80%.

  For transport vehicles, the exergy (energy quality) level must be high to produce mechanical power at high conversion efficiencies. Also the stored energy density must be high enough to complete much or all of the journey with an acceptable payload. Land and sea transport is less demanding, allowing the use of batteries or liquid or gaseous fuels, possibly hydrogen. However aviation is most demanding, and requires liquid hydrocarbon fuels, preferably synthesised using renewable energy. Direct use of hydrogen in aviation would require all-new aircraft and fuelling infrastructure worldwide.

  Electricity is a perfect energy quality match for the mechanical power required for transport vehicles to overcome the resistances to motion over the journey distance. So the energy efficiency of electric transport is very high, with minimal losses – and these can be harnessed for cabin heating, while regenerative braking enables energy recovery. Conversely, liquid and gaseous transport fuels have a lower energy quality than electricity, so significant losses are incurred in the thermodynamic conversion to mechanical power. In the zero-carbon context, renewable electricity from sources such as solar and wind incurs significant losses in the production of liquid or gaseous transport fuels. However, such losses can be used for heating via heat networks.

  About half of current transport fuels is for Light Duty Vehicles (LDVs) – cars and vans. The other half is for Heavy Duty Vehicles (HDVs) – trucks, buses, non-electric trains, ships and aircraft.

  Battery Electric Vehicles for Transport

  The affordability, battery energy density and driving range of BEVs is increasing year by year, so there is a clear prospect of almost all LDVs being replaced by BEVs by 2050 or so. Many (trolley-)buses, trams and trains have long used direct electricity for traction, usually via overhead wires. Battery electric medium and heavy trucks and buses are being developed and sold widely by many makers. Most trucks and buses are 'captive fleets' that can be charged at their base. If charging is needed away from the base, trucks can use plug-in high-rate chargers and buses can use high-rate chargers, via wireless pads beneath, or contacts or wires overhead.

  Hydrogen Fuel for Transport

  'The low energy density of compressed hydrogen requires a pressure vessel eight times the size of a diesel tank'. This limits hydrogen fuel cells to trucks and trains, and short-range ships, such as ferries, and aircraft, such as inland flights. High energy density is even more important for ships and aircraft operating long, trans-oceanic stage lengths.

  With hydrogen, an extremely small leak when parked, refuelling or in motion could cause a fire or explosion. This could lead to a loss of confidence and abandonment of the hydrogen option, wasting time, money, energy and carbon. Safety is crucial for aviation, especially over the oceans. Validating any radically new fuel such as hydrogen would take at least a decade and require all aircraft to be replaced at huge expense. Conversely – as with bio-based fuels - Renewable Synthetic Fuels (RSFs) could be introduced progressively as blends with existing fossil-based fuels.

For many transport applications of fuel cells, to enable quick warmup, they must operate at low temperatures of about 100 C. Such Proton-Exchange Membrane (PEM) fuel cells require catalysts to achieve high outputs. However, so far only those using Platinum Group Metals (PGMs) have proved sufficiently effective. These are very scarce and expensive, although the amount has been greatly reduced – e.g. to monomolecular coatings on substrates. Even so, this limits the use of fuel cells.

Hydrogen is used to fuel a very few trucks, trains and ships, with fuel cells powering electric motors. Most are in 'captive fleets' which avoids the need for an extensive hydrogen infrastructure. However, almost all hydrogen is made from natural gas and is carbon intensive, with very little made using renewable sources, such as electricity and biomass. Also, the hydrogen fuelled vehicles are considerably more expensive and are under competitive pressure from BEVs and RSFs. Moreover, wider use of hydrogen fuelled vehicles would require an all-new infrastructure, while BEVs can use the existing electricity infrastructure, independently of the decarbonisation of electricity.

Renewable Synthetic Fuels for Transport

RSFs can be introduced via the existing infrastructure into existing and new non-electric trains, ships and aircraft. Some are 'drop-in' fuels, which can directly replace fossil-based fuels, such as gasoline, jet fuel (kerosene) and diesel. This means no loss of vehicle range, payload or other functionality and a flexible and seamless transition to near-zero carbon. Ships may use such diesel or possibly synthetic methane or ammonia, where their lower energy densities are less important, and they may be cheaper.

Most renewable hydrogen will be made by electrolysis of water, which is the first step in making renewable synthetic fuels. So for the decarbonisation of non-electric transport this becomes a given, and the choice is between hydrogen and fuel cells in new vehicles, with a new distribution infrastructure, or RSFs in existing vehicles, with the existing distribution infrastructure. With the competition for land, water and nutrients between food and energy crops, bio-fuels could only ever be a minor share.

A notable report on decarbonising aviation argues that it cannot be achieved sufficiently by reducing aircraft fuel consumption. It also says that biofuels can only be relied on for 11.4% by 2050. Hence the report concentrates on 'electrofuels' - meaning hydrocarbons, rather than hydrogen. The reject heat from electrolysis, methanation, and conversion to e.g. kerosene can be cascaded to District Heating (DH).

Conclusions on Transport

Decarbonising transport can be effected by reducing transport volumes for freight and passengers.

As the decarbonisation of electricity by 2050 is in prospect, direct electric traction will continue to be important for trolley-buses, trams and trains. The remainder can be met mostly with Battery Electric propulsion for Light Duty Vehicles (cars and vans), and Renewable Synthetic Fuels for Heavy Duty Vehicles (trucks, non-electric trains, ships and aircraft).

There is no case for using hydrogen for transport, because for Light Duty Vehicles BEVs are superior, and for Heavy Duty Vehicles, Renewable Synthetic Fuels are superior. However, hydrogen in Fuel Cell Vehicles may play niche roles in road, rail and marine transport.

All Renewable Synthetic Fuels require hydrogen as a feedstock, produced with renewable energy by electrolysis for the lowest carbon intensity. This avoids the risks of CCS. The CO2 for synthetic hydrocarbons can come from point sources, such as iron, steel, and cement plants. It is easy to liquefy for shipping to the RSF plant.

- *how the proposed measures—and any other recommended measures—could best be co-ordinated;*
  BEVs and charging provisions near homes and on highways are already receiving attention from government.

- *the dependency of the Government's proposed plans on carbon capture and storage, any risks associated with this and how any risks should be mitigated; and*
  The production of hydrogen from natural gas with CCS is not sustainable. Natural gas is depletable and CO2 storage volumes are finite. Moreover, there are risks of CO2 leakage over geological timescales. Yet the companies proposing CCS are not prepared to carry the risks, so a report to the CCC suggested that these must be at least partially underwritten by the Government. However, such leaks could be lethal.

- *potential business models that could attract private investment and stimulate widespread adoption of hydrogen as a*

Net Zero fuel;
Delivery of transport decarbonisation with novel vehicles and fuels would be – as now - by corporate entities with good access to finance at low interest rates. These are almost always for-profit companies.

For zero-carbon transport, joint ventures are being formed to manufacture Renewable Synthetic Fuels from hydrogen and point source CO2. Eight projects are shown in my table 'Low Carbon Aviation Fuel Projects'. The largest so far is the Copenhagen project, which will use wind energy to produce hydrogen by electrolysis. This has three phases – 1) of 10 MW to make renewable hydrogen, and 2) of 250 MW and 3) of 1.3 GW to make Renewable Synthetic Fuels.

For zero-carbon heat, only heat networks can harness the vast resources of reject and renewable heat. They can also access tanks and covered ponds storing heat from surplus renewable electricity, and thus manage its variability. Heat is a utility like water and sewage, and piecemeal installations and competition between networks make no sense. Decarbonisation via energy savings measures, District Heating and Heat Pumps should not be made the responsibility of individual citizens, who lack the skills to specify them and access to low-cost capital. The 'Green Deal' was a fiasco, with only 15,000 issued from 2012 to 2015.

DH is technically mature and bankable, so can be funded over long periods, such as 30 years, and financed with low-cost capital, borrowed at government rates. In Denmark, such systems are often owned by non-profit consumer co-operatives or by the local authority, as for many decades. This enables decarbonisation of heat at much lower Internal Rates of Return (IRR). A for-profit Energy Service Company (ESCO) may require an IRR of 14%, but a Council-lead company in Denmark requires only 4%, when the approximate interest rate for borrowing capital is less than 2%.

Even in the UK, local authorities plan and deliver (via contractors) all other services, such as access roads, water, sewage, electricity and gas. These are planned by professionals – often engineering consultants - and bought in bulk in competitive markets. In best practice, as required in Denmark since 1978, the local authority plans and delivers (via contractors) a local heat plan consistent with the national heat plan, as part of the national decarbonisation plan.

Deploying energy savings measures, District Heating (DH) and Heat Pumps (HPs) at scale would provide local jobs in every city, town and village in the country.

2. The progress of recent and ongoing trials of hydrogen in the UK and abroad, and the next steps to most effectively build on this progress;
Experience with hydrogen for transport is that it is not suitable for internal combustion engines for land vehicles or aviation. Hydrogen for fuel cell powered vehicles cannot be more than a niche player, due to the need for Platinum Group Metals as catalysts. Most transport fuels will be Renewable Synthetic Fuels made from renewable hydrogen and CO2.

There is no experience abroad with hydrogen for space and water heat. While some pilot projects have started in the UK, these have not shown that the challenges at 3. (below) can be solved at competitive cost.

3. The engineering and commercial challenges associated with using hydrogen as a fuel, including production, storage, distribution and metrology, and how the Government could best address these;
As a fuel for heat, hydrogen is far more prone to leakage than natural gas and is extremely easily ignited, leading to explosions and/or fires. These characteristics are inherent and cannot be changed. Moreover, the capacity of the existing gas grid depends on the volumetric energy density and the pipe diameter after lining with plastic pipe. Together these would reduce it by about 84% - i.e. to about 16%. This would prevent the use of 100% hydrogen in the existing gas network without very extensive and expensive replacements to carry the heat load. Furthermore, gas networks cannot harness the vast resources of reject and renewable heat.

4. The infrastructure that hydrogen as a Net Zero fuel will require in the short- and longer-term, and any associated risks and opportunities;
For space and water heating, the exergy level is low – far lower than those of fuel gases such as natural gas and hydrogen. So for such loads, fuel gases have very low exergetic conversion efficiencies. Yet in the UK and elsewhere, low exergy heat is rejected from huge numbers of cooling towers, large and small. Low exergy renewable heat can also come from solar heat collectors and geothermal boreholes. This reject and renewable heat can be harnessed for space heating and cooling by heat networks, but not by gas (hydrogen or NG) or electric networks. By matching the exergy of the energy carrier and the loads, and harnessing such sources, Copenhagen expects to be carbon neutral for all space heating and cooling by 2025.

Hydrogen has no role as a fuel for heat. Best practice in Europe and elsewhere is to replace natural gas, oil and coal with heat networks (maybe 70%) and electric heat pumps (maybe 30%) by 2050.

5. Cost-benefit analysis of using hydrogen to meet Net Zero as well as the potential environmental impact of technologies required for its widespread use; and

This is not applicable, as hydrogen is not suitable for heat or (as such) for transport. It will be a feedstock for Renewable Synthetic Fuels for transport. Any cost-benefit analysis would need to include the CO2 supply for the latter. Presumably this has been done for several projects, including the largest so far, in Copenhagen (see above and my table).

6. The relative advantages and disadvantages of hydrogen compared to other low-carbon options (such as electrification or heat networks), the applications for which hydrogen should be prioritised and why, and how any uncertainty in the optimal technology should be managed.
There is no practice of hydrogen heating worldwide. Also, the only country with widespread electrical heating is Norway.

To decarbonise the heat sector, heat demands should be reduced by energy savings measures, such as insulation etc, in bulk deployments wherever they are carbon cost effective versus heat supply. However, much of the UK building stock is old and very poorly insulated, and even newer buildings are still poorly insulated. It would be very hard to improve existing buildings or build enough new - e.g. to the Passive House standard, saving 80 to 90% - in the few decades before 2050. Also, there are many 'heritage' buildings that allow very little thermal improvement. So the UK must depend heavily on the supply of decarbonised heat.

The human body temperature is 37 C, and a comfortable room temperature is about 23 C. So the best exergy match for space and water heating, requiring e.g. 50 to 60 C, is DH using water at typically 70 C. As it is able to reach near zero carbon, it is also future proof. This contrasts with gas, which could produce a flame temperature of about 2000 C, or electricity which could produce an arc temperature of 3000 to 20,000 C. The last two are clearly overkill, and would lead to losses of energy. For heat below 100 C, electricity should be limited to small demands or used to drive heat pumps. However, the heat pumps should be large and central, supplying heat networks.

Existing individual heat pumps can only deliver about 60 C under winter design conditions, whereas most UK dwellings have radiators designed for 80 C. Thus existing and new dwellings would require larger radiator areas or underfloor heating. Conversely, district heating can deliver a water temperature of 80 C under winter design conditions to suit the radiators installed in most UK dwellings.

DH enables harnessing the reject heat from industry and commerce, as evidenced by the myriads of cooling towers and air-blast coolers, large and small, in the UK, along with the reject heat from electrolysers and synthetic fuel production plants. DH can also harness renewable sources such as solar heat collectors (best at large scale), deep geothermal heat (only affordable at scale) and renewable electricity (via central resistive heaters or heat pumps). Moreover, diurnal heat stores enable even more advantage to be taken of low electricity prices. Yet none of this heat energy could be harnessed by gas or electricity networks.

The Thermodynamic Heating Efficiency of heat from Combined Heat and Power (CHP) plants is about twice that of electric heat pumps. (See my paper 'The Role of Hydrogen in Achieving Net Zero'). Existing power-only plants can be converted for CHP operation, often by removing the last blade rows of the steam turbines. Even where they are located some distance from the heat loads in cities, it is feasible and economic to transport the heat several tens of kilometers via insulated pipelines. Also, central plant can have access to low-cost storage and peak plant. So in Danish heat networks, the central plant is about half-sized to the nominal load and the peak plant supplies only about 5 to 10% of the total heat.

DH avoids the need for fresh water for evaporation in power station cooling towers. In the UK, this accounted for some 44% of fresh water abstraction. Using the DH system to cool the power station and heat the city saves water, energy, carbon and money.

In using water as the energy carrier, DH is similar to sprinkler systems. So DH is very much safer than gas or electric heating for all buildings, including high-rise buildings. Modern DH systems use water at annual average flow temperatures of typically 70 C, and in the latest 'Fourth Generation' systems, down to 50 C, to reduce heat losses. These can displace gas heating and compete with individual heat pumps.

Local heat plans usually reflect population - and hence heat load - densities.
High densities – as in Central Business Districts, hospitals and education campuses - are highly favourable for district heating.
Intermediate densities may be currently suited by natural gas and later replaced by district heating.
The lowest urban densities could be suited by heat pumps and rural buildings by heat pumps and various biofuels.
District heating should be deployed first in the centre where the heat load density is greatest. The high-rise buildings of the central business district bring the greatest return in heat sales per site area, and help to pay for the wider deployment of DH.

To take advantage of the above (safety, reject heat, and renewable energy), DH supplies over 60% of the heated floor area in Denmark and Copenhagen should be carbon neutral for heating by 2025. DH networks are widespread, especially on the European continent. Also there is considerable scope for expansion of DH in Europe, including the UK.

In a study for the UK, all heat is zero carbon, with 42% district heat, 5% hydrogen boilers, 52% heat pumps and 1% direct electric by 2050. Given the limits and risks of CCS, and thus of fossil-derived hydrogen, hydrogen boilers may not happen. Rather than producing hydrogen for heat by electrolysis with renewable electricity, the latter would be better used for district heating or heat pumps. There is then no role for hydrogen in decarbonising the heat sector in the UK or elsewhere.

Evidence for the factual statements above is in my paper 'The Role of Hydrogen in Achieving Net Zero'.

The Role of Hydrogen in Achieving Net Zero

1 The Energetic Context

All sound policies must obey the laws of science, including those of thermodynamics, which apply to all technologies. Engineering is the art of designing solutions within the constraints of the scientific laws, best-practice technologies and energy, carbon, time and money budgets. Experience shows that no one technology is suitable for all energy sectors - or even one. With a national carbon target of zero by 2050, rather than 'the role of hydrogen ?', one should ask 'how to decarbonise ?'. This paper addresses the question for transport and heat. The technology options are considered within the above constraints and budgets to determine the scope for each.

It is a duty of government to ensure the provision of food and shelter for all. However, experience in the Covid 19 lockdown is that transport, both freight and passenger, can be reduced by up to 90%. Only food transport, of which imports are about 50%, is essential. On the other hand, shelter accounts for much of the heat demand, which may remain unchanged overall.

For transport vehicles, the exergy (energy quality) level must be high to produce mechanical power at high conversion efficiencies. Also the stored energy density must be high enough to complete much or all of the journey with an acceptable payload. Land and sea transport is less demanding, allowing the use of batteries or liquid or gaseous fuels, possibly hydrogen. However aviation is most demanding, and requires liquid hydrocarbon fuels, preferably synthesised using renewable energy. Direct use of hydrogen in aviation would require all-new aircraft and fuelling infrastructure worldwide.

For space and water heating, the exergy level is low – far lower than those of fuel gases such as natural gas and hydrogen. So for such loads, fuel gases have very low exergetic conversion efficiencies. Yet in the UK and elsewhere, low exergy heat is rejected from huge numbers of cooling towers, large and small. Low exergy renewable heat can also come from solar heat collectors and geothermal boreholes. This reject and renewable heat can be harnessed for space heating and cooling by heat networks, but not by gas or electric networks. By matching the exergy of the energy carrier and the loads, and harnessing such sources, Copenhagen expects to be carbon neutral for all space heating and cooling by 2025.

1.1 Decarbonisation by Reducing Energy and Carbon

The first step in decarbonising should be to reduce the energy demand and carbon emissions – as the most sustainable option.

The potential demand-side energy reductions are estimated in two major papers by Cullen and Allwood et al.
(2010-03-05 Theoretical efficiency limits for energy conversion devices, Cullen and Allwood,
https://www.sciencedirect.com/science/article/abs/pii/S0360544210000265).
The Abstract includes: 'global demand for energy could be reduced by almost 90 per cent if all energy conversion devices were
operated at their theoretical maximum efficiency'.
All energy conversion devices should be able to operate at about half their theoretical maximum efficiency – as is the case for internal combustion engines. If so, the global demand for energy could be reduced by about 45%.
(2011-01-12 Reducing Energy Demand: What Are the Practical Limits ?, Cullen, Allwood and Borgstein,
https://pubs.acs.org/doi/pdf/10.1021/es102641n).
The Abstract includes: 'The result demonstrates that 73% of global energy use could be saved by practically achievable design changes to passive systems'.
Hence by combining energy conversion devices at about half their theoretical efficiency (saving 45%) with the practical passive system changes (saving 73%), the global energy saving could be 100 - (100-45)*(100-73) = 85%.

'Looking towards a target of net zero emissions by 2050, Professor Allwood argued that even taking into account plans to eliminate coal, oil and gas within the next 30 years, if we choose to eliminate offsets and trading as alternatives to true emissions reduction, reaching a zero emissions target will be difficult. He suggested that present policies heavily rely on breakthrough technology in its solutions, such as carbon capture and storage, which are not yet operating at scale'.
'He argues that we should not formulate policies reliant upon breakthrough technologies becoming viable solutions within the next 30 years'.
'Instead, in the short term, we should focus on the wide adoption of currently available and incremental technologies, as discussed in his Absolute Zero report. Professor Allwood has emphasised the need for an increased focus on compatible innovations such as electric heat pumps, smaller household appliances, and smaller, electrified vehicles. This could be accompanied by efforts to reduce consumption by using less and using differently, an area of research which has been the main action of the Use Less Group'.
2019-12-04 Absolute Zero: The UK's Energy Transition, Julian Allwood et al,
http://www.csap.cam.ac.uk/news/article-absolute-zero-uks-energy-transition/
and:

2019-11-29 Absolute Zero: The UK's Energy Transition,
https://www.repository.cam.ac.uk/bitstream/handle/1810/299414/Absolute-Zero-digital-280120-v2.pdf
This report also addresses the decarbonisation of materials, including steel and cement, which are notable examples of the 'industrial processes' mentioned in the BEIS Report (below).

1.2 Decarbonising the Transport Sector

For Transport, electricity is a perfect energy quality match for the mechanical power required for transport vehicles to overcome the resistances to motion over the journey distance. So the energy efficiency of electric transport is very high, with minimal losses – and even these can be harnessed for cabin heating, while regenerative braking enables energy recovery. Conversely, liquid and gaseous transport fuels have a lower energy quality than electricity, so significant losses are incurred in the thermodynamic conversion to mechanical power. In the zero-carbon context, renewable electricity from sources such as solar and wind incurs significant losses in the production of liquid and gaseous transport fuels. However, because the conversion plants are fixed, such losses can be used for heating via heat networks.

1.2.1 Battery Electric Vehicles for Transport

About half of transport fuels is for Light Duty Vehicles (LDVs) – cars and vans.
The affordability, battery energy density and driving range of BEVs is increasing year by year, so there is a clear prospect of almost all LDVs being replaced by BEVs by 2050 or so.
(2020-06-10 This Stunning Chart Shows Why Battery Electric Vehicles Win,
https://cleantechnica.com/2020/06/10/this-stunning-chart-shows-why-battery-electric-vehicles-win/).

The other half of transport fuels is for Heavy Duty Vehicles (HDVs) – trucks, buses, non-electric trains, ships and aircraft. Many (trolley-)buses, trams and trains have long used direct electricity for traction, usually via overhead wires. Battery electric medium and heavy trucks and buses are being developed and sold widely by many makers. Most trucks and buses are 'captive fleets' that can be charged at their base. If charging is needed away from the base, trucks can use plug-in high-rate chargers and buses can use high-rate chargers, via wireless pads beneath, or contacts or wires overhead.

1.2.2 Hydrogen Fuel in Transport

'The low energy density of compressed hydrogen requires a pressure vessel eight times the size of a diesel tank'.
(2019-07-26 Clearing the Line, Professional Engineering, Issue 5, 2019, p 51, https://www.imeche.org/news/news-article/railway-must-be-decarbonised-to-help-meet-ambitious-environment-targets).
This constrains hydrogen fuel cells to trucks and trains, and short-range ships, such as ferries, and aircraft, such as inland flights. High energy density is even more important for ships and aircraft operating long, trans-oceanic stage lengths.

With hydrogen, an extremely small leak when refuelling or in motion could cause a fire or explosion.
(2017 Risks associated with alternative fuels in road tunnels and underground garages, p 28, https://www.diva-portal.org/smash/get/diva2%3A1081095/FULLTEXT01.pdf).
This could lead to a loss of confidence and abandonment of the hydrogen option, wasting time, money, energy and carbon.

Safety is crucial for aviation, especially over the oceans. Validating any radically new fuel such as hydrogen would take at least a decade and require all aircraft to be replaced at huge expense. Conversely – as with bio-based fuels - RSFs could be introduced progressively as blends with existing fossil-based fuels.

Hydrogen is used to fuel a very few trucks, trains and ships, with fuel cells powering electric motors. Most are in 'captive fleets' which avoids the need for an extensive hydrogen infrastructure. However, almost all hydrogen is made from natural gas and is carbon intensive, with very little made using renewable sources, such as electricity and biomass. Also, the hydrogen fuelled vehicles are considerably more expensive and are under competitive pressure from BEVs and Renewable Synthetic Fuels (RSFs). Moreover, wider use of hydrogen fuelled vehicles would require an all-new infrastructure, while BEVs can use the existing electricity infrastructure, independently of the decarbonisation of electricity.

For more on Hydrogen as an Option for Transport, see Appendix 1.

1.2.3 Renewable Synthetic Fuels for Transport

RSFs can be introduced via the existing infrastructure into the existing and new non-electric trains, ships and aircraft. Some are 'drop-in' fuels, which can directly replace fossil-based fuels, such as gasoline, jet fuel (kerosene) and diesel. This means no loss of vehicle range, payload or other functionality and a flexible and seamless transition to near-zero carbon.
(Power-to-Gas, http://www.hz-inova.com/cms/en/home?page_id=4896 and

EtoGas Power-to-Gas Technology, http://www.hz-inova.com/cms/wp-content/uploads/2018/02/Etogas_Online_E.pdf and Prometheus Fuels, https://www.prometheusfuels.com/ and: Synhelion, https://synhelion.com/).
In Germany, renewable synthetic fuels are supported by DENA within a wider programme for Power-to-X.
(Power to X: Technologien, https://www.dena.de/fileadmin/dena/Dokumente/Pdf/607/9264_Power_to_X_Technologien.pdf).

Renewable hydrogen and renewable fuels could be made with bio feedstocks – both wastes and energy crops.
(2013-11 Technological Innovation Systems: The case of hydrogen from waste, https://orca.cf.ac.uk/59170/1/Jen_Baxter_PhD_Technological_Innovation_Systems_March_2014_(1)-signed.pdf).
The Abstract includes: 'A further conclusion is that by addressing the production of hydrogen from waste using these methods, hydrogen technologies are shown to be still in an emergent state'. Thus they are not ready or proven.

With the competition for land, water and nutrients between food and energy crops, bio-fuels could only ever be a minor share. Most renewable hydrogen will be made by electrolysis of water, which is the first step in making renewable synthetic fuels. So for the decarbonisation of non-electric transport this becomes a given, and the choice is between hydrogen and fuel cells in new vehicles, with a new distribution infrastructure, or RSFs in existing vehicles, with the existing distribution infrastructure.

For marine use, the present fossil-based fuels contain significant sulphur, leading to SOx emissions, and heavy metals, such as vanadium. RSFs would have neither, so that exhaust catalysts could be used to control emissions of NOx - a GHG.

A notable report on decarbonising aviation argues that it cannot be achieved sufficiently by reducing aircraft fuel consumption. It also says that biofuels can only be relied on for 11.4% by 2050. Hence the report concentrates on 'electrofuels' - meaning hydrocarbons, rather than hydrogen. (2018-10 'Roadmap to decarbonising European aviation', https://www.transportenvironment.org/sites/te/files/publications/2018_10_Aviation_decarbonisation_paper_final.pdf).

The Summary includes:
'To succeed in putting aviation on a pathway to decarbonisation, new types of alternative fuels need to be brought forward. The report focuses on synthetic fuels, namely electrofuels, which will be needed to close the gap. Electrofuels are produced through combining hydrogen with carbon from CO 2 . With the hydrogen produced using additional renewable electricity and with the correct source of CO 2 (ideally air capture), such fuels can be close to near zero emissions and carbon circular. Again however strict safeguards are needed to ensure synthetic kerosene would be produced only from zero emission electricity.
If produced at scale, electrofuels are likely to cost between three and six times more than untaxed jet fuel. At a cost of E2,100 per tonne in 2050, electrofuel uptake will increase ticket prices by 59%, resulting in a 28% reduction in projected passenger demand compared to a business-as-usual scenario. However, compared to the ticket price with an equivalent CO 2 price of E 150 a tonne, the ticket price increase would only be 23%'.
'Using electrofuels to meet the expected remaining fuel demand for aviation in 2050 would require renewable electricity equivalent to some 28% of Europe's total electricity generation in 2015 or 95% of the electricity currently generated using renewables in Europe'.

Page 26 includes:
'Aviation Energy Demand (Mtoe) 53.3 (in 2015) 71.3 (in 2050)'.
[They assume some fuel saving due to 'operational efficiency', but as the skies are already crowded, increased air transport volumes would reduce operational efficiency due to increased stacking (circling waiting to land) and diversions].

Page 26 includes:
'PtL conversion efficiency 38% (in 2020) 50% (in 2050)'.
[However, the reject heat from electrolysis, methanation, and conversion to kerosene can be cascaded to District Heating].

For the second stage of RSF production, the Fischer-Tropsch process for the production of gasoline, jet fuel and diesel has been proven over many decades. Likewise, the methanation, methanol, gasoline pathway processes are mature.

‘A benefit of the proposed pathway is that it builds on a backbone of existing large-scale technology, i.e. the so-called gas-to-liquid or GTL technology where liquid fuels are produced from methane via synthesis gas. Synthesis gas, or syngas, is a mix of hydrogen and carbon monoxide, being an intermediate in the conversion of methane to liquid fuels. Several of such large-scale GTL plants are in operation across the world converting natural gas into liquid fuels. The same technology can be applied to bio-methane and green syngas. Such a plant can in principle be contracted ‘tomorrow’ – after a detailed feasibility study for a specific location – and be built and in operation by 2025 at the latest’.
‘The pathway is robust and flexible in the sense that feedstocks can be any type of methane and syngas. The merit of this is that the feedstock of bio-methane can be supplemented by electro-methane or syngas made from hydrogen and CO2 and by syngas made from electricity and CO2, producing thereby so-called electro-fuel via the same GTL technology. The fuels are the same, only the feedstock is different. The technology for producing electro-methane is documented in demonstration scale by several stakeholders and judged to be available for operation in full scale by 2027 at the latest. Moreover, production of

syngas directly from CO2 and electricity by so-called co-electrolysis is successfully demonstrated and judged to be available in full scale by 2030, potentially even before so this is a conservative estimate. Techniques for carbon capture are well known and implemented in full scale, for example on many biogas plants, and applying the technique on flue gases from waste and biomass incineration is under development and judged to be available in full scale by 2027. Finally, techniques for direct capture of CO2 from the atmosphere is successfully demonstrated in pilot scale and judged to be available in full scale by 2030'.
(2019-10-28 A pre-feasibility study on sustainable aviation fuel from biogas, hydrogen and CO2, Mortensen et al, https://findresearcher.sdu.dk:8443/ws/portalfiles/portal/155625931/Nordic_aviation_fuel_production_28_10_2019_final.pdf)

COWI of Denmark are involved in the Copenhagen RSF project. This has three phases – 1) of 10 MW to produce renewable hydrogen, and 2) of 250 MW and 3) of 1.3 GW to produce renewable synthetic fuels.
'Copenhagen Airports, A.P. Moller - Maersk, DSV Panalpina, DFDS, SAS and Ørsted have joined forces in a new partnership with the vision to develop new innovative solutions to secure a greener future for the partners and society. The vision of the partnership is to develop a new ground-breaking hydrogen and e-fuel production facility as soon as 2023 which, when fully scaled-up by 2030, could deliver more than 250,000 tonnes of sustainable fuel for busses, trucks, maritime vessels and airplanes every year. Production would potentially be based on a total electrolyser capacity of 1.3 gigawatts.
COWI and BCG act as knowledge partners for the project, and the project is supported by the Municipality of Copenhagen in line with Copenhagen's ambitious policies for decarbonisation. However, the partnership hopes that the project can, over time, act as a catalyst for similar projects in other parts of Denmark and internationally.
Denmark's abundant offshore wind resources and diverse supply chain within sustainable solutions have the potential to make Denmark a hub for the development of Power-to-X solutions for which there will be a considerable demand in the future. This can solidify Denmark's position as a green energy leader and create jobs both short and long-term. Denmark is also a leading nation within transport and logistics and thus has a unique starting point to develop new sustainable transport solutions, while also helping to decarbonise core parts of the economy and secure long-term competitiveness'.
(2020-05-20 Delivering the sustainable fuels of the future, https://presscloud.com/file/33/330870924970883/Fact_sheet.pdf).

1.2.4 Conclusions on Transport

Decarbonising transport can be effected by reducing transport volumes for freight and passengers by up to 90%. As the decarbonisation of electricity by 2050 is in prospect, direct electric traction will continue to be important for trolley-buses, trams and trains. The remainder can be met mostly with Battery Electric propulsion for Light Duty Vehicles, and Renewable Synthetic Fuels for Heavy Duty Vehicles.

For many transport applications of fuel cells, to enable quick warmup, they must operate at low temperatures of about 100 C. Such Proton-Exchange Membrane (PEM) fuel cells require catalysts to achieve high outputs. However, so far only those using Platinum Group Metals (PGMs) have proved sufficiently effective. These are very scarce and expensive, although the amount has been greatly reduced – e.g. to monomolecular coatings on substrates. Light Duty Vehicles (LDVs) (cars and vans) with a lifetime of e.g. 4000 full-load hours, require relatively light PGM loadings, but Heavy Duty Vehicles (HDVs) (trucks, buses, trains, ships and aircraft) require more. Indeed, unless effective catalysts of other than PGMs are found, the worldwide total power capacity of all the Fuel Cell Electric Vehicles for road, rail, marine and air transport will be extremely limited. High temperature Solid Oxide Fuel Cells (SOFCs) do not require catalysts, but have significant start-up times and thermal losses.

There is no case for using hydrogen for transport, because for light duty vehicles (cars and vans) BEVs are superior, and for heavy duty vehicles (trucks, non-electric trains, ships and aircraft), renewable synthetic fuels are superior. However, hydrogen in Fuel Cell Vehicles may play niche roles in road, rail and marine transport.

Neither hydrogen nor renewable synthetic fuels would solve the aviation emissions problem. This is because non-CO2 impacts comprise about two-thirds of the net radiative forcing. (2021-01-01 The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. Page 1, https://www.sciencedirect.com/science/article/pii/S1352231020305689/pdf).
This requires aviation demand reduction or offsets in other sectors.

Delivery of transport decarbonisation with novel vehicles and fuels would be – as now - by corporate entities with good access to finance at low interest rates. These are almost always for-profit companies.

1.3 Decarbonising the Heat Sector

The heat demand discussed here is that at temperatures below 100 C – mainly for space and water heating in buildings.
Some heat at higher temperatures is used in industry, but often direct electric heating could be used, rather than natural gas, synthetic methane or hydrogen. (2018-10 Decarbonizing the Heat Sector, http://cms.energypolicy.co.uk/heat/313).

Heat demands should be reduced by energy savings measures, such as insulation etc, by deployment at scale wherever they are carbon cost effective versus heat supply. However, much of the UK building stock is old and very poorly insulated, and even newer buildings are still poorly insulated. It would be very hard to improve existing buildings or build enough new - e.g. to the Passive House standard, saving 80 to 90% - in the few decades before 2050. Also, there are many 'heritage' buildings that allow very little thermal improvement. So the UK must depend heavily on the supply of decarbonised heat.

For heat below 100 C, electricity is thermodynamic overkill, so should be limited to small demands or used to drive heat pumps. However, the heat pumps should be large and central, supplying heat networks. The output of a heat pump for a single house may be 6 kWth, while that for a district heating system may be 60 MWth – 10,000-fold larger. The specific cost of capital plant typically scales as the 0.6 power of the unit output. So the cost of the 60 MWth heat pump is only about 10000^0.6 = 251 x that of a 6 kW heat pump, yet replaces 10,000 of the latter. Indeed, with a diversity factor of 0.5 for a large network of e.g. 10,000 houses, the large heat pump could be of only 30 MWth. (2001-09-02 Untersuchungen der Gleichzeitigheit in kleinen und mittleren Nahwaermenetzen, http://www.bios-bioenergy.at/uploads/media/Paper-Winter-Gleichzeitigkeit-Euroheat-2001-09-02.pdf). Also, central plant can have access to low-cost storage and peak plant. So in Danish heat networks, the central plant is about half-sized while the peak plant supplies only about e.g 5% of the total heat.

Hydrogen, like other gaseous and liquid fuels, cannot harness any of the reject heat from thermal power plants fuelled with waste and biomass, and from industry, solar and geothermal heat.

Hydrogen production is about 70 million tonnes a year, most from natural gas and some from coal. This releases about 830 million tonnes a year of CO2 – two per cent of global GHG emissions – almost all to the atmosphere.
(2019-06 The Future of Hydrogen, IEA, Page 38, https://webstore.iea.org/download/direct/2803).
The resulting CO2 could be Captured and Sequestrated (CCS), usually by pumping it down into former oil and gas fields. However, this is expensive in initial and operating costs, and as the fossil fuel is depletable and any sequestration volume is finite, it is not sustainable. These limit the time before hydrogen must be produced by electrolysis, using renewable electricity. Moreover, the companies proposing CCS are not prepared to carry the risks (e.g. of leakage over geological timescales), so a report to the CCC suggested that these must be at least partially underwritten by the Government. (2016-05 A STRATEGIC APPROACH FOR DEVELOPING CCS IN THE UK, Page 6, https://www.theccc.org.uk/wp-content/uploads/2016/07/Poyry_-_A_Strategic_Approach_For_Developing_CCS_in_the_UK.pdf).
Yet such leakage could be lethal, as CO2 is heavier than air and does not support life. (2017-04-15 This Small Lake in Africa Once Killed 1,700 People Overnight, And We Still Don't Know Why, https://www.sciencealert.com/how-this-small-lake-in-africa-once-killed-1-700-people-overnight-and-we-still-don-t-know-why).

Many of the issues concerning hydrogen for transport apply also to heat. See Section 1.2.2 onwards.

For more on Hydrogen as an option for Heat, see Appendix 2

1.3.1 District Heating Networks for Heat

Safety
In using water as the energy carrier, DH is similar to sprinkler systems. So DH is very much safer than gas or electric heating for all buildings, including high-rise buildings. Modern DH systems use water at flow temperatures of typically 70 C, and the latest systems, even lower, down to 50 C, to reduce heat losses. Temperatures above 100 C, with pressures to prevent boiling, would be found only in large trunk pipelines that would usually be buried and routed well away from inhabited buildings.

Exergy
Exergy depends on the work potential, and hence via the Second Law of Thermodynamics, on the potential top temperature. The human body temperature is 37 C, and a comfortable room temperature is about 23 C. So the best exergy match for space and water heating, requiring e.g. 50 to 60 C, is DH using water at typically 70 C. As it is able to reach near zero carbon, it is also future proof. This contrasts with gas, which could produce a flame temperature of about 2000 C, or electricity which could produce an arc temperature of 3000 to 20,000 C. (Gas burner, https://en.wikipedia.org/wiki/Gas_burner and: Temperature of a MIG Welder, https://hypertextbook.com/facts/2003/EstherDorzin.shtml).
The last two are clearly overkill, and would lead to losses of energy.

Thermodynamic Heat
A Combined Heat and Power (CHP) plant embodies a 'Virtual Heat Pump', which has a Coefficient of Performance (COP) (=Heat out/Power in) and a Thermodynamic Heating Efficiency (THE) (=Heat Out/Incremental Heat In).
(2003-01-19 'Energy Solutions for 60% Carbon Reduction, Part 1', http://cms.energypolicy.co.uk/allsectors/248).
P 6 'Referring to Fig. 2, the thermal efficiency of the engine is about 0.5, and the COP for the electric heat pump is about 3, which gives a THE of about 1.5. However, for CHP, the thermal efficiency of the engine is still about 0.5, but the COP of the 'virtual heat pump' is about 8, which gives a THE of about 4 or 400 %. ... Moreover, while an electric heat pump of comparable output would be expensive, the 'virtual heat pump' of CHP capability adds little or nothing to the cost of a turbine-generating

set. (It contains the same number of components, and actually fewer rows of turbine blades)'.

P 10 'A complete District Heating system always includes fuel-fired heat-only boilers, that are intended for emergencies, and while the heating load is being built up. Thus they are used to supply buildings as they are connected to the network, and before connection of another CHP plant. Moreover, the heat-only boilers are also used to supply e.g. 5 to 10 % of the annual heat energy in helping meet peak loads, which may halve the maximum demand on the CHP plant, and thus lowers the overall cost'.
'Even after allowing for the effect of a small amount of heat from heat-only boiler plant at higher heat loads, and for the heat distribution losses, the annual average THE can still be about 3.3 or 330 %. Since the efficiency of domestic gas boilers may be only 0.65, such thermodynamic heating can deliver savings in fuel for heating of about (1/0.65 - 1/3.3)/(1/0.65) = (1 - 0.65/3.3) = 0.80 or 80 %'.
(2015-11 The Real Merits of Large CHP-DH, Gordon Taylor, Slides 4-7, http://cms.energypolicy.co.uk/heat/270)

There is ample scope for harnessing the reject heat from gas-fired power stations, as these now account for 39.5% of the electricity generated in the UK. (2019 DUKES, p 89, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/840015/DUKES_2019_MASTER_COPY.pdf).
Existing Gas Turbine Combined Cycle (GTCC) power-only plants can be converted for CHP operation, often by removing the last blade rows of the steam turbines. Even where the plants are located some distance from the heat loads in cities, it is feasible and economic to transport the heat several tens of kilometers via insulated pipelines.

New GTCC plants should not be power-only, as proposed by Drax. (2020-05-22 UK approval for biggest gas power station in Europe ruled legal, https://www.theguardian.com/environment/2020/may/22/uk-approval-for-biggest-gas-power-station-europe-ruled-legal-high-court-climate-planning). It may be the biggest in Europe, but they still intend to waste half the fuel. Instead, they should be designed for CHP operation and supply heat to nearby cities. By displacing gas heating of buildings, this would help to decarbonise the UK. And as the gas fired power plants are displaced by renewable sources (wind and solar), the DH networks would carry increasing amounts of other reject and renewable heat.

Reject Heat
DH enables harnessing the reject heat also from industry and commerce, as evidenced by the myriads of cooling towers and air-blast coolers, large and small, in the UK. DH can also harness the reject heat from electrolysers and synthetic fuel production plants. Yet none of this heat energy could be harnessed by gas or electricity networks.

Renewable Heat
DH can also harness renewable sources such as solar heat collectors (best at large scale), deep geothermal heat (only affordable at scale) and renewable electricity (via central resistive heaters or heat pumps). Moreover by connecting diurnal heat stores to the DH networks, even more advantage can be taken of low electricity prices. These can be very low, especially in Europe, and when wind generation is high. (Nord Pool, https://www.nordpoolgroup.com/Market-data1/#/nordic/chart). Furthermore, as the renewable fraction increases, the electricity available at low power prices will increase.

CTR - part of the Copenhagen Heat Network - is expanding electric boilers to 120 MW, powered by surplus wind electricity. (2020 Electric Kettle in a Green Energy System ?, Hot Cool 2020, No 2, p 12, http://www.e-pages.dk/dbdh/76/12).

Diversity Factor
This is a characteristic of all networks. (2001-09-02 Untersuchungen der Gleichzeitigheit in kleinen und mittleren Nahwaermenetzen, http://www.bios-bioenergy.at/uploads/media/Paper-Winter-Gleichzeitigkeit-Euroheat-2001-09-02.pdf).
For DH, the central plant (Combined Heat and Power and Heat Only Boiler etc) with much of the cost, can be downsized by e.g. 50%, while in the buildings, the low cost Heat Interface Unit and heat emitters are sized for 100%.
For gas networks, the central plant can be downsized by e.g. 50%, but in the buildings the gas boilers with much of the cost, and the heat emitters, must be sized for 100%.
For electricity networks, the central generating plant can be downsized by e.g. 50%, as can the distribution transformers, while in the buildings the heaters, whether resistive or heat pumps, where much of the cost lies, and the heat emitters must be sized for 100%.

DH networks are widespread, especially on the European continent. (2004 THE CASE FOR DISTRICT HEATING: 1000 CITIES CANNOT BE WRONG, https://projects.bre.co.uk/DHCAN/pdf/PolicyGuide.pdf).
Also there is considerable scope for expansion of DH in Europe, including the UK.
(2006-10-02 ECOHEATCOOL Work package 4 Possibilities with more district heating in Europe, https://www.euroheat.org/wp-content/uploads/2016/02/Ecoheatcool_WP4_Web.pdf).

Denmark passed the Heat Supply Act of 1979, whereby oil and electric heating was to be phased out, and cities divided into

DH and gas areas. Moreover, gas heating was to be allowed for only 15 years, until DH could replace it. Also all large power stations had to be built for CHP operation, supplying heat for DH networks. To take advantage of the above (safety, exergy, thermodynamic heat, reject heat, and renewable energy), DH supplies some 60% of the heated floor area in Denmark and Copenhagen should be carbon neutral for heating by 2025. (2019-05-21 This is how Copenhagen plans to go carbon-neutral by 2025, https://www.weforum.org/agenda/2019/05/the-copenhagen-effect-how-europe-can-become-heat-efficient/).

Local heat plans usually reflect population - and hence heat load - densities.
(MAYOR OF LONDON Heat Map, https://maps.london.gov.uk/heatmap
and: 2020 Heating and Cooling Data for All of Europe: HotMaps, Hot Cool 2020, No 2, p 8, http://www.e-pages.dk/dbdh/76/8)
These may be of three concentric zones. (Urban models in MEDCs, https://www.bbc.co.uk/bitesize/guides/zckdg82/revision/1)
High densities – as in Central Business Districts, hospitals and education campuses - are highly favourable for district heating.
Intermediate densities may be suited by natural gas and later replaced by district heating, including the 'Fourth Generation'. (4GDH definition, https://www.4dh.eu/about-4dh/4gdh-definition).
The lowest urban densities could be suited by heat pumps and rural buildings by heat pumps and various biofuels.
District heating should be deployed first in the centre where the heat load density is greatest. The high-rise buildings of the central business district bring the greatest return in heat sales per site area, and help to pay for wider deployment of DH.

DH can avoid the need for fresh water for evaporation in power station cooling towers. In the UK, this accounted for some 44% of fresh water abstraction. (2006-02 BALANCING WATER SUPPLY AND THE ENVIRONMENT, https://researchbriefings.parliament.uk/ResearchBriefing/Summary/POST-PN-259).
Using the DH system to cool the power station and heat the city saves water, energy, carbon and money.

1.3.2 (Individual) Electric Heat Pumps for Heat

All heat pumps require a heat source, usually either ambient air or the ground. Air source HPs need periodic automatic defrosting, which interrupts the heat output and incurs energy penalties. Ground source HPs may therefore be preferred, especially if the HP is reversible to Air Conditioning, but the ground heat exchanger (coil or borehole) is more expensive. However, a borehole, which is costly, can be shared between buildings via a low temperature, water-based (brine) network.

To avoid excessive use of the backup heater, which is often a resistive electric heater, Electric Heat Pumps (EHPs) require very careful design and sizing to the heat load, together with good controls. Any switch to the backup heater – especially if prolonged, as in failover – must be made obvious to the user, to enable diagnosis and repair.
(2012-03 Detailed analysis from the first phase of the Energy Saving Trust's heat pump field trial, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/48327/5045-heat-pump-field-trials.pdf).

With widespread deployment of EHPs, the Global Warming Potential of the refrigerant is very important. The preferred choice should be CO2, which has a GWP of only 1, and has been demonstrated by multiple equipment suppliers.

For more on District Heating and Heat Pumps for Heat, see Appendix 3.

1.3.3 Conclusions on Heat Measures

To decarbonise the heat sector, heat demands should be reduced by energy savings measures, such as insulation etc, in bulk rollouts wherever they are carbon cost effective versus heat supply. (2020-01-24 Smart Energy Aalborg: Matching end-use heat saving measures and heat supply costs to achieve least-cost heat supply, https://journals.aau.dk/index.php/sepm/article/download/3398/3184/).

The STRATEGO WP2 main report quantifies the impact of implementing various energy efficiency measures in the heating and cooling sectors of five EU Member States: Czech Republic, Croatia, Italy, Romania, and the United Kingdom.
Table 1 includes: United Kingdom: Heat Savings 40%, District Heating 70%, Individual Heating Technology – Heat Pumps etc (by difference) 30%. District Heat Supply from Renewable Heat & Excess Heat 45%. (This is defined as geothermal, solar thermal, large heat pumps, electric boilers, and excess heat from existing industrial and waste incineration plants. Biomass and excess heat from thermal power plants is not included in this share).
(2016-02-03 Enhanced Heating and Cooling Plans to Quantify the Impact of Increased Energy Efficiency in EU Member States, https://silo.tips/downloadFile/enhanced-heating-and-cooling-plans-to-quantify-the-impact-of-increased-energy-ef).

With high population and heat load densities, District Heating is the preferred solution for over 60% of the total, as in Denmark and other countries in Europe, while at low densities, heat pumps and some biomass/biofuels are preferred. There is no role for hydrogen in decarbonising the heat sector in the UK or elsewhere.

1.3.4 Deploying the Decarbonisation of Heat

For deploying District Heating, the government has launched the Heat Networks Investment Project.
(2018-12-21 Heat Networks Investment Project (HNIP): overview and how to apply,
https://www.gov.uk/government/collections/heat-networks-investment-project-hnip-overview-and-how-to-apply
and 2018-10-15 Delivering Financial Support for Heat Networks, England and Wales,
https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/748477/hnip-launch.pdf).
However, treating DH as a financial market is not appropriate when the national objective is zero carbon by 2050. Heat is a utility like water and sewage, and piecemeal installations and competition between networks makes no sense. Decarbonisation via energy savings measures, District Heating and Heat Pumps should not be made the responsibility of individual citizens, who lack both the skills and the access to low-cost capital. The 'Green Deal' was a failure, with only 15,000 issued from 2012 to 2015. (The Green Deal, https://en.wikipedia.org/wiki/The_Green_Deal).

Instead, local – e.g. city – authorities should follow a national outline plan and be responsible for commissioning and delivering decarbonisation of heat. The local heat plan includes dividing the area between a district heating network and a natural gas network, regardless of ownership of the buildings. In Denmark, the gas network area is often defined for only 15 years, after which it is expected to be converted to district heating. For the latter, the Heat Interface Units (HIUs) can be owned by the district heating company, so the owners or occupiers do not have to specify, buy or finance them and ownership of the buildings is immaterial.

DH is technically mature and bankable, so can be funded over long periods, such as 30 years, and financed with low-cost capital, borrowed at government rates. In Denmark, district heating and cooling systems are often non-profit consumer co-operatives or owned by the local authority. (2016 District Heating and Cooling – A Matter of Ownership. http://www.e-pages.dk/dbdh/53/9). This pattern has been used in Denmark for many decades, and enables decarbonisation to go ahead at much lower Internal Rates of Return (IRR). A for-profit Energy Service Company (ESCO) may require an IRR of 14%, but a Council-lead company in Denmark requires only 4%, when the approximate interest rate for borrowing capital is < 2%.
(2019 IRR: Internal Rate of Return and how it affects development of DH projects, http://www.e-pages.dk/dbdh/69/7).

Local authorities may also plan energy saving measures for all properties, regardless of ownership. There would be important economies of scale in equipment purchase and in deployment – e.g. street by street. Adjacent properties are usually of similar type and floor-plan, so insulation and other measures may be bought and installed in bulk at far lower cost and with much higher quality. Having both supply and demand measures in the same hands is almost essential for achieving 'smart', cost-optimal solutions. (2020-01-24 Smart Energy Aalborg: Matching end-use heat saving measures and heat supply costs to achieve least-cost heat supply, https://journals.aau.dk/index.php/sepm/article/download/3398/3184/).

Deploying energy savings measures, District Heating and Heat Pumps at scale would provide local jobs in every city, town and village in the country.

2 The role of hydrogen in achieving Net Zero – as Proposed by the BEIS and CCC

These are mentioned in: The role of hydrogen in achieving Net Zero
https://committees.parliament.uk/work/890/the-role-of-hydrogen-in-achieving-net-zero/
and: Call for evidence: The role of hydrogen in achieving Net Zero,
https://committees.parliament.uk/call-for-evidence/337/the-role-of-hydrogen-in-achieving-net-zero/
The Call for Evidence above also mentions this report from the CCC:
2020-06-25 Reducing UK emissions: 2020 Progress Report to Parliament, https://www.theccc.org.uk/publication/reducing-uk-emissions-2020-progress-report-to-parliament/

The proposals in the major reports from the BEIS and the CCC are considered in the light of Section 1 above.
The former includes mention of the Coalition for the Energy Efficiency of Buildings report.
This contains their proposals for the deployment of the measures for the decarbonisation of heat.

2.1 The BEIS Report:

2020-11-18 The Ten Point Plan for a Green Industrial Revolution (HTML version)
https://www.gov.uk/government/publications/the-ten-point-plan-for-a-green-industrial-revolution/title#point-2-driving-the-growth-of-low-carbon-hydrogen
Of which:
Point 2: Driving the growth of low carbon hydrogen,
and:

Point 7: Greener buildings
This includes:
'We will aim for 600,000 heat pump installations per year by 2028, creating a market led incentive framework to drive growth, and will bring forward regulations to support this especially in off gas grid properties. This ambition still leaves open the choice as to whether we ultimately pursue hydrogen heating, an electrified heating system, or a mixture of both, whilst we continue to pilot the options'.
This suggests that the options have already been chosen as hydrogen heating or electrified heating or a mixture of both, despite the claim in the Coalition for the Energy Efficiency of Buildings report to have considered international best practice. (2020-06-23 Financing energy efficient buildings: the path to retrofit at scale, Page 3, https://www.greenfinanceinstitute.co.uk/wp-content/uploads/2020/06/Financing-energy-efficient-buildings-the-path-to-retrofit-at-scale.pdf)

[This claim cannot be true since there is no practice of hydrogen heating worldwide. Also, the only country with widespread electrical heating is Norway. However, this has very large resources of hydro electricity and generally low population density. Moreover, the Danish Heat Plan of 1978 includes a fund for converting electric heating to natural gas heating and heat networks. Indeed, best practice in heating is widely recognised as heat networks, as practiced for many decades in Denmark and elsewhere, especially in Europe. (2004 THE CASE FOR DISTRICT HEATING: 1000 CITIES CANNOT BE WRONG, https://projects.bre.co.uk/DHCAN/pdf/PolicyGuide.pdf)].

And:
Point 10: Green finance and innovation
This includes:
'Case study: The Green Finance Institute – building partnerships to accelerate green finance

The Green Finance Institute, launched in July 2019 is led by Chair, Sir Roger Gifford, senior banker at SEB and former Lord Mayor of the City of London, and CEO, Dr Rhian-Mari Thomas OBE, former Barclays executive.

Seed funded by the UK government and the City of London Corporation, the Institute champions the UK's green finance brand internationally and brings together global experts and practitioners to co-design sector-specific solutions that channel capital towards a clean, resilient and environmentally sustainable economy.

The Institute's early successes have included establishing a Coalition for the Energy Efficiency of Buildings and subsequent Zero Carbon Heating Taskforce of over 200 expert members, launching a Green Finance Education Charter, developing the case for the UK's first Green Sovereign Bond from investors with more than $10 trillion assets under management and co-hosting the Green Horizons Summit, which featured global leaders from the public and private sector and attracted over 300,000 viewers across 90 countries'.

2.1.1 The Coalition for the Energy Efficiency of Buildings Report

2020-06-23 Financing energy efficient buildings: the path to retrofit at scale, https://www.greenfinanceinstitute.co.uk/wp-content/uploads/2020/06/Financing-energy-efficient-buildings-the-path-to-retrofit-at-scale.pdf
Page 3 includes:
'This report sets out the findings to date and the intended next steps of the Coalition for the Energy Efficiency of Buildings.
• Established by the Green Finance Institute in 2019, the Coalition brings together a powerful multistakeholder group focused on developing market solutions to scale up the finance needed to retrofit UK homes to high standards of energy efficiency, and deliver significant social and environmental benefits.
• Building on existing research, international best practices, and a focused review of the state of UK market for financing energy performance retrofits, the Coalition puts forward 21 scalable demonstrator projects, designed to overcome the barriers to mobilising capital towards the socialrented, private-rented and owner-occupied residential sectors.
• The Coalition will take forward a portfolio of these demonstrator projects, helping to practically demonstrate the viability of much-needed financing solutions for energy efficient buildings, both in the UK and across the globe, in the run-up to important UN climate talks to be co-hosted by the UK and Italy in 2021.
• The report identifies further government policy measures that would help bolster the commerciality and scalability of the demonstrators and respond to the social and economic impacts of the Covid-19 pandemic. A key recommendation is the inclusion of both energy efficiency and climate resilience investment in the government's economic recovery plans.
• The report outlines further areas of work the Coalition will explore with a growing network of stakeholders, as it continues its uniquely collaborative and pragmatic approach to this critical agenda'.
[This paper shows that best practice in mainland Europe has identified the mix of decarbonisation measures for buildings. What is needed now is not demonstrator projects, but local heat plans for all cities and towns, followed by deployment of such measures.

Pages 21-36 includes financial and legal proposals. These are needlessly complicated and would result in excessive fees and on-going charges. Individual houseowners cannot accept the risk or access low cost finance. As in Denmark, local authorities are best placed to procure the decarbonisation measures which carry very low risk and can be financed at government rates.

After all, local authorities plan and deliver (via contractors) all other services, such as access roads, water, sewage, electricity and gas. These are planned by professionals and bought in bulk in competitive markets. In best practice, as required in Denmark since 1978, the local authority plans and delivers (via contractors) a local heat plan consistent with the national heat plan, as part of the national decarbonisation plan].

2.2 The CCC Report

CCC Sixth Carbon Budget, https://www.theccc.org.uk/publication/sixth-carbon-budget/
There is a report of 448 pages and a series of presentations. The latter offer the shortest summaries:

https://www.theccc.org.uk/wp-content/uploads/2020/12/Unpacking-the-Sixth-Carbon-Budget-the-transition-for-buildings.pdf
Slide 24 Local Area Energy Planning. Mention of 'Zoning for Heat Networks'.
[The figure shows a patchwork of colours rather than the large contiguous areas needed for district heating].

https://www.theccc.org.uk/wp-content/uploads/2020/12/Unpacking-the-Sixth-Carbon-Budget-the-transition-for-energy.pdf
Slide 11 Fossil fuels largely phased out.
- Petroleum is mainly restricted to aviation.
[There is no scope for CO2 offset by other sectors, so aviation must use Renewable Synthetic Fuel]
- Natural Gas is limited to combustion with CCS for power generation and industrial processes, not buildings.
[These can be replaced by low cost renewables with pumped hydro storage, and by green hydrogen for industrial processes. (2020-01-22 Development of a Global Atlas of Off-River Pumped Hydro Storage, http://www.energypolicy.co.uk/2020-01-22_Pumped_Hydro_Storage_1f.pdf]
Slide 12 Hydrogen supply and demand.
[This paper finds no role for hydrogen in transport or heat]
Slide 14 Electricity generation mix. One source is named 'Firm power' (includes nuclear, see Slide 17).
'New sources of dispatchable low-carbon generation (e.g. gas CCS and/or hydrogen) to balance variable weather-dependent renewables'.
['Firm Power' and 'New Sources...' could be replaced by low cost renewables with pumped hydro storage]

https://www.theccc.org.uk/wp-content/uploads/2020/12/Unpacking-the-Sixth-Carbon-Budget-the-transition-for-manufacturing-construction-and-fossil-fuel-supply.pdf
Slide 29 CCS Infrastructure map
[Slide 17 in the 'Transition for Energy' presentation (above) shows Dispatchable low-carbon power at £80 to 185/MWh in 2050. This must cast doubt on the cost-effectiveness of CCS.
Also, natural gas is depletable and any sequestration volume is finite, so CCS is not sustainable, and there are risks of CO2 leakage over geological time. See Section 1.3 above]

https://www.theccc.org.uk/wp-content/uploads/2020/12/Unpacking-the-Sixth-Carbon-Budget-the-transition-for-transport.pdf
Slide 9 Key recommendations include: 'Budget scope. The budget should cover all greenhouse gas emissions, including those from international aviation and shipping, and removals of CO2 from the atmosphere'.
[This underlines the importance of achieving zero carbon for International Aviation and Shipping. See Section 1.2.3].
Slide 15 Proportion of new car sales that are BEVs.
[In the USA, the average vehicle lifetime is 16.6 years, and the time to replace 90% of the vehicle fleet is 19.6 years. (2019-02-15 Vehicle fleet turnover and the future of fuel economy, Page 2, https://iopscience.iop.org/article/10.1088/1748-9326/aaf4d2/pdf).
Assuming that the UK is similar, the transition to BEVs could be accelerated by grants or taxes].
Slide 19 Aviation, including flat demand.
[This differs from the projections of the International Civil Aviation Organization (ICAO), https://www.icao.int/environmental-protection/pages/climate-change.aspx].
Slide 21 Shipping. Mostly zero-carbon fuel by 2050.
[Neoline is building ocean-going wind assisted freighters offering carbon savings of 80%. https://www.neoline.eu/en/]
Slide 23 Recommendations for IAS (International aviation and shipping).
These include: 'Non-CO2 effects:
• We recommend a minimum goal that there should be no additional aviation non-CO2 warming beyond 2050.
• Further research is required to reduce scientific uncertainties and test mitigation options, but action on non-CO2 effects should not result in higher CO2 emissions'.

[See Section 1.2.4].

[Professor Julian Allwood recommends energy saving and increased energy efficiency - both conversion and cascading. His group is of long standing and based in the largest engineering department and one of the oldest universities in the country. They find the technical potential energy saving to be up to 85%. See Section 1.1 above].

https://www.theccc.org.uk/wp-content/uploads/2020/12/Unpacking-the-Sixth-Carbon-Budget-the-transition-for-Agriculture-and-Land-use.pdf
Slide 11 Changes in land use.
'Around one-third of agricultural land is freed up through changes in output and more efficient farming practices'.
[However, there is no recognition of:
- the need to replace much of the food at present imported from the EU and the USA.
- increases in population and standards of living, including food intake and diet - more meat.
- climate change reducing crop yields – through heat, pests, drought, and floods.
(2019-08-08 Climate crisis reducing land's ability to sustain humanity, says IPCC,
https://www.theguardian.com/environment/2019/aug/08/climate-crisis-reducing-lands-ability-to-sustain-humanity-says-ipcc).
In the case of the USA, this is being aggravated by soil degradation.
(2015-03-11 North American Soil Degradation: Processes, Practices, and Mitigating Strategies,
https://www.mdpi.com/2071-1050/7/3/2936/pdf).]
Slides 12, 14 Massive diet change is assumed.
[What if this does not happen ? What if the UK cannot pay for food imports ? Rationing or starvation ?]

(2020-12-09 The Sixth Carbon Budget The UK's path to Net Zero,
https://www.theccc.org.uk/wp-content/uploads/2020/12/The-Sixth-Carbon-Budget-The-UKs-path-to-Net-Zero.pdf).
Page 115 'Low-carbon heating in the Balanced Net Zero Pathway
By 2030 37% of public and commercial heat demand is met by low-carbon sources. Of this low-carbon heat demand 65% is met by heat pumps, 32% district heating and 3% biomass. By 2050 all heat demand is met by low-carbon sources of which 52% is heat pumps, 42% is district heat, 5% is hydrogen boilers and around 1% is new direct electric heating'.

[By 2050, all heat is zero carbon, with 42% district heat, 5% hydrogen boilers, 52% heat pumps and 1% direct electric.
Given the uncertainties of CCS, and thus for fossil-derived hydrogen, hydrogen boilers may not happen. Rather than producing hydrogen for heat by electrolysis with renewable electricity, the latter would be better used for district heating or heat pumps.

Choosing between these should take account of the Comparison of Heat Pumps and District Heating in Appendix 3.
The most important differences are:
Existing heat pumps can only deliver about 60 C under winter design conditions, whereas most UK dwellings have radiators designed for 80 C. Thus existing and new dwellings would require much higher radiator areas or underfloor heating.
District heating can deliver a water temperature of 80 C under winter design conditions to suit the radiators installed in most UK dwellings.

Electric heat pumps have a Coefficient of Performance (COP) at winter design conditions of about 3 to 4. If the peak electricity comes from thermal power stations with an efficiency of 0.5, the Thermodynamic Heating Efficiency (Heat Output/Fuel Input) would be about 1.5 to 2.
If district heating is supplied with heat from a Combined Heat and Power station with an electrical efficiency of 0.5, the Thermodynamic Heating Efficiency (Heat Output/Incremental Fuel Input) would be about 4. Even with 5 to 10% of peak heat and with transmission losses, the THE would still be about 3.3. This is about twice that of electric heat pumps.

Only district heating can harness waste and biomass, many sources of reject and renewable heat, and renewable electricity.

Denmark has already installed district heating to meet about 60% of the national heat load, and is developing a 'Fourth Generation' version to displace gas heating and compete with individual heat pumps. All this is available for inspection and is extensively reported on in English and other languages. (Danish Board of District Heating, https://dbdh.dk)].

Gordon Taylor, B.Sc., M.Sc., M.I.Mech.E.
Chartered Mechanical Engineer
19 The Vale, Stock, Ingatestone, Essex, CM4 9PW, U.K.
Tel: +44(0)1277 840569
Email: gordon@energypolicy.co.uk
Web: http://www.energypolicy.co.uk

Appendix 1 More on Hydrogen as an Option for Transport

Flammability, Leakage, Embrittlement

'Yet, hydrogen has its own major safety issues. It is highly flammable with an ignition energy 20 times smaller than that of natural gas or gasoline. It can be ignited by cell phones and electrical storms located miles away. Hence, leaks pose a significant fire hazard. At the same time, it is (one of) the most leak-prone of gases. Odorants like sulfur are impractical, in part because they poison fuel cells. Hydrogen burns nearly invisibly, and people have unwittingly stepped into hydrogen flames. Hydrogen can cause many metals, including the carbon steel widely used in gas pipelines, to become brittle. In addition, any high-pressure storage tank presents a risk of rupture. For these reasons, hydrogen is subject to strict and cumbersome codes and standards, especially when used in an enclosed space where a leak might create a growing gas bubble.

Some 22% or more of hydrogen accidents are caused by undetected hydrogen leaks. This "despite the special training, standard operating procedures, protective clothing, electronic flame gas detectors provided to the limited number of hydrogen workers," as Russell Moy, former group leader for energy storage programs at Ford Motors has wrote in the November 2003 Energy Law Journal. Moy concludes "with this track record, it is difficult to imagine how hydrogen risks can be managed acceptably by the general public when wide-scale deployment of the safety precautions would be costly and public compliance impossible to ensure." Thus, major innovations in safety will be required before a hydrogen economy is practical'.

(2004-03-03 Reviewing the Hydrogen Fuel and FreedomCAR Initiatives, https://biomassboard.gov/pdfs/romm.pdf *)*.

Energy Density

The volumetric energy density of hydrogen is less than one-third that of natural gas (mostly methane). This affects both fuel storage and the power capacity of pipelines and networks. (See below).

Hydrogen fuelling infrastructure

Hydrogen is usually bulk stored and distributed as a gas at high pressure, e.g. 200 bar, and then dispensed at e.g. 800 bar to be stored in the vehicle tank at e.g. 700 bar. But the compression of gases is energy-intensive. (See below).

Another possibility is storage and distribution as liquid hydrogen, but this involves extremely low temperatures, about – 253 C. Even with highly effective insulation, this results in boil-off losses from storage, both in bulk and in the vehicle.

For the CUTE bus project, bulk storage of liquid hydrogen was used in London at the Hornchurch depot. However, the boil-off losses were excessive. (2009 HYDROGEN TRANSPORTS, p 13, http://www.eltis.org/sites/default/files/case-studies/documents/hfc_brochure_10_12_09_4.pdf).

'Moreover, liquid hydrogen storage systems lose some hydrogen gas by boil-off. This is due to unavoidable heat leakage, and must be permitted for safety reasons. The loss rate is dependent on the size of the store, but would be significant for those used in vehicles, and may amount to 3 to 4 per cent a day [16]. While this gas may be used when the vehicle is operated, it would have to be vented if the vehicle was parked. For example, if parked at an airport for 14 days, the loss of hydrogen could be 50 to 60 per cent'.

(2003-04-15 The Future of the Hydrogen Economy: Bright or Bleak?, p 15. http://cms.energypolicy.co.uk/transport/254).

'Yet, a 2002 analysis by Argonne National Laboratory found that even with improved technology, "the hydrogen delivery infrastructure to serve 40% of the light duty fleet is likely to cost over $500 billion."'

(2004-03-03 Reviewing the Hydrogen Fuel and FreedomCAR Initiatives, p 5, https://biomassboard.gov/pdfs/romm.pdf).

Leakage, boil-off and the risk of accidents

Leakage, boil-off and the risk of accidents may exclude hydrogen-fuelled vehicles from underground parking garages and long tunnels such as the Channel Tunnel and the Alpine tunnels.

(2009-02-20 HYTUNNEL, http://www.hysafe.net/download/1763/Hyunnel_Final%20ReportDraft_20Feb09_final.pdf

and: 2017 Risks associated with alternative fuels in road tunnels and underground garages, https://www.diva-portal.org/smash/get/diva2%3A1081095/FULLTEXT01.pdf).

Well-to-Tank Efficiency

Here is an analysis, based on the applicable scientific laws and best-practice technologies, of the production, packaging (by compression and liquefaction) and delivery of hydrogen as a transport fuel.

The Abstract includes:

'The analysis reveals that much more energy is needed to operate a hydrogen economy than is required for fossil energy supply and distribution today. In fact, the input of electrical energy to make, package, transport, store and transfer hydrogen may easily exceed the hydrogen energy delivered to the end user - implying an well-to-tank efficiency of less than 50 per cent. However, precious energy can be saved by packaging hydrogen chemically in a synthetic liquid hydrocarbon like methanol or ethanol'.

[Or 'drop-in' fuels, such as gasoline (petrol), aviation kerosene and diesel].

Pages 29, 30 'Even assuming ideal processes and current industrial practice, the analysis reveals that considerable amounts of energy are lost between the electrical source energy and the hydrogen energy delivered to the consumer. For road delivery of compressed hydrogen, Path A, the electrical energy input exceeds the HHV energy of the delivered hydrogen by a factor of at

least 1.69. In the case of liquid hydrogen, Path B, the factor is at least 2.12. For on-site hydrogen production, Path C, the factor is at least 1.69. For delivery of hydrogen by chemical hydrides, Path D, the factor is at least 1.95. It is unlikely that any of these would be attractive. Hence elemental hydrogen may provide practical solutions in some niche markets, but it cannot become important in a future energy economy.
Today, the losses between oil wells and filling stations for transportation, refining and distribution, are about 12%. Thus the well-to-tank efficiency of gasoline is about 88 per cent, and is slightly higher for diesel fuel. As shown above, in an elemental hydrogen economy, depending on the path chosen and even assuming many ideal processes, the upstream losses would be much higher, at 69% to over 100%. Hence even in the best attainable case, the well-to-tank efficiency on an HHV basis cannot be much above 50%'.
'All the losses with the elemental Hydrogen Economy are directly related to the nature of hydrogen. Hence they cannot be significantly reduced by any amount of research and development. We have to accept that hydrogen is the lightest element and its physical properties do not suit the requirements of the energy market. The production, packaging, storage, transfer and delivery of the gas are so energy consuming that other solutions must be considered. Mankind cannot afford to waste energy for uncertain benefits; the market economy will always seek practical solutions and, as energy becomes more expensive, select the most energy-efficient. Judged by this criterion, the elemental "Hydrogen-Economy" can never become a reality'.
(2003-04-15 The Future of the Hydrogen Economy: Bright or Bleak?, http://cms.energypolicy.co.uk/transport/254).

Hydrogen in ICE Vehicles
At inlet to an IC engine hydrogen is a gas with a volumetric energy density about one-third that of methane, and about 12.7/(34 x 1000) = 1/2677th that of liquid gasoline or diesel fuel. So the hydrogen gas allows much less air into the cylinder and the volumetric efficiency of the IC engine is very low, and has to be offset by a very large engine displacement.
There were early experiments by Roger Billings, latterly with large displacement engines (V8s).
(Hydrogen Fuel Cars 1807 – 1986, http://www.hydrogencarsnow.com/index.php/1807-1986/).

BMW developed and produced 100 cars with large displacement V12 engines, and refuelling robots for the liquid hydrogen.
(BMW Hydrogen 7, https://en.wikipedia.org/wiki/BMW_Hydrogen_7)
Liquefaction of hydrogen requires large amounts of energy and storage at – 240 C. Even with best-practice insulation, the hydrogen tanks suffer significant boil-off losses. These can empty the tank when parked for e.g. a fortnight at an airport. Also such low temperatures can cause severe burns, so fuelling is best done via robots.
(2016-08-17 Why Did BMW Really Stop Making the Hydrogen 7 Model?, https://www.bmwblog.com/2016/08/17/bmw-stop-making-hydrogen-7-model/).

Hydrogen in Fuel Cell Vehicles
IC engines suffer from the irreversibility of combustion of about 33%. (1994-10-05 Sources of combustion irreversibility, https://www.researchgate.net/profile/Noam_Lior/publication/245311845_Sources_of_Combustion_Irreversibility/links/5423fe840cf26120b7a70d2c/Sources-of-Combustion-Irreversibility.pdf)
Fuel cells avoid this but Proton Exchange Membrane (PEM) cells have significant voltage losses. These are about 29% at no load, and increase with load. (2017 Fuel Cells and the Self Ignition Temperature of Hydrogen, Ulf Bossel, https://iopscience.iop.org/article/10.1149/07801.2365ecst/pdf
and 2017-04-25 Why a OCV of 1.23 Volt cannot be obtained, Ulf Bossel, https://www.youtube.com/watch?v=cIm4rFZeeEQ).
The conversion efficiency can be 60%, and at high load, 40%. The latter is only similar to the best IC engines.

Fuel Cell Electric Vehicles (FCEVs) are similar to Plug-in Hybrid Electric Vehicles (PHEVs), as Battery Electric Vehicles (BEVs) with range-extenders, in this case a fuel cell. Yet fuel cells and their onboard fuel storage are more costly than ICEs and their fuel tanks. This assumes that the batteries and electric motors are the same for both vehicle types.

Here are four references to the CUTE project on hydrogen fuel cell buses in Europe:

1) 2004-03-03 Report of the Transport Select Committee Visit to Transport for London
https://publications.parliament.uk/pa/cm200304/cmselect/cmtran/319/31917.htm
This includes:
'76. The three London buses are part of a two year trial under the CUTE project (Clean Urban Transport for Europe). BP provides the hydrogen at a temporary fuelling station in Hackney, and the fuel company is seeking permission for a permanent facility in Hornchurch.[270] BP would open this facility up to other projects.

77. The buses can travel approximately 150 km on the hydrogen gas stored onboard in nine tanks. Each of the participating cities is obtaining the gas by different means and Natural Gas is the source of the hydrogen for the London buses. Although using Natural Gas to produce hydrogen does emit carbon dioxide, we were told there was a reduction of 40 per cent compared to emissions from a diesel engine. TfL predicted it would be at least 10 years before the buses would be commercially available. TfL will also have 12 hybrid diesel vehicles by the end of 2004.

78. As part of the pilot project, the fuel cells are serviced by technicians every 80 hours and the buses have daily checks on performance and safety. TfL explained there had been some teething problems with the vehicles initially, but there is a good reaction with both drivers and passengers. The buses are reported to be slightly more 'sluggish' on the uptake than conventional buses, but smoother and quieter once running'.

2) 2008-07-28 london's hydrogen buses, http://bristlingbadger.blogspot.com/2008/07/londons-hydrogen-buses.html
This includes:
'CUTE's own report on their trial says that when the hydrogen was made from natural gas, the buses had around two and a half times the climate impact of using normal diesel buses(8), ..'
And:
'CUTE did their own maths and calculated that grid electrolysis generates 4.71 times the emissions of a diesel bus(18), ...'
(This was when grid electricity was much more carbon intensive).
And:
'So, even if the hydrogen itself were made of thin air and utterly carbon-free, a bus using liquid hydrogen is responsible for nearly three times the emissions of a diesel bus simply for the liquefaction process'.

3) 2010-04 Hydrogen as a fuel source for vehicles. Options for a hydrogen bus energy supply system based on Economic & Environmental considerations, C.A. Berridge, http://oro.open.ac.uk/60737/1/528247.pdf
Page 2 includes:
'Overall, the results of this research will show that:-
• Hydrogen is potentially competitive with diesel in terms of cost of production, but not for cost of distribution. Overall distribution costs make hydrogen pathways more expensive than diesel.
• Localised production of hydrogen is not competitive with centralised production at present. So it is likely that a hydrogen distribution system is going to be needed It is possible that future localised production systems may be competitive but would depend on reduced capital equipment costs.
• The cheapest hydrogen pathways may not be the pathways with the least emissions
• The storage of hydrogen appears to be a major part of distribution costs.
• Gaseous hydrogen delivery by road tanker can only meet small niche markets
• Transporting hydrogen in liquid state is not viable for any supply chain lengths and demands in the UK (within the boundaries of this model ie: 200km and 5,000kg/day).
• Gaseous hydrogen delivery by pipeline is needed if a reasonable uptake is sought. This would require significant investment'.

4) 2015-09-09 Fuel Cell Electric Buses – Potential for Sustainable Public Transport in Europe,
https://www.fuelcellbuses.eu/sites/default/files/documents/150909_FINAL_Bus_Study_Report_OUT_0.PDF
Page 4 includes:
'Environmental benefits extend well beyond zero local emissions. Hydrogen as a road fuel yields significant potential for carbon neutrality on a well-to-wheel basis along the entire hydrogen value chain, including production and means of delivery. Hydrogen can be produced with electricity from 100% renewable energy sources. Hence, operating FC buses can be achieved with zero CO2 emissions along the entire hydrogen value chain. By using hydrogen produced from renewable energy sources only, one standard FC bus would save approximately 800 tonnes of CO2 in its lifetime of 12 years compared to a conventional diesel bus'.

[This assumes that hydrogen is made by electrolysis, compressed to 350 bar and delivered to the refuelling station using 100% renewable electricity or fuel. But if the fuel used for delivery is 100% renewable, it could be used directly in a diesel bus].

[1) is factual. 2) and 3) are highly critical of the CUTE project. 4) is the official report and makes very optimistic assumptions].

BMW are now developing cars with hydrogen fuel cells.
(2020-07-25 BMW to pilot second-generation hydrogen fuel cell drives in small series from 2022,
https://www.greencarcongress.com/2020/07/20200725-bmw.html).
This includes:
'The BMW Group will pilot the second generation of hydrogen fuel cell drives in a small series in the BMW i Hydrogen NEXT based on the current BMW X5 from 2022. The fuel cell stack and the overall system are original developments of the BMW Group; individual cells of the fuel cell will come from Toyota.
The BMW Group has been working with Toyota Motor Corporation on fuel cell drive systems since 2013. Since summer 2015, the BMW Group has been testing development vehicles based on the BMW 5 Series GT, which are equipped with a jointly developed fuel cell system'.
And:
'Two 700 bar tanks are housed in the vehicle itself, which together hold six kilograms of hydrogen'.
[6 kg is the equivalent of 6 US gallons of gasoline. This implies a range perhaps half that of a gasoline-fuelled ICEV].

MAN of Germany are developing both H2-ICE and H2-FC for trucks and buses etc.
(2020-10-20 MAN presents hydrogen roadmap; use in fuel cells and combustion engines, https://www.greencarcongress.com/2020/10/20201020-man.html).
This includes:
'Apart from the rapid development of battery technology, hydrogen is a good complementary option as an alternative fuel for long-distance transport. MAN plans to build prototype vehicles as early as next year in line with the currently ongoing development projects. MAN is testing both the use of a fuel cell and an H2 combustion engine.
When in use, fuel cells do not cause any climate-damaging emissions, as they only emit water vapor. In addition, thanks to the on-board power generation, their range of approximately 800 km is large enough for long-distance truck transport with a high payload.
The hydrogen combustion engine, on the other hand, offers a more readily available and robust solution thanks to the well-known basic technology and could thus serve as a bridging technology.
Practical trials in cooperation with selected customers are planned for 2023/24. The aim is to test the entire hydrogen ecosystem in transport logistics'.

ITM Power of the UK have a capacity to build electrolysers up to 1 GW/y.
(2019-10-30 ITM Power: Bessemer Park, 1GW per annum electrolyser manufacturing facility, https://www.youtube.com/watch?v=zWiFJ5NKz0c&feature=emb_title).

Appendix 2 More on Hydrogen as an option for Heat

Safety
Gas heating poses risks of fire and explosion for all buildings and these can be disastrous for high-rise buildings. (Grenfell Tower fire, https://en.wikipedia.org/wiki/Grenfell_Tower_fire and Ronan Point, https://en.wikipedia.org/wiki/Ronan_Point).
These risks would be particularly high for hydrogen as it very prone to leakage and the flammability range is very wide at 4 to 75% by volume. (2017 Risks associated with alternative fuels in road tunnels and underground garages, p 28, https://www.diva-portal.org/smash/get/diva2%3A1081095/FULLTEXT01.pdf).

'New hydrogen meters and sensors would have to be fitted to every building in a hydrogen conversion program and appliances would have to be converted unless the government was to legislate to make them hydrogen-ready in advance'.
(2013-05-09 Conversion of the UK gas system to transport hydrogen, Abstract, https://www.sciencedirect.com/science/article/pii/S0360319913006800?via%3Dihub).

Combustion
For boilers with simple burners and open-loop control, as now, the gas must have a Wobbe Number within a small range for safe combustion. So the gas network can allow only maybe 15 to 20% of hydrogen to dilute natural gas (mostly methane).
'All appliances sold after 1996 must be able to sustain 23% hydrogen under current regulations'.
(2020-01-24 Zero-carbon hydrogen injected into gas grid for first time in groundbreaking UK trial, https://www.theguardian.com/environment/2020/jan/24/hydrogen-uk-gas-grid-keele-university).
To allow the use of 100% hydrogen would require replacement of all the burners and controls – in practice all the boilers. If the boiler and fuel changeovers overlapped, rather than occurring together, the boilers would have to be equipped with more costly closed loop controllers, to allow the safe use of 100% methane to 100% hydrogen.

Network Capacity
The network power capacity depends on the volumetric energy density and the pipe diameter after lining with plastic pipe to reduce the leakage of methane. With hydrogen, the lower volumetric energy density reduces network capacity to 12.7/40 = 32%. I assumed that lining reduced the pipe diameter to 70% of the original, which would reduce the flowrate to 0.7^2 = 49%. The combined effect might reduce the network power capacity and the linepack (energy) storage of the gas grid to about 0.32 x 0.49 = 16% - i.e. by 84%. This is so low that even if the problems of safety, combustion, and leakage could be solved, it might well prevent the use of 100% hydrogen in the existing gas network. This could require very extensive and expensive replacements to carry the heat load.

2013-05-09 Conversion of the UK gas system to transport hydrogen, Paul Dodds and Stephanie Demoullin, UCL., https://www.sciencedirect.com/science/article/pii/S0360319913006800/pdf
The Abstract includes:
'We conclude that hydrogen can be transported safely in the low-pressure pipes but we identify concerns over the reduced capacity of the system and the much lower linepack storage compared to natural gas. New hydrogen meters and sensors would have to be fitted to every building in a hydrogen conversion program and appliances would have to be converted unless the government was to legislate to make them hydrogen-ready in advance'.

2016-07-05 H21 Leeds City Gate, (A study by Northern Gas Networks and others),

http://www.northerngasnetworks.co.uk/wp-content/uploads/2016/07/H21-Report-Interactive-PDF-July-2016.pdf
The Executive Summary includes:
'Even natural gas (predominantly methane), the lowest carbon dioxide emitter per unit of energy of any fossil fuel, produces about 180 gm/kWh CO_2 equivalent whereas hydrogen emits zero (at the point of use). The change over from natural gas to hydrogen has the potential to provide a very deep carbon emission reduction.
The true carbon footprint of hydrogen depends on its source. For example, grid power electrolysis has very high emissions whereas hydrogen made from stripping the carbon atom from natural gas has about 50 gm/kWh CO_2 equivalent including indirect emissions, a large reduction over the existing unabated natural gas fuel. Renewable based electrolysis could be used, but for the foreseeable future the required quantities do not look realistic.
This report suggests that we can significantly decarbonise parts of the existing gas network at minimal additional cost to consumers. This would significantly contribute to the UK's 2050 and Paris Agreement commitments, remove the risks of carbon monoxide poisoning, increase energy storage, potentially remove air pollution from vehicles, and enable new product development and innovation for manufacturing and industrial businesses'.
And:
'Over 80% of the UK population now use this gas network for heating and cooking. A hydrogen conversion would follow a similar process to the original town gas to natural gas conversion undertaken so successfully and within living memory. The process will involve minimal disruption for the customer (domestic or commercial) and require no large scale modifications to their property.
Since 2002, the UK has been undertaking the Iron Mains Replacement Programme (IMRP), upgrading the majority of its distribution pipes to polyethylene. This is a risk prioritised, Health and Safety Executive mandated initiative due to complete in 2032. These polyethylene pipes are considered to be suitable for transporting 100% hydrogen'.

2017-08-07 Trial to phase in hydrogen as fuel to begin in north-west,
https://www.theguardian.com/business/2017/aug/07/trial-to-phase-in-hydrogen-as-fuel-to-begin-in-north-west
This includes:
'The existing gas network also meant there was a ready-made way to distribute it.
But to fully switch to hydrogen, the 26m gas boilers in the UK would need to be swapped for hydrogen-compatible models. About 85% of homes are heated by gas. "It does require changes in people's homes and it is likely to be expensive, so we are looking at a number of alternative pathways," said Parkin.
That is the reason for the Liverpool-Manchester scheme's initial focus on industrial users. The area was selected because it has a population of 5m and represents about 11% of Britain's industrial sector. As well as reducing the number of boilers that need to be converted, industrial heat demand is relatively steady compared with the fluctuating demand from homes, which would probably require the company to build hydrogen storage, an additional cost.
The carbon savings will come from the way the hydrogen is produced. It will be made from natural gas using a method known as steam reforming, but Cadent's plan is to capture the carbon monoxide and small amount of carbon dioxide generated during the process.
The captured carbon will be pumped using existing pipelines and stored in Hamilton gas field in the Irish sea, which is due to be decommissioned in the early 2020s – a cost that could be avoided if the facility is repurposed as a repository for carbon.
Whether the project goes ahead depends on tests underway on a private gas network at Keele University to identify how much hydrogen can safely be mixed in with methane for heating.
An investment decision in the early 2020s would mean construction starting in the middle of the next decade.
As a regulated monopoly, Cadent's costs would ultimately be borne by energy bill payers, though the regulator Ofgem would have to approve the anticipated £600m capital cost'.

2020-06-01 Positive results from the UK's first grid-injected hydrogen pilot based at Keele University, (HyDeploy),
https://www.keele.ac.uk/discover/news/2020/june/hydeploy-update/pilot-positive-results.php
This includes:
'HyDeploy, now well into its pilot period, is a ground-breaking green energy demonstration that is supplying a blend of up to 20% hydrogen by volume with natural gas to 130 homes and faculty buildings at Keele University.
The project is demonstrating that a blend of up to 20% hydrogen can reduce climate-damaging carbon emissions from heating the nation's homes, while at the same time enabling customers to use their gas supply as normal, without any changes needed to gas appliances or pipework.
Results so far show that gas appliances using the blend are functioning normally and no differences to the gas supply in houses and businesses has been reported. The project is also, for the first time in the UK, gathering views of those using a hydrogen blend in their homes'.

[However 20% hydrogen, even if renewable, is nothing like enough for the UK to meet it's climate targets].

Appendix 3 More on Heat Pumps and District Heating

Disadvantages of heat pumps:

- Heat pumps would have to deliver a water temperature of 80 C under winter design conditions, to suit the radiators installed in most UK dwellings.
- Each has to be sized for the maximum load possible for each building – i.e. at maximum occupancy, with high hot water demands. If not, it would switch on the backup resistance heater – greatly adding to the electricity load in cold weather.
- Air source heat pumps build up frost on the outdoor coil in the moist UK winter. This has to be removed periodically – usually by reversing the heat pump cycle – during which time heat is pumped out of the building.
- The Coefficient of Performance (COP) (Heat Out/Power In) of electric heat pumps at winter design conditions is about 3 to 4. If the peak electricity comes from thermal power stations with an efficiency of 0.5, the Thermodynamic Heating Efficiency (Heat Output/Fuel Input) would be about 1.5 to 2.

Advantages of district heating:
- It can deliver a water temperature of 80 C under winter design conditions to suit the radiators installed in most UK dwellings.
- Each Heat Interface Unit would be sized for the maximum load possible for each building – i.e. at maximum occupancy, with high hot water demands. However, the central plant need meet only half of the total heat demand, due to diversity.
(2001-09-02 Untersuchungen der Gleichzeitigheit in kleinen und mittleren Nahwaermenetzen, http://www.bios-bioenergy.at/uploads/media/Paper-Winter-Gleichzeitigkeit-Euroheat-2001-09-02.pdf).
- District heating delivers heat continuously, even under 'frosting' conditions.
- If supplied with heat from a Combined Heat and Power station with an electrical efficiency of 0.5, the Thermodynamic Heating Efficiency (=Heat Output/Incremental Fuel Input) would be about 4. Even with 5 to 10% of peak heat and with transmission losses, the THE would still be about 3.3.
(2003-01-19 'Energy Solutions for 60% Carbon Reduction, Part 1', p 10, http://cms.energypolicy.co.uk/allsectors/248).
This is about twice that of electric heat pumps.

Individual heat pumps have moving parts, such as compressors, and – for air source – fans. Having outputs much higher than refrigerators, they emit some noise in operation. Conversely, the building Heat Interface Units of district heating systems contain only pumps of 10s of Watts, which are silent in operation.

District heating central plants and networks are installed and run by professionals ensuring reliable service, low emissions, energy efficiency, water quality and good maintenance, so have long lives.
However, individual heat pumps are often poorly installed, run by end-users, and poorly maintained, so have short lives.

Low Carbon Aviation Fuel Projects **Gordon Taylor** **2020-07-15**

Carbon Supplier	**Hydrogen Supplier**	**Fuel Synthesis**	**Fuel Output**
* World Energy SAF project, USA, with Lufthansa and Shell, https://www.worldenergy.net/products/sustainable-aviation-fuel-saf/			
Bio-wastes	???	???	35000 tons/year
* Sky NRG project DSL-01 in Delfzijl, https://skynrg.com/press-releases/klm-skynrg-and-shv-energy-announce-project-first-european-plant-for-sustainable-aviation-fuel/			
Bio-wastes	Nouryon and Gasunie	F-T from Haldor Topsoe	100000 tonnes/year (2022)
* Bayou Fuels, Natchez, USA, https://www.velocys.com/projects/bayou-fuels/			
Woody biomass	<none>	F-T from Velocys	~ 77600 tonnes/y
* Altalto project in Immingham, UK, with British Airways and Shell, https://www.altalto.com/			
Bio-wastes	Electrolyser (PEM) from ITM	F-T from Velocys	~ 48000 tonnes/y (mid-2020's)
* Rotterdam The Hague Airport project by EDL Anlagenbau and SkyNRG, https://www.thechemicalengineer.com/news/producing-sustainable-aviation-fuel-in-the-netherlands/			
CO2 (DAC) from Climeworks	Electrolyser (SOEC) from Sunfire	F-T from INERATEC	1000 litres/day
* Norske e-Fuel project, https://www.norsk-e-fuel.com/en/			
CO2 (DAC) from Climeworks	Electrolyser (SOEC) from Sunfire	F-T from INERATEC	8000 tonnes/year (by 2023)

CO_2 (DAC) from Climeworks	Electrolyser (SOEC) from Sunfire	F-T from INERATEC	80000 tonnes/year (by 2026)

* Repsol project, Bilbao, Spain, https://www.repsol.com/en/press-room/press-releases/2020/repsol-to-develop-two-major-emissions-reductions-projects-in-spain.cshtml

CO_2 from nearby Petronor refinery	???	???	~ 2400 tonnes/year (in 2024)

* Copenhagen project, https://presscloud.com/file/33/330870924970883/Fact_sheet.pdf

<none>	10 MW	N/A	Hydrogen only (in 2023)
CO_2 from waste incineration	250 MW	???	~ 42000 tons/y (by 2027)
CO_2 from waste incineration	1.3 GW	???	250000 tons/y (in 2030)

(January 2021)