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Towards 2050 net zero carbon infrastructure: a critical review of key decarbonization challenges in the domestic heating sector in the UK

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ABSTRACT

One of the most challenging sectors to meet "Net Zero emissions" target by 2050 in the UK is the domestic heating sector. This paper provides a comprehensive literature review of the main challenges of heating systems transition to low carbon technologies in which three distinct categories of challenges are discussed. The first challenge is of decarbonizing heat at the supply side, considering specifically the difficulties in integrating hydrogen as a low-carbon heating substitute to the dominant natural gas. The next challenge is of decarbonizing heat at the demand side, and research into the difficulties of retrofitting the existing UK housing stock, of digitalizing heating energy systems, as well as ensuring both retrofits and digitalization do not disproportionately affect vulnerable groups in society. The need for demonstrating innovative solutions to these challenges leads to the final focus, which is the challenge of modeling and demonstrating future energy systems heating scenarios. This work concludes with recommendations for the energy research community and policy makers to tackle urgent challenges facing the decarbonization of the UK heating sector.

KEYWORDS

Heating decarbonisation; hydrogen integration; housing retrofit; energy justice; heating scenarios modelling

1. Introduction

A wide set of decarbonization programs and policies exist globally that attempt to generate market signals, redirect investments, encourage (or mandate) low-carbon technology adaption and support green growth while simultaneously mitigating the impact of climate change. Among these, a notable range of activities concern the decarbonization of energy systems. For example, in the United Kingdom (UK), this has resulted in the last two office of governments drafting policy commitments to guide the economy toward a net zero carbon (NZC) status by 2050. In the press release of Department for Business, Energy and Industrial Strategy (2021b), it has been highlighted that this process is structured through a phased approach of 5-year carbon budgets in which the last (6th) legislated carbon budget (2033–2037) aims to achieve a greenhouse gases (GHG) reduction of 78% by 2035 (against 1990 baseline).

The future energy scenarios developed by National Grid (2020, 1–166) show that the energy system decarbonization relies on a pivotal role for the electricity grid that, through increased renewable generation, smart controls, storage and flexibility, will be decarbonized by 2035 ahead of the 2050

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target. Among the most difficult sectors to decarbonize is the domestic heating sector. This sector can be decarbonized by decreasing the use of natural gas boilers and substituting that with hydrogen, heat pumps, biomass/biogas inherited heat networks, and improving the building fabric. For example, the UK's 2020 Energy White paper suggests, in addition to improving the building fabric, an annual installation of 600 K heat pumps (by 2028) and 5 GW of hydrogen production (by 2030) to decarbonize the UK heating sector (National Grid 2020, 1–166). Natural gas, which is used to heat approximately 85% of households within the UK, is predicted to be mixed with biomass or hydrogen as highlighted by National Grid (2020, 1–166) and Lovell and Foxon (2021, 147–158). These efforts, in aggregation, form a complex and time-constrained portfolio of solutions that as well as political and market forces, are impacted by the speed by which individual members of society are prepared to move and adapt.

Morris et al. (2022) have identified challenges of decarbonization of domestic heating to be: the technological and behavioral engagement of the consumers and businesses to achieve the required changes for heating decarbonization; short-sighted government strategy; unclear long-term strategy for the existing infrastructure such as the gas network and inefficient building stock; insufficient supply chain; and the high cost associated with heating decarbonization. This work offers an up-to-date perspective on dominant themes in the decarbonization of heating, which expands on those challenges previously identified. We consider broader techno-economic and societal challenges of decarbonizing the heating systems. Starting with the supply end, the role of hydrogen energy and its potential is investigated. This is followed by the end-user challenges, including that of building retrofit in the UK by considering several case studies. In the ensuing discussions, the role of digital energy and IoT infrastructure and how these can ease and speed up NZC energy transitions are outlined. The dilemma of how to ensure the transition remains fair and avoids penalizing vulnerable groups and creating additional, or exacerbating existing, fuel poverty is also examined. Informing the policy-makers, businesses, main stakeholders, and end-users about the technical-economic-environmental impacts of the technologies and solutions for decarbonization of the heating sector require the development of models and demonstrators, which is itself considered another unique challenge. Current state-of-the-art energy system models and demonstrators are reviewed, the fundamental inferences that are generated are highlighted, and the gaps that remain are outlined for the research community to resolve.

The challenges facing the decarbonization of the heating sector in the UK, which will be discussed in this paper, are identified after a careful review of the future decarbonization scenarios set by National Grid (the Electricity System Operator for Great Britain). Hence, these scenarios will be first discussed and analyzed. Then, each of the challenges facing these scenarios will be discussed. After that, recommendations for the energy research community and policymakers to tackle these challenges will be given. Finally, the applicability of these recommendations designed for the UK for the other European Countries will be discussed.

2. Quantitative overview of domestic heat decarbonization in the UK

A wide range of net-zero energy scenarios (NZES) have been developed by different bodies in the UK, such as the National Grid and the Climate Change Committee (CCC). These NZES assume a range of energy demands, supply mixes and carbon emissions. Further, they also have assumptions about the energy demands and the power capacities and energy outputs of key technologies and these are specified with varying levels of detail. In addition to National Grid and CCC, the Department of Business, Enterprise, Industrial Strategy (BEIS) (now Department for Energy Security & Net Zero) publishes every year energy projections for analyzing and projecting future energy use and greenhouse gas emissions in the UK (Department for Business, Energy & Industrial Strategy 2021a). These projections are based on assumptions of future economic growth, fossil fuel prices, electricity generation costs, UK population and other key variables regularly updated. This paper will use the four scenarios developed by National Grid (National Grid 2021) to quantitatively highlight the challenges associated with heating decarbonization in the UK. The rationale for this choice stems from the fact that the FES scenarios are developed by the UK's electricity and gas transmission network's system operator. These scenarios employ historical electricity and gas demand data, alongside projections related to economic output, energy prices, and the adoption rates of energy efficiency measures and end-use technologies. Through regression analyses, these factors are utilized to generate forecasts for energy demand across the residential, commercial, and industrial sectors of the UK economy. Moreover, the FES scenarios are based on different changes in energy demand, differing rates of technology uptake for various technologies, and distinct levels of flexibility in energy consumption. Contrastingly, the exploratory scenarios by CCC are based on varying levels of optimism concerning credible amounts of behavioral changes and the decreasing costs of key technologies. These scenarios rely on government datasets and research from the energy systems community to derive demand projections (Dixon, Bell, and Brush 2022; Johnson, Betts-Davies, and Barrett 2023). In relation to the scenarios developed by BEIS, these instances explore the implications of a significantly electrified economy, an increased role for hydrogen and carbon absorption, as well as heightened technological innovation (Johnson, Betts-Davies, and Barrett 2023). Nonetheless, these scenarios do not explicitly report changes in final demand. Instead, they emphasize the significance of transitions on the supply side and the energy efficiency options. Though this paper draws on the FES scenarios, it is important to underscore that the scenarios developed by CCC and BEIS hold considerable value within their individual contexts. They contribute significantly to providing a comprehensive understanding of the energy transition landscape. A detailed comparison between the different sets of scenarios developed by National Grid, CCC, and BEIS can be found in (Dixon, Bell, and Brush 2022; Johnson, Betts-Davies, and Barrett 2023).

National Grid (2021, 66–90) has defined the future energy scenarios, which outline four different pathways for the future of energy until 2050. Each pathway considers the required amount of energy and from where this amount could come. This section aims to give a quantitative overview of the domestic heating decarbonization scenarios and then show the link with the challenges defined in the previous section. Later, in this paper, we discussed how these challenges are addressed in the literature.

In the first pathway called "Steady progression," heavy reliance is still on natural gas for domestic heating even with improved home insulation. In this scenario, the energy system in the UK achieves significant annual carbon emissions reductions but it does not meet the 2050 net zero target. The pathway called "Consumer transformation" does meet the 2050 net zero target and adopts measures that have a greater impact on consumers and require a high level of consumer engagement. The homeowner will use an electric heat pump with a low-temperature heating system, make extensive changes to improve their home's energy efficiency and smartly control the electricity demand to provide flexibility to the system. In the third pathway called "System transformation," the typical domestic consumer will experience less disruption than in the "Consumer transformation" pathway. The typical consumer will use a hydrogen boiler and will not largely enhance the energy efficiency. In this pathway, the total hydrogen demand will be high, produced from natural gas with carbon capture and storage. In the fourth pathway called "Leading the Way," the energy consumers are engaged in reducing and managing their energy consumption. The engagement of the consumers aims to drive down energy demand through improving energy efficiency, with homes retrofitted with insulation such as triple glazing and external wall insulation. In this pathway, green hydrogen is used to decarbonize industrial processes (National Grid 2021).

A detailed study of these pathways shows that the residential sector requires the following routes to decarbonize and support the energy sector:

- Electrification and use of low carbon technologies such as hydrogen boilers, heat pumps, and district heating. Installing these technologies, in homes requires consumer engagement. The infrastructure (hydrogen or electricity) availability and consumer choice will drive the choice of the technology to be installed.

- Demand reduction through increased thermal efficiency measures and adjusted consumer behavior. Encouraging homeowners to apply energy efficiency measures such as retrofitting insulation in lofts and walls can reduce energy demand significantly. Moreover, convincing homeowners to decrease the set point of their heating systems by 1°C (on average) can lead to up to a 13% reduction in heat demand in comparison to today's levels of demand.
- Use of green hydrogen, which produces no emission at the end consumer level.
- Increasing the flexibility of the energy system. The way in which homeowners use low-carbon heating technologies could help in managing a future electricity system dominated by renewable energy sources.

Figure 1 depicts the annual residential energy demand in 2050, where all scenarios demonstrate an overall reduction in energy demand compared with 2020. This figure shows that the energy demand in 2020 is supplied from natural gas (334 TWh/year), electricity (23 TWh/year), and the oil/petroleum (44 TWh/year). In 2050, the contribution of hydrogen increases to supply the energy demand and the amount of this energy depends on the decarbonization pathway: 15 (TWh/year) in the "Consumer Transformation" pathway, 190 (TWh/year) in the "System Transformation" pathway and 44 (TWh/year) in the "Leading the Way" pathway. The hydrogen will be blended with natural gas in the "Steady Progression" and the amount of the blended gas used to supply heat demand is estimated as 246 (TWh/year).

Figure 2 shows the annual demand for heating homes. It can be seen that the "Consumer Transformation" pathway has a lower total annual demand compared to the "Leading the Way" pathway. Such change is due to the former having more heat pumps installed in homes after 2040. The number of installed residential heat pumps has been depicted in Figure 3. This figure reveals that, in 2050, the residential heat pump will be installed in around 26 million homes in 2050 in the "Consumer Transformation" pathway; however, the uptake of the heat pump in the "Leading the Way" pathway will be around 22 million. Figure 4 demonstrates the annual electricity demand for residential heating homes. The behavioral change of the energy consumer (turning thermostats down) offsets increased heat pump uptake in the "Consumer Transformation" and "Leading the Way" pathways in the early years. Later, increased uptake of the heat pumps in these two pathways increased the electricity

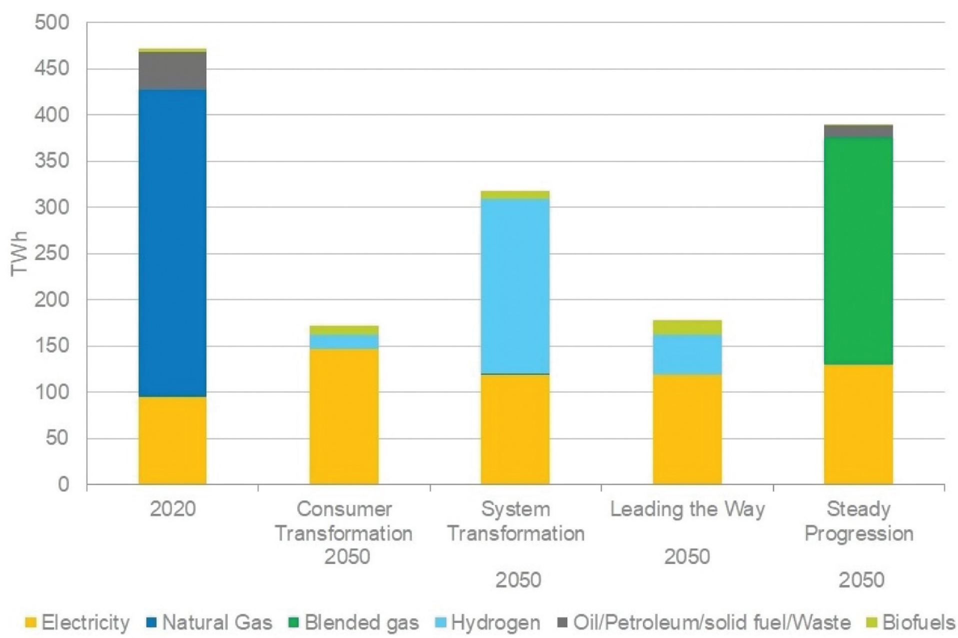

Figure 1. Annual residential energy demand in 2020 and 2050 (National Grid 2021, 65).

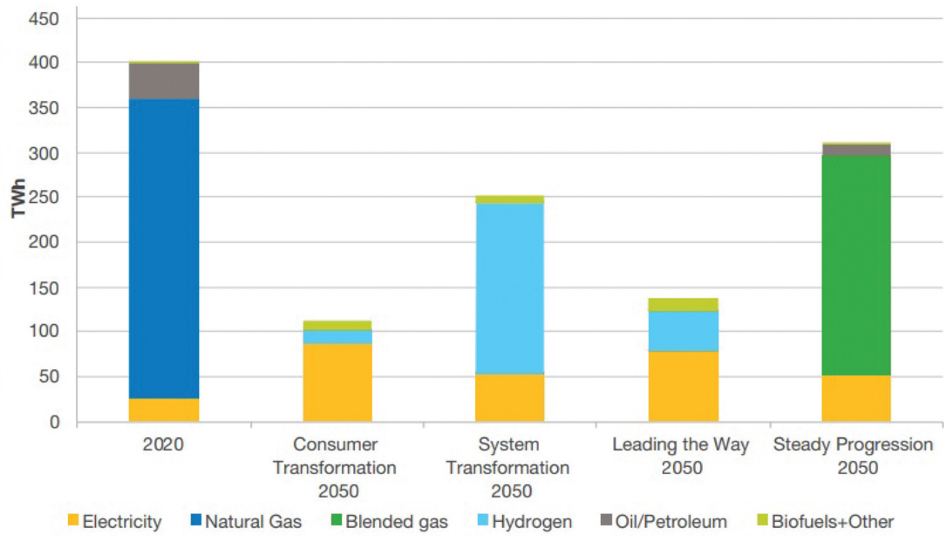

Figure 2. Annual residential heating demand in 2020 and 2050 (National Grid 2021, 66).

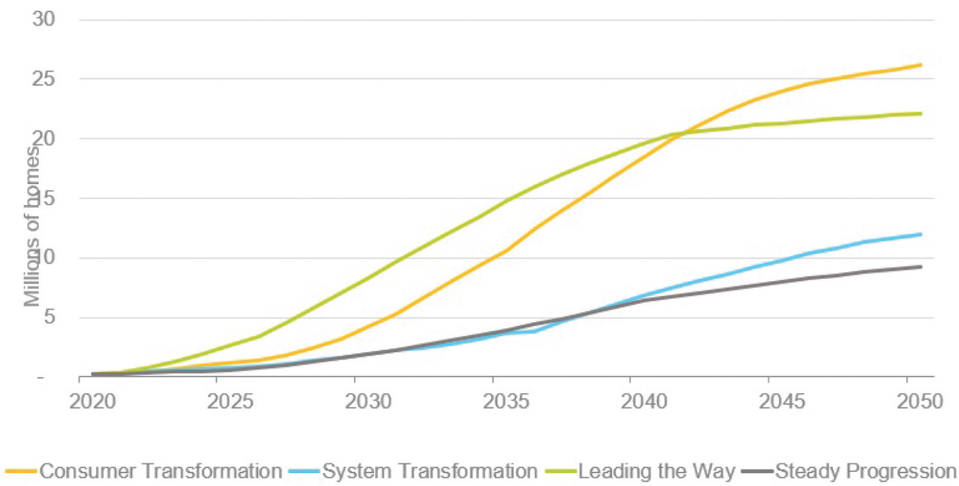

Figure 3. Residential heat pump uptake (National Grid 2021, 81).

consumption to 86 TWh/year and 77.5 TWh/year, for the “Consumer Transformation” and “Leading the Way” pathways, respectively.

Figure 5 shows the uptake of residential hydrogen boilers in the UK will start in 2028 and 2030 for “Leading the Way” and “System transformation” pathways where the number of installed Hydrogen boilers, in 2050, will be around 22 million for the System transformation” pathway and around 6.698 million for the “Leading the Way” pathway. Figure 6 shows the annual hydrogen demand for residential heating. It can be seen that the hydrogen rollout in the “Leading the Way” and “System transformation” pathways will start in 2028 and 2030, respectively. Hydrogen boilers contribute to the surge in hydrogen demand after 2028.

A detailed analysis of the information given in Figures 1–6 shows that: 1) all future energy scenarios demonstrate an overall reduction in energy demand and residential heating energy demand compared with 2020. In addition, hydrogen plays an important role in each scenario to meet the energy demand

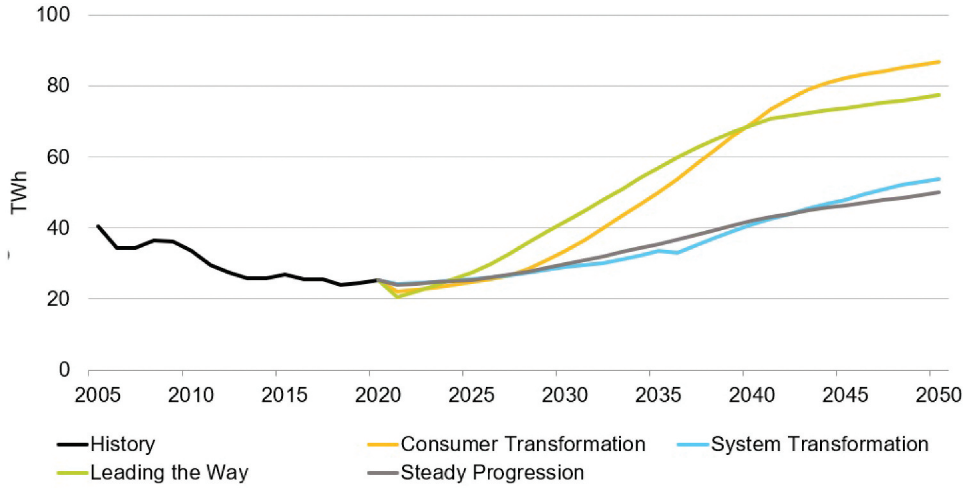

Figure 4. Annual electricity demand for residential heating (National Grid 2021, 77).

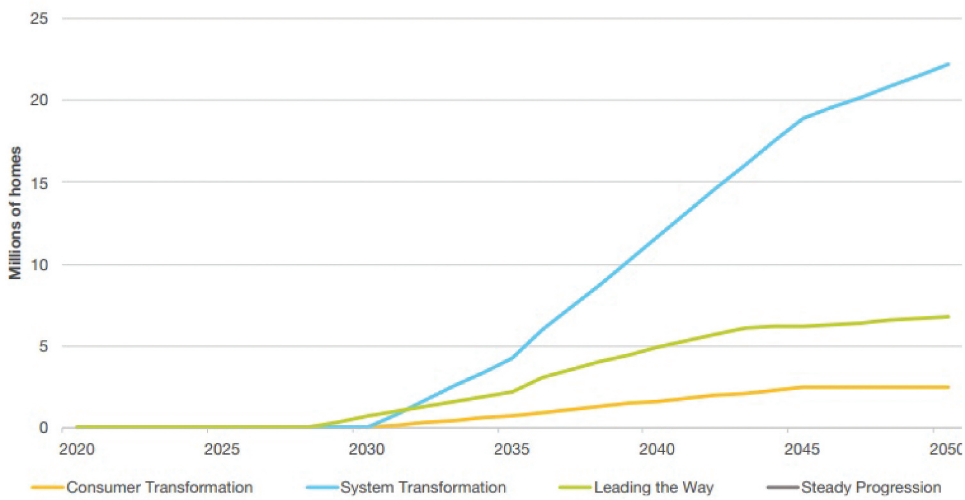

Figure 5. Residential hydrogen boilers uptake (National Grid 2021, 81).

(Figures 1 and 2). This would mean the hydrogen supply chain must be integrated into the energy system in the UK. This integration of hydrogen into the supply chain can be challenging; 2) the role of consumer engagement in reducing the heating energy demand is remarkable in future energy scenarios. In Figure 2, the lowest heating energy demand is for the "Consumer Transformation" scenario. This engagement can be through different ways, such for instance, installing more efficient heating technologies, participating in demand-side response programs, and retrofitting houses to reduce heat loss. The high use of electrical low-carbon technologies (such as heat pumps) will increase the electricity demand (Figures 3 and 4), and the high adoption of hydrogen boilers will increase the hydrogen demand (Figures 5 and 6). The technical, environmental, and economic evaluation of the impact of the consumers' engagement to decarbonize the heating sector requires developing efficient models for future energy systems, which can take into account all or most of these engagement aspects. Developing this type of model can be challenging. The engagement of energy consumers through retrofitting of homes to enhance their energy efficiency, and assessing the impact on the energy

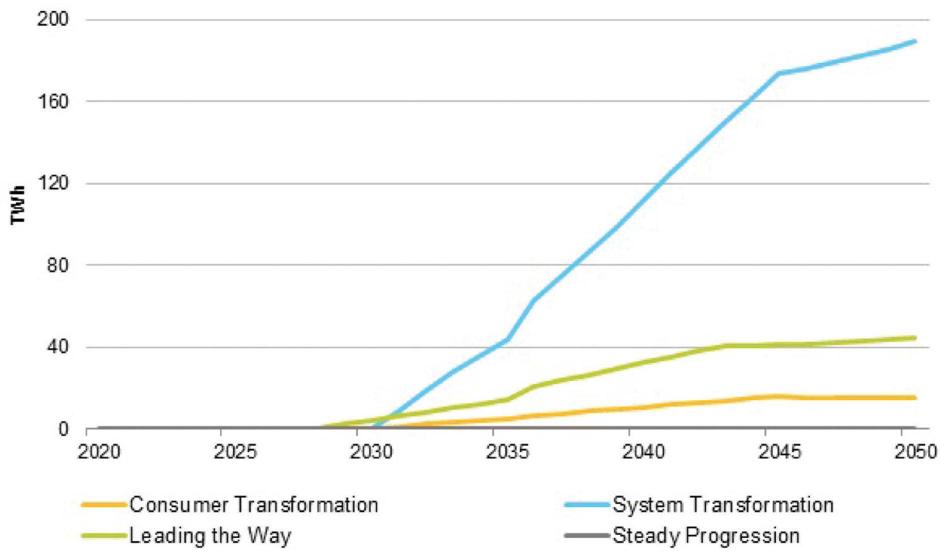

Figure 6. Annual hydrogen demand for residential heating (National Grid 2021, 78).

system, is also challenging. Furthermore, the participation of the energy consumer in reducing the heating energy demand by controlling smartly the set-point of the heating system, through the home automation systems, requires digitalization of the heating system which can also be a new challenge facing the decarbonization scenarios. Finally, these engagement activities might affect vulnerable groups; hence, this must be assessed and can be one of the challenges facing the implementation of the decarbonization scenarios in the domestic heating sector. To sum up, implementing these decarbonization scenarios in the domestic heating sector will lead to different challenges, and in particular, we focus on the challenges of:

(1) Integrating hydrogen at the supply side
(2) Retrofitting the existing UK housing stock
(3) Digitalising the heating energy system will enable the energy consumer to control smartly the energy demand (including the heating demand) through home automation system which would provide information about the energy demand/usage. This knowledge of energy usage will enable consumers to reduce their energy demand (Khanna et al. 2020; Nikkhah et al. 2021, 2021)
(4) Deployment of fair transition in relation to vulnerable groups. The second and third challenges require increasing consumer engagement on heat decarbonization, and consequently, vulnerable energy customer groups may be more affected which adds a further challenge to heat decarbonization.
(5) Modelling of the future energy system. A continuous assessment of the efficiency of these decarbonization routes is required and this necessitates the development of robust modeling of future energy systems. This adds an additional challenge, which is the need for models, which can evaluate the energy system after implementing the decarbonization routes.

Not only can hydrogen contribute to the decarbonization of the heating sector in the UK, but also other low-carbon technologies, such as heat pumps and heat networks, can also contribute to this decarbonization process. Further, the use of these technologies will lead to other challenges which are not within the scope of this paper. More information about the challenges related to the use of these technologies for decarbonizing the heating sector in the UK can be found in (Scamman et al. 2020, 1–28). A comparison between the different options of heat decarbonization is also given in (Scamman et al. 2020, 23–24). This paper aims to discuss these five challenges and give recommendations for the energy research community and policymakers to tackle these challenges facing the decarbonization of the UK heating sector.

3. The challenge of integrating hydrogen into heating systems

As a clean energy carrier suitable for use in both heat and electricity systems, hydrogen is considered a clean and promising energy sector for the 21st century (Zhang et al. 2021, 100080). It can be a socially and technically viable low-carbon residential heating solution, particularly due to the absence of direct CO_2 emission in the end use and its ability to act across (and couple) multiple energy vectors. Reace Louise, Carolina, and Joe (2021, 100901) and Fakeeha et al. (2018, 405–414) found that 96% of hydrogen is currently derived from technologies that reform fossil fuel feedstock. The proportion of Hydrogen from electrolysis technologies stands globally at around 4%, which is predicted to rise as a function of global interest in green hydrogen. Green hydrogen production is possible through renewably sourced electricity with electrolysis, solar thermal or biological processes where biogenic waste is utilized as feedstock for biofuel production including bio-hydrogen. Emerging hydrogen production technologies include photocatalytic water splitting, solar energy water splitting and nuclear water electrolysis, which are expected to advance in the next two decades and replace present gray hydrogen production technologies in the long term (Zhang et al. 2021, 100080). It is important to highlight that associating the gray hydrogen production technologies with carbon capture and storage (CCS) technologies makes the produced hydrogen lower carbon, and this is commonly referred to as blue Hydrogen.

Although hydrogen undoubtedly carries significant potential to decarbonize energy systems, it also faces a set of challenges which extend beyond mere technical matters. In the UK, for example, government policies on hydrogen remain largely under-developed with very few definitive targets (Reace Louise, Carolina, and Joe 2021, 100901), where among its few commitments were the Hydrogen Supply Programme of 2018 that allocated 28 million to assess the readiness of H_2 rollout in the UK (Joy and Al-Zaili 2021, 32735–32749). Department for Business, Energy & Industrial Strategy (2021b) has developed the hydrogen strategy to set out how the UK will drive progressively in the 2020s, to deliver the 5GW production ambition by 2030 and position hydrogen to meet the UK Sixth Carbon Budget (Climate Change Committee 2020) and net zero commitments.

While retail prices of hydrogen per unit mass or volume remain several multiples larger than comparative fossil fuels it might replace (Dawood, Anda, and Shafiullah 2020; Khouya 2020; Lowes and Rosenow 2023), it is generally accepted that scaling up of production is the biggest driver of hydrogen cost reduction (followed by supply chain improvement). The last International Energy Agency (IEA) report on the global production of hydrogen stated that the annual production of 90 Mt in 2020 was almost entirely met by fossil fuels, accounting for 900 Mt of direct CO_2 emissions (International Energy Agency IEA 2020). In the following sections, key barriers to the adoption of green hydrogen in domestic heating of cost, storage and transport, by-product heat utilization, end-use (including the cost of fuel cells), and integration into home heating sector, are discussed.

3.1. Cost of hydrogen production

Whilst a wide range of values exists on the retail price of hydrogen, some of the more competitive figures are outlined here. Respective nonrenewable hydrogen retail prices based on production from coal, natural gas (NG) and nuclear have been as low as \$0.27/kg (advanced gasification with sequestration of coal) (Gray & Tomlinson, 2002, p. 2002), \$1.7/kg (conventional steam methane reforming)(Chisalita & Cormos, 2019, p.331-344) and \$1.75/kg (sulphur–iodine thermochemical in modular Helium nuclear reactors) (Richards et al. 2006, 36–50). However, renewably generated hydrogen has a much greater retail price with figures ranging from \$2.4/kg (biomass gasification) (Sentis et al. 2016), \$5.57/kg (solar PV assisted electrolysis) (Touili et al. 2020, 26785–26799), and \$7.1/kg (electrolysis from wind) (Leahy, McKeogh, Murphy, Cummins, et al., 2021, p. 24620–24631).

Hydrogen (H_2) retail price is very sensitive to production scale and process efficiency, and reasonably sensitive to economic forecasting (future inflation considered as discount factor) as well as feedstock cost. For instance, the high price of methane gas during the period of late 2021 until mid-2022 will affect significantly the retail price of H_2. In addition, a range of 8% to 25% has been reported on Internal Rate of Returns (IRR) calculations of hydrogen retail price across studies carried out from 1998 to 2020 (Bartels, Pate, and Olson 2010; Fakeeha et al. 2018; Khouya 2020), which reflects the diversity in the economic landscape of different countries. This makes comparative assessment of cost studies extremely difficult and any standardization results in a departure from the assumptions of case-specific studies. However, the magnitude of the difference between renewable vs. nonrenewable hydrogen outlined earlier points to the considerable challenge of making green hydrogen economically feasible. The following innovations, however, are outlined in the literature as areas of greatest opportunities for the cost of renewably-derived hydrogen to decline in the medium-term future:

- Solar resources: historically, the median price of PVs for residential installation has been around \$5.92/W of peak installed capacity, with similar figures reported for system installations at larger scales. However, thin film PVs are under development, with some available on the market for as little as \$1/W of peak installed capacity. This can fundamentally change the solar-derived hydrogen retail price (Haegel et al., 2019, p. 836–838).
- Wind power: The mean capital cost of medium to large scale wind farm installations in Europe has been reported at \$1,974/kW of installed capacity, with offshore installations costing twice as much (International Renewable Energy Agency IRENA 2023). There is no perceptible trend in the cost reduction of onshore wind; however, offshore deployment has observed reductions at magnitudes of around 30%, which may continue into the future with improved engineering techniques.
- Biomass: deriving hydrogen from biomass contains multiple processes that are both thermochemical (pyrolysis or gasification) and biological (direct or indirect bio-photolysis, biological water-gas shift reaction, photo fermentation and dark fermentation) in nature (Bartels, Pate, and Olson 2010, 8371–8384). Predictions of future trends in biomass-derived hydrogen economics require detailed technical knowledge of these processes and the availability of appropriate skills and resources, but there is potential benefit from cost reductions if H_2 production is coupled with intensive agriculture.
- Supply-line consolidation: Key to reducing the costs in any process is a streamlined purchasing process. This has motivated multiple stakeholders to form consortia aimed at reducing green hydrogen retail price with one instance of solar-derived H_2 anticipated delivery at a similar price to fossil fuels by 2030 (McPhy group 2021).

In short, while hydrogen production is a well-established industrial exercise for gray hydrogen from fossil fuel sources, the main research focus here is low or zero carbon H_2 production at scale and in an economically viable manner. This combination of scale and cost reduction will contribute to a reduced cost of decarbonization of the energy system, and while location-specific and project-specific considerations act to inform the best pathways, it is on a cost, energy and exergy efficiency that future hydrogen production technologies need to compete. These key performance indicators (KPIs) were examined against a backdrop of 19 separate H_2 production procedures which identified the hybrid nuclear thermochemical cycle to have the highest overall rating. Photo-electrochemical and PV-based electrolysis were least competitive when assessed across all KPIs (Dincer and Acar 2015, 11094–11111).

3.2. Hydrogen storage and transport challenges

In the absence of a medium, hydrogen is challenging to store and transport, as it must either be compressed to a high pressure (700 bar and above), liquefied or converted to a hydrogen carrier to enable storage with reasonable facilities (Makhloufi and Kezibri 2021a, 34777–

34787). This has led to a wide range of research investigating multiple organic compounds, such as commercially available ammonia (NH3), as an intermediary for storing and transporting H_2. Ammonia's density (674 g/l) offers significant advantages over storing H_2 (71 g/l). Although ammonia is currently produced from nonrenewable sources, it may be renewably manufactured in the future (Makhloufi and Kezibri 2021b, 34777–34787). Large-scale ammonia decomposition remains the most challenging technical aspect (Makhloufi and Kezibri 2021a, 34777–34787). For organic H_2 carriers, the greatest challenges are the development of a catalyst system that allows hydrogenation and dehydrogenation of the carrier, and the identification of mediums with high gravimetric capacities for hydrogen (Shimbayashi and Fujita 2020, 130946).

While in gaseous form, H_2 has a small energy density and is outperformed by other fuels including natural gas (Reace Louise, Carolina, and Joe 2021), in liquefied form it can be an excellent energy carrier as per kilogram it contains nearly three times as much energy (33.3 kWh/kg) as equivalent petrol or diesel (12 kWh/kg). H_2 liquefaction requires substantial amounts of energy due to the need for very low temperatures (about −253°C). Liquefaction can claim up to 36% of embodied energy of H_2 and hence an active area of research is the optimization of this process (IDEALHY project 2021). Hydrogen storage tanks require specially insulated vessels to substantially reduce the chances of contamination with air or oxygen (Ratnakar et al. 2021, 24149–24168).

3.3. Hydrogen as an alternative to natural gas (NG)

If we are to replace NG with hydrogen as a heating and domestic hot water fuel, the properties of these two need to be considered, to inform the required appliance adaptation. This is currently being investigated by manufacturers of household appliances (either for new H_2 appliances, the adaption of existing appliances or the potential for dual-fuel appliances that can switch between hydrogen and NG). Hydrogen burns with a greater flame velocity than NG and has a nearly colorless and odorless flame. Enabling H_2 leak detection is therefore considered one of the principal challenges (de Vries and Levinsky 2020, 114116) for use in the domestic setting and research communities are developing new approval and regulation standards to avoid flashback and leak risks in hydrogen appliances. A report commissioned by the UK Government recommended an initial phase of H_2 only appliances (as opposed to dual fuel appliances) to bring about a safe hydrogen age and concludes that the government intervention in the market is required to enable this transition of fuels to be undertaken safely and successfully (Frazer-Nash Consultancy, 2018).

3.4. Utilisation of heat as a by-product of hydrogen production

Co-generation of heat and power is a long-standing practice in the built-environment and industrial processes. However, the utilization of heat from a hydrogen production facility (i.e. valorization of heat) still remains a science and economics challenge. Industries with the potential of producing high-temperature gas or liquids as a by-product of core processes have traditionally been looking at ways to improve their process efficiency by recovering surplus heat. This, for instance, has been researched heavily in steelworks (Zaccara et al. 2020) and nuclear power plants (Xu, Dong, and Ren 2017, 35–54), where typically surplus heat is available at temperatures of around 800–1000 $^{\circ}C$ (high enough to enable H_2 production in itself). Therefore, there is a wide scope of scientific literature that examines the recovery of high-temperature heat to generate steam for H_2 production in sustainable processes such as polymer electrolyte membrane electrolysis, solid oxide electrolyze cell electrolysis, and biomass gasification. This opens up the possibility of a hydrogen production facility being able to offer combined heat and power resources to its host community.

3.5. Cost and further development of fuel cells

Currently, fuel cells (FCs) are primarily used in a limited capacity for residential and commercial buildings to enable space and water heating, though they are also suitable for industrial plants and district heat networks as well as for transport applications. Their technical performance has greatly improved in recent years and installed costs have fallen to around $15,800 for 1 kW residential systems and $1.32 m for a 400 kW commercial system. FC costs continue to further reduce at a rate of 10–15% per year (Advanced Propulsion Centre UK 2023, 8–9). While FC technology is a well-established form of utilizing H_2 for the generation of electricity and heat, current research mainly focuses on a complex combination of technologies that can improve overall system efficiencies of FCs within the wider energy system, so that both the electrical power and by-product heats are fully utilized. At a system level, the research challenges relate to the appraisal of tri-generation using fuel cells to provide heat and power to buildings and H_2 to FC vehicles (Li, Ogden, and Yang 2013, 668–679), or coupling of proton membrane or solid oxide FC with other prime movers (i.e. combined cycle gas turbine) to derive better overall system exergy and thermal management (Li, Ogden, and Yang 2013, 668–679; Rosner, Rao, and Samuelsen 2020, 112952; Vijay and Hawkes 2018, 874–886; Zhang, Xu, and Lin 2020, 115806). At an FC level, current research is building on decades of existing work to further improve FC catalysts, starting material and solvents, as well as improving the timing and operational efficiencies of FCs (Chen et al. 2020, 100075) (Gittleman, Kongkanand, Masten, & Gu, 2019, p.81–89).

3.6. Summary of the challenge of integrating hydrogen into heating systems

In Section 3, it has been shown that there is a wide range of research aimed at improving the efficiencies and economics of hydrogen production, particularly from renewable sources that (at scales above 100 MW) are currently on average between 2 and 5 times more expensive than the cheapest production routes of H_2 from nonrenewable fuels. A growing international market and political interest has the potential to facilitate a decline in renewable hydrogen cost, particularly given that multiple consortia and all oil majors have an active hydrogen investment program. The decrease in the cost of renewable hydrogen will consequently help the UK to produce the amount of the hydrogen energy required for the residential heating sector by 2050 (estimated as 189.6 TWh and 44.3 TWh in the “System transformation” and “Leading the Way” pathways, as indicated in Figure 6). On the other hand, the declined cost of renewable hydrogen generation will also decrease the retail price of the hydrogen which, in its turn, will encourage the households’ owners to use the hydrogen boilers in these two pathways. Encouraging households to use hydrogen boilers assumes that the UK was able to produce the required amount of hydrogen to meet the associated demand. If the different efforts to produce this amount of hydrogen were unsuccessful, other low-carbon heating technologies, such as the heat pump, would need to be adopted in greater quantities to make up for any shortfall from hydrogen heating.

The literature consulted in Section 3 also suggests that a 1st generation hydrogen-only appliance needs to be characterized to displace NG, while government intervention is required to support and regulate manufacturers both in the successful adaption of hydrogen-specific (1st generation) and dual-fuel (2nd generation) home and commercial appliances.

4. Challenges of retrofit of housing stock

Achieving net zero carbon emissions by 2050 may be accelerated with improved energy efficiency within the housing sector (Bergman and Foxon 2020, 101386), as approximately 27.8 million homes (Office for National Statistics 2020) account for 20.8% of annual carbon dioxide emissions in the UK (Department for Business, Energy and Industrial Strategy 2021a). With 80% of current homes expected to be used in 2050 (Putnam and Brown 2021, 102102), numerous strategies and programs have been implemented to encourage investments in housing retrofitting. For example, the UK Government has dedicated a 2bn fund to retrofit the housing stock, for installation of double-glazed windows and insulation of cavity walls and floors (Hosseini, Allahham, Vahidinasab, Walker, & Taylor, 2021a, p.106481). Retrofit is seen as vital in the transition to Net-Zero due to the fact the UK has one of the most inefficient (from an energy performance viewpoint) housing stocks in Europe (Lovell and Foxon 2021).

The UK has, through the Department of Energy and Climate Change (DECC), implemented policies to jumpstart improvement within the energy efficiency sector (Bergman and Foxon 2020, 101386; Elsharkawy and Rutherford 2018, 295–306). Largely regarded as the most successful in addressing fuel poverty is the Warm Front Policy (2000–2013), which provided energy efficiency upgrades to households classified as fuel-poor. The Warm Front removed 2.36 million households from fuel poverty with reductions of carbon dioxide emissions per home by 1.5 tons per year (Sovacool 2015, 361–371). Within the timeframe (2000–2013), supplier obligation policies (SOs) made it incumbent upon energy suppliers to meet carbon emission targets by improving household energy efficiency. Consequently, the UK established two major SOs: the Carbon Emissions Reduction Target (CERT) and the Community Energy Saving Programme (CESP) (Department of Energy and Climate Change 2014, 116).

CERT (2008–2012) mandated that the six major gas and electricity suppliers, namely: British Gas, EDF Energy, E.ON, npower, Scottish Power and SSE must meet certain carbon emissions reduction targets by improving the energy efficiencies of existing households in the UK within a five-year window (Department of Energy and Climate Change 2014, 116).

Shortly after CERT was the launch of CESP, which lasted from 2009 to 2012. CESP was designed to improve energy efficiency of low-income households by tasking large energy suppliers and generators to provide energy saving measures (Duffy 2014, 116; Elsharkawy and Rutherford 2018, 295–306) including district heating system upgrade, double glazing and district heating heat meters for individual households (Watson 2013, 116). CESP required that energy saving measures were delivered within a geographical location through selection based on the income levels (Department of Energy and Climate Change 2014, 116). This program has been less favorably viewed in comparison to CERT, partly due to the complex legislative requirements by Ofgem (Department of Energy and Climate Change 2014, 116).

In 2013 came the replacement of both CERT and CESP, as well as the Warm Front, by the Energy Company Obligation (ECO). Similar to CESP, it was specifically geared toward low-income households to tackle fuel poverty. In the same year, the Green Deal was launched (2013–2015), which aimed to transform the financing of energy efficiency by offering pay-as-you-save private loans to householders (Bergman and Foxon 2020, 101386; Sovacool 2015, 361–371). The ambitious target for Green Deal was set at 2 million housing retrofits per annum, with loan repayments levied on energy bills (Putnam and Brown 2021, 102102). However, the program was scrapped in 2016 after only delivering 20,000 retrofits from 2013 to 2015 (Bergman and Foxon 2020, 101386).

While these programs have been designed to deal with reducing carbon emissions, they have not achieved their specified aims. For example, the Warm Front scheme did not meet the target of ensuring that by 2010, no vulnerable households would remain in fuel poverty (Sovacool 2015, 361–371). CESP was only able to achieve 16.31 of the 19.25 Mt CO2 target, earning a 15.3% shortfall. Although CERT had reduced over and above the set CO2 targets, two energy companies, namely British Gas and SSE, could not meet their obligations, resulting in failure to reach the main target (Abraham 2013) Failure of the Green Deal was attributed to a combination of factors, including its complexity, high interest rates, and limited engagement with consumers (Bergman and Foxon 2020, 101386).

In spite of the implemented policies, the majority of homes in England and Wales are still classified as energy inefficient (Palmer and Webb 2018). The low level of home retrofits points to the need for stronger policies to facilitate households in their transition toward net zero emissions. The common trend of failure for policies to meet the outlined targets suggests the urgent need to re-strategise and create an inclusive roadmap which incorporates not only the financial aspects but also on the social and behavioral factors that would affect success. Grassroot retrofit initiatives can complement government policies through engaging members of the community and increasing awareness of the need for energy-efficient homes as well as enlightening "fuel-poor" households regarding available financial grants. This bottom-top approach, if included within the government retrofit policy framework, may significantly accelerate the pace toward net zero emissions (Putnam and Brown 2021, 102102).

The following sections highlight some major barriers to household retrofitting within the UK, identified through a critical review of the literature.

4.1. Retrofit options in the UK case studies

Currently, it is challenging to identify and deploy the best retrofit option in terms of Techno-Economic-Environmental (TEE) performance, especially with limited available budget. A limited number of publications in recent years have demonstrated and evaluated energy performance of possible retrofit options in practice, compared to a higher number of publications that have only performed simulation for evaluation of retrofit options. Figure 7 shows three different buildings as a case study for deciding the best retrofit options.

In case study 1 a social housing building located in Newcastle upon Tyne was considered, and retrofit of double-glazing windows and solid external wall insulation were studied. The key findings of this study were (i) a reduction of around 27%–34% in space heating consumption was observed; and (ii) the aforementioned physical retrofits for energy efficiency improvement had more impact on energy consumption reduction compared to the behavioral factors (turning on the heat system) (Hosseini, Allahham, Walker, & Taylor, 2021b, p.119968). More research is needed to investigate the extent of the impact of the behavioral factors (Helgesen, Lind, Ivanova, & Tomasgard, 2018, p.196–212).

Case study 2 looked at the deep retrofit of a residential building using a "TeaCosy" approach for a complete surrounding of the building with Passivhaus-type envelope. The retrofit included building envelope (window, roof, wall, ground floor slab and door), lighting, replacing the existing gas boiler with a biomass boiler, and photovoltaic system. The key findings were (i) 50% building energy performance improvements (38% "CIBSE degree days"-normalized), 55% carbon reduction (40% "CIBSE degree days"-normalized), 1,399 kgCO$_2$/y carbon reduction from gas (1,043 kgCO$_2$/y

(a) (b) (c)

Figure 7. The UK case studies with demonstration of various retrofit options (images sourced from (hosseini, Allahham, Walker, & Taylor, 2021b) (Clegg and Mancarella 2015), and (Manshadi and Khodayar 2018), respectively): (a) case study 1: a high-rise social housing building, (b) case study 2: a residential building, and (c) case study 3: Salford energy house.

"CIBSE degree days"-normalized), occupants' wellbeing improvement observed through questionnaires and interviews; and (ii) payback period of 38 years (without considering health benefits for a family of four), and 16 years (considering the health benefits) (Clegg and Mancarella 2015, 1234–1244).

Case study 3 is the Salford Energy House located at Salford, which was a "hard to retrofit" fully metered terraced house built inside a chamber with the possibility of replicating any weather conditions and occupant behavior. The retrofit of floor, roof, internal and external walls and glazing were studied. The research found: (i) close agreement was observed between two experimental building analysis methods (coheating and Quick U-building (QUB)); (ii) solid wall insulation led to the greatest (around 46%) heat loss reduction; and (iii) glazing, floor and loft insulation retrofit led to 7%, 7%, and 4%, respectively, reduction in heat losses Manshadi and Khodayar (2018).

4.2. Politics

The UK government is criticized as lacking in political direction and agenda with regard to energy efficiency (Bergman and Foxon 2020, 101386). Policies have consistently been changed with successive governments (Elsharkawy and Rutherford 2018, 295–306), leading to failures with respect to the uptake of some energy efficiency schemes in addition to the reduced level of confidence from the public and private investors. Some schemes, such as the Green Deal, were terminated prematurely, as the government deemed it unsuccessful due to low uptake from homeowners. The Green Deal is yet to be replaced with a similar policy (Bergman and Foxon 2020, 101386; Putnam and Brown 2021, 102102). While bottom-up grass root initiatives have emerged as possible alternative routes to retrofitting, it is clear that they still require financial and regulatory support from the government (Putnam and Brown 2021, 102102).

4.3. Social barriers

Occupant use of retrofitted homes can inadvertently lead to a significant reduction in projected savings. Policies related to energy efficiency have exclusively focused on investment behavior in a top-down fashion, while neglecting the possible impacts of human behavior such as energy consumption patterns. To exemplify, survey results from (Elsharkawy and Rutherford 2018, 295–306) revealed the actual savings from energy bills were 30% less than the projected target for CESP in a community in Nottingham. Further, a study in Sunderland found reduced draft control behavior post retrofit (Walker, Lowery, and Theobald 2014, 102–114). Additionally, household occupants may potentially raise temperatures after home refurbishments, effectively reducing energy savings. This is sometimes referred to as "Comfort take-back" or "rebound effect" (Walker, Lowery, and Theobald 2014, 102–114). This points to the urgent need to understand the underlying behavioral decision toward energy consumption on an individual level, and impacts of interventions to reward conscious efforts in reducing the use of energy.

4.4. Summary of the challenge of retrofit of housing stock

In relation to the future energy scenarios in the UK, improving the homes energy efficiency and retrofitting homes' insulation are extremely important to achieve the goals of the "Consumer transformation" and "Leading the Way" pathways. However, retrofitting the housing stock has been shown to be one of the main challenges toward the energy systems transition. As per the literature review above shows, retrofit scale up is slow due to a combination of cost, weak policy incentives, consumer behavior and lack of awareness. It may therefore be concluded that the current method of top-down government policies cannot entirely reach net zero emissions within the housing sector without engaging the public and increasing awareness of energy efficiency.

5. The challenge of deployment of digital energy and IoT infrastructure

With digitalization, information can enable energy demand to be aligned to periods with greater levels of sunlight and wind intensity, effectively shifting demand patterns to when supply is at its peak. This demand management plays a significant role in reducing carbon emissions associated with heat in homes (Carmichael et al. 2020). Achieving this demand management requires the installation of smart meters at the energy end-users. Adding smart meters to homes/building introduces the concept of smart homes, which refers to dwellings in which all the devices are connected through Internet-of-Things (IoT) that facilitates monitoring, control and management of the energy for the occupants via an application on a smartphone or on computer. In this way, the occupants will enjoy an enhanced level of information to improve sustainability, security, and living standard, through application of IoT, cloud computing, Artificial Intelligence (AI), Machine learning (ML) and big data analytics. Improvements include:

- Application of Artificial Intelligence (AI) and Machine Learning (ML) to model and forecast building energy consumption with human behavior being a strong predictor/feature (Bourdeau et al. 2019, 101533) (Wang and Srinivasan 2017, 796–808), (Fathi, Srinivasan, Fenner, & Fathi, 2020) or regression models to forecast the electricity load of commercial buildings (Yildiz, Bilbao, and Sproul 2017, 1104–1122);
- Application of Reinforcement Learning (RL) to control the comfort of the occupants (thermal, lighting and air quality) (Han et al., 2019, p.101748) or RL (Vázquez-Canteli and Nagy 2019, 1072–1089) (AI and ML models (Antonopoulos et al. 2020, 109899)) data driven predictive control methods (Kathirgamanathan et al. 2021, 110120) for demand side management to support grid stability;
- Application of Artificial Neural Networks (ANNs), fuzzy-logic and neuro-fuzzy (the combination of both with an enhanced performance) to predict the thermal efficiency of buildings and optimization of the thermal performance, and hence inclusion in the control strategies of the building (Pezeshki and Mazinani 2019, 495–525);
- Application of deterministic and data-driven models to predict the energy saving and performance improvement of different building retrofit scenarios or application of ML models to all the stages of development of buildings, i.e. design, commission, operation & maintenance, control, and retrofit (Hong, Wang, Luo, & Zhang, 2020, p.109831);
- Application of AI-based methods for fault detection and diagnosis (FDD) in the building energy system (Zhao et al. 2019, 85–101);
- Application of ML models for structural design and performance assessment of buildings (Sun, Burton, and Huang 2021, 101816);
- Application of ML models to predict occupancy and window-opening behavior, and identification of the most important feature/predictors that can enhance the performance of the models (Dai, Liu, and Zhang 2020, 110159); and
- Application of AI, ML and big data for design and operation of energy-efficient buildings considering occupant living comfort (Mehmood et al. 2019, 109383) including sizing of hybrid energy devices, e.g. renewable generation and storage (Zahraee, Assadi, and Saidur 2016, 617–630).

5.1. Data access and confidentiality

It is clear that the benefit of reduced heat energy consumption and subsequent decarbonization derived from smart technologies hinges upon the free flow of operational data across the energy sector, in order to allow sufficient integration of various energy producers, grid operators and consumers. However, difficulties in accessing data posed by some network operators due to commercial confidentiality, and fragmentation of data ownership and protective regulations such as GDPR, have hindered the progress of energy digitization, especially when compared with other sectors of the economy (Rhodes 2020). This barrier prevents comparisons and assessments across the digital spectrum, which would otherwise have aided consumers in making informed decisions (Carmichael et al. 2020). Facilitating the adoption of digital technologies would require stakeholders to establish guidelines in order to balance privacy, security and consumer trust with consumer data access and usage (International Energy Agency 2017a).

5.2. Standby consumption of IoT devices

It is estimated that energy digitalization across the building stock has reduced the global energy demand by 10% from 2017 to 2040 (International Energy Agency 2017a). This continued growth in digitalization has also led to the increased adoption of smart devices, partly due to the falling costs of smart energy sensors, advances in digital computing and data storage devices (Rhodes 2020). The potential for adding new digital devices and services which consume energy in stand-by mode has given rise to the possibility of off-setting the energy savings that occur due to the adoption of energy digitization. For example, power consumption of IoT devices in standby mode is projected to grow to 46 TWh by 2025, 78% of which would come from home automation (International Energy Agency 2016). Policies to improve device efficiency and to reduce standby power consumption will be critical to limit energy demand growth with increasing energy digitalization.

5.3. Summary of the challenge of deployment of digital energy and IoT infrastructure

Providing flexibility to the energy system and controlling the energy demand smartly are some of the important aspects that the ”Consumer transformation” and ”Leading the Way” decarbonization pathways rely on. The digitalization of energy system and the deployment of IoT infrastructure are required to facilitate the above aspects. The review of the literature on role of digitalization and IoT on facilitating the energy transition reveals that more material and digital technologies have been investigated on the power networks compared to the gas networks. The reason might be due to the sensitivity of the power systems to any change in demand or generations, demand side energy management, distributed generation and storage, as well as more conventional requirements of power systems including maintaining the frequency and voltages within the system. This has led to more reliance of the power system on IoT and big data processing and related technologies and frameworks compared to the gas network systems. This is a gap which needs further investigation especially with emergence of new paradigms in the gas networks for instance for adopting hydrogen distribution and appliances for decarbonizing homes.

It was highlighted that implementing big data infrastructure along with AI, ML/DL techniques can help to draw significant insights from big data in energy systems transition toward carbon targets. Finally, the challenges hindering the progress of energy digitalization including data access and confidentiality, as well as the standby consumption of IoT devices were discussed.

6. The challenge of deployment of fair transition in relation to vulnerable groups

Another challenge of energy systems transition is to ensure a “fair” transition is deployed so that all the groups of the society are benefiting from the advantages, since those groups most vulnerable to fuel poverty are often overlooked during policy making and deployment of a just transition.

It has been found that it is possible to design and deploy energy transition pathways, with consideration of the needs of the vulnerable groups, to ensure a fair transition for all groups in society (Jenkins, Sovacool, and McCauley 2018, 66–74). It should be noted that the concept of “transport poverty” and the lack of affordability of transport has been discussed in the literature (Mattioli, Lucas, and Marsden 2018, 114–125); however, this is not within the scope of this section. As discussed in the literature, the vulnerable groups at most risk of fuel poverty include (Carolyn et al. 2018; Mark and Carolyn 2018a, 2018b, 2018c) (Gillard, Snell, & Be-van, 2017, p.53–61): (i) People with some form of disability or with long-term illnesses; (ii) Families with low income and children; and (iii) Elderly people. These people have specific needs and conditions which need to be considered for a fair energy transition factors including unemployment, unsuitable housing, fluctuating health conditions, rurality, and higher energy demand (e.g. due to higher warmth comfort levels or the operation of medical equipment) have been shown to be more significant for disabled and individuals with long-term illnesses (Gillard et al., 2017; Mark and Carolyn 2018b).

6.1. The angles and types of justice

Research has highlighted that a just/fair transition has three angles: (i) Climate justice, which considers the burdens and benefits of climate change from a human rights viewpoint; (ii) Energy justice, which considers application of human rights during the entire energy life-cycle; and (iii) Environmental justice, which aims at treating all the individuals equally and involving them in all the stages of development and deployment of the environmental laws and policies (Heffron, 2021, p.9–19). In this section, the energy justice angle is further described.

The literature has identified three types of energy justice, all of which have been highlighted to be relevant considered in relation to the groups most vulnerable to fuel poverty (Mark and Carolyn 2018a), (Gillard et al., 2017, p.53–61) (Thomas, Demski, and Pidgeon 2020, 101494):,

- **Distributional justice**: This considers the way the energy goods and services are distributed within the society so that all the groups have the same level and extent of access to them. Hence, fuel poverty is considered a distributive issue, meaning that vulnerable groups have less access to energy efficiency measures and technologies compared to the majority of the society.
- **Recognition justice**: This refers to the fact that the energy needs of all the groups need to be recognized and taken into account during policy making and deployment. It should be considered that fuel poor people would have different energy needs in order to have the same extent of opportunity and wellbeing standards as the other groups of the society.
- **Procedural justice**: This considers that all the groups of the society should be involved during procedures and policy design and implementation. Hence, the specific needs of vulnerable groups need to be heard by enabling them to have knowledgeable representatives in all the stages of policy design and deployment.

6.2. Rural versus urban poverty and emotional impact

Fuel poverty in the rural and urban areas of the UK has been compared. It has been found that on average the experience of poverty in the urban areas is more persistent and longer than the poverty in the rural areas. However, the rural fuel poor households are more vulnerable to any energy price increase and this hits them harder than the urban fuel poor households. This shows that both the households and their spatial situation needs to be considered carefully to ensure the effectiveness of any policy (Roberts, Vera-Toscano, and Phimister 2015, 216–223).

Research into the impact of emotions on the energy vulnerability has shown that (i) different emotions, e.g. worry, fear, and care practices influence the patterns of energy utilization and payment, and potentially worsen the energy vulnerability; and (ii) embarrassment, care, stigma, and trust can impede or prevent support for vulnerable households. For example, in (Longhurst and Hargreaves 2019, 101207) researchers found that “as well as being a highly emotional experience in itself, the emotional practices bound up with energy vulnerability also have important effects that impact on the support energy vulnerable households receive.”

6.3. Challenge of deploying energy efficiency measures and hydrogen blending

Groups vulnerable to fuel poverty including those on low incomes often live in the most energy-inefficient housing ("How lockdown is disrupting the usual coping strategies of the fuel poor," 2020). It has been highlighted that insulating UK homes, and replacing their fossil fuel burning boilers with low carbon heating technologies have several benefits including reduced fuel poverty, energy justice, and contribution to the carbon reduction targets (Richard, Phil, and Rob 2020). Fuel-poor groups normally under-heat their homes, however, and it has been found that financially supporting these groups with the high capital costs of retrofit technologies can lead to an increase in their heat energy consumption ("rebound effect").

The challenges of retrofit of the homes of vulnerable groups with energy-efficient measures have been investigated from the view point of the three types of energy justice as below (Gillard et al., 2017, p.53–61):

- **Distributional justice**: Fair distribution and access of the vulnerable groups to energy efficiency measures has several benefits including "local spending and employment, increased property values and higher subjective wellbeing associated with improved community appearances" as argued in (Gillard et al., 2017, p.53–61).
- **Recognitional justice**: The specific needs of fuel-poor groups and the way they adapt to energy efficiency measures needs to be thoroughly recognized, which can be facilitated in several ways including through trusted intermediaries, referrals and collaboration of social and health workers and energy scheme providers (Gillard et al., 2017, p.53-61).
- **Procedural justice**: It has been highlighted that the representatives familiar with the needs and conditions of the vulnerable groups need to be involved during policy design and implementation, to help boost the engagement and uptake of the energy-efficient technologies by the vulnerable groups. Also, it has been found that transferring the costs of energy retrofit measures to the final customers will hit the low-income and fuel poor groups the hardest (Gillard et al., 2017, p.53–61).

Within the framework of procedural justice, the UK Government has rolled out the Smart Meter Implementation Program (SMIP) (equipping homes and businesses with smart meters) with the intended benefit of energy cost savings for the network operators as well as the final customers. However, it has been observed that several vulnerable groups including the elderly, disabled, and those of lower education attainment could not effectively communicate with the In-House Display (IHD) devices to take the most advantage of this program and reduced their energy demand and costs. This necessitates the program providers to provide better information to these groups (Sovacool et al. 2017, 767–781).

Within the framework of distributional justice (Mark and Carolyn 2018a), argues that "improving the energy efficiency of fuel-poor homes can cut energy bills and improve health, comfort and well-being." However, since the current energy efficiency schemes are patchy, it is hard to ensure this will happen for all the vulnerable groups across the UK, which necessitates further improvement to policy (Mark and Carolyn 2018b). Also, current energy efficiency schemes risk being designed for the lowest cost installations ("the numbers game"), whereas they should ensure a positive engagement and uptake of the technology by all societal groups (Mark and Carolyn 2018a). Furthermore, it has been found that vulnerable groups are often not eligible to receive support on these schemes. Hence, previous research implies that the specific needs of the fuel-poor should recognized, approaches need to be consistent across the UK, and the cooperation with non-energy sectors and need to be further improved (Carolyn et al. 2018).

The energy justice aspect of hydrogen deployment for vulnerable groups has also been studied in the literature. The public will resist hydrogen deployment if they are exposed directly to the costs of Hydrogen blending in the existing gas network (Scott and Powells 2019). It has been highlighted that hydrogen perception research should build on and encompass the energy and social sciences research, to address the corresponding economic, justice and social implications of an emerging hydrogen agenda and to ensure an inclusive approach for analysis (Scott and Powells 2020, 101346). Also, research has identified that the enforcement of a hydrogen transition, paid for either through tax or higher energy bills, will exacerbate fuel poverty. Therefore, all the possible options for funding the costs and governance of hydrogen deployment need to be investigated (Scott and Powells 2020, 101346).

6.4. Cost implications and barriers of energy transition in relation to vulnerable groups

Some vulnerable groups, e.g. disabled, or those with long-standing health problems, would have different energy needs than the national average, to enjoy the same level of welfare (Carolyn et al. 2018; Gillard et al., 2017). This needs to be recognized and the corresponding costs adjustments made during the design and implementation of the policies for energy schemes (Evensen et al. 2018, 451–459). In a survey carried out in (Evensen et al. 2018, 451–459), it was noted that the wealthier members of the public need to pay more to cover the costs of energy transition compared to the vulnerable groups. The increase in energy bills as a result of deployment of low carbon technologies, and of increase in international energy prices, will lead to fuel-poor people struggling to cope with the increased cost of living. This will lead to reduced levels of power and heat consumption by these groups in order to stay within household budget and avoid debt (Foxon, 2013, p.10–24). A Time-of-Use (ToU) incentive system could enable vulnerable groups to benefit from engaging in possible energy flexibility plans in order to stay within household budget and avoid debt (Thomas, Demski, and Pidgeon 2020, 101494).

Several barriers to energy efficiency retrofit have been highlighted in literature and are briefly summarized as follows: (i) Disruption to routine, or damage and mess to the homes of vulnerable groups (Mark and Carolyn 2018b); (ii) Administrative or physical work than needs to be carried out by the individuals to deploy the energy efficiency measures (Mark and Carolyn 2018b); (iii) cost (indirect/direct) implications of implementing the energy efficiency plans and technologies (Mark and Carolyn 2018b); (iv) The fuel-poor households are not always identified as eligible to receive support, and mechanisms to reach these households need to improve including through data quality, data sharing and data matching to more effectively target these groups (Carolyn et al. 2018). Also, these households are not specifically reached through public marketing of the schemes. These households can be identified and reached through a number of approaches including working in the same place as the individuals from these vulnerable groups, and through communities and trusted intermediaries and local authorities (Mark and Carolyn 2018b). (v) Lack of awareness of help and support available to vulnerable and fuel poor households (Mark and Carolyn 2018a). Also, the information material supplied to them can hugely impact the engagement and uptake of energy efficiency measures. The National Energy Action (NEA) has produced guidelines for the development of information specific to vulnerable groups (National Energy Action 2020a); (vi) poor understanding of the specific needs and conditions of these groups (Carolyn et al. 2018); and (vii) "a lack of understanding about how to upgrade their properties and the ever-changing landscape of grant funding and inaccessible customer journeys" as discussed in (Mark and Carolyn 2018a).

6.5. Role of local authorities and communities

The closest representatives of the national government to the groups vulnerable to fuel poverty, i.e. the local authorities, have shown to be crucial in speeding up and facilitating a fair energy transition, especially in relation to vulnerable groups (Jenkins, Sovacool, and McCauley 2018, 66–74), (Gillard et al., 2017, p.53–61) (Bolton and Foxon 2015, 538–550; Chilvers, Pallett, and Hargreaves 2018, 199–210; Reeves 2016, 276; Sioned and Rosie 2020b). Given a fair energy transition cannot happen unless it is an inclusive plan then local authorities can be trusted intermediaries for people across all sectors of society

(Chilvers, Pallett, and Hargreaves 2018, 199–210), Sioned and Rosie (2020b) (Sioned and Rosie 2020a).

Local authorities can facilitate a fair energy transition for the vulnerable groups in a number of ways including: (i) design and deployment of more inclusive and open plans and procedures to foster contribution of all residents; (ii) actively searching and supporting the energy plans implemented by the residents themselves; (iii) fostering local renewable energy generated at the local/community level; (iv) prioritising the joint-ventures owned by the communities or residents; (v) Linking energy developments with health, welfare, planning, culture, environmental and education issues; (vi) utilizing innovative tools and supporting collaboration with industry to enable residents to create ways to implement resilient and sustainable economies at the local level (Sioned and Rosie 2020b).

Also, support to local professional initiatives in reaching the fuel poor households can be provided as resources and data of the local authority, and sharing of expertise of the methods for effective engagement (Reeves 2016, 276). Fostering of a "civic culture" has the potential to support and increase public engagement in deployment of the energy efficiency schemes, and deliver better engagement and uptake of these measure by vulnerable groups so that they are also involved in and benefit from a fair energy transition (Gillard et al., 2017, p.53–61).

6.6. Policy implications and regulatory frameworks

The role of policy and regulations for a fair energy systems transition particularly should be concerned with vulnerable societal groups. Ref (Evensen et al. 2018, p.451–459) highlights that the national government policies have a more impactful role than other bodies. It is highlighted that the policy should consider all the three types of justices in relation to vulnerable groups to be effective and make real changes. In other words:

- it should carefully understand the specific needs of the vulnerable groups (recognitional justice) (Mark and Carolyn 2018a, 2018b), (Gillard et al., 2017, p.53–61) (Sovacool et al. 2017, 767–781; Thomas, Demski, and Pidgeon 2020, 101494), to avoid further injustice (Evensen et al. 2018, 451–459) and not to prioritize some vulnerable groups over others Mark and Carolyn (2018a). The "one size fits all" solutions do not work in this respect, and the policies need to be tailored according to the conditions and needs of every household (Jack, Graeme, and Keith 2020). Also, the role of emotions and the life experience of the vulnerable groups should be carefully taken into account (Longhurst and Hargreaves 2019, 101207);
- it should be fairly distributed in all the parts of the country so that all people from different age, gender, race, minorities and geography (rural/urban) engage with the schemes (distributional justice) (Roberts, Vera-Toscano, and Phimister 2015, 216–223). Once the specific needs and conditions of the vulnerable groups are carefully considered, this can inform the practicality of delivery of a distributionally fair transition especially in relation to vulnerable groups (Longhurst and Hargreaves 2019, 101207); and
- vulnerable groups have representatives knowledgeable of their needs and additional demands who can represent them during policy design and implementation (procedural justice) (Gillard et al., 2017, p.53–61).

Regarding energy efficiency policies, it is highlighted that more access to high-quality data, data matching and data sharing should be provided to enable more effective targeting and providing the vulnerable households with energy plans according to their conditions (Gillard et al., 2017; Mark and Carolyn 2018a, 2018b, 2018c). Also, the trustworthiness of the promoted energy efficiency plans need to be raised to improve the support and awareness to the vulnerable groups (Mark and Carolyn 2018a). Additionally, the national government should design and deploy more consistent and fair transition plans, since the current schemes and policies are patchy and imbalanced across different regions (Mark and Carolyn 2018a, 2018b, 2018c).

6.7. *Summary of the challenge of deployment of fair transition in relation to vulnerable groups*

The challenges associated with vulnerable groups have been identified and discussed through the lens of the three types of energy justice: distributional, procedural and recognitional justice. It has also been identified that these groups are the least likely to have direct access to interventions, and hence local authorities have a big role to play in order to improve their access to energy efficiency measures.

From a political view point, it has been established that the UK Government, BEIS, Ofgem, regulators, and energy suppliers and companies need to rethink and improve the policy to reach the vulnerable groups, raise their awareness to seek support and help, address energy utility debt, and support prepayment (PPM) customers (National Energy Action 2020b). There are several approaches to finance the energy schemes in relation to fuel poor households, including application of levies on energy bills to deploy energy efficiency plans, supplier obligation schemes such as the Energy Company Obligation (ECO); or public tax (Mark and Carolyn 2018a).

7. The challenge of modeling and demonstration of energy systems and test house

In order to pave the way for transition of energy systems, the challenges mentioned in previous sections of the paper need to be demonstrated first at a local scale to understand, the barriers and to devise innovative solutions. Afterwards, standards can be rolled out at the national scale so that the national energy system meets the "Net Zero" carbon target by 2050. Modelling of energy systems, and the theoretical evaluation, optimization and planning of future energy system scenarios, is an essential part to inform subsequent or parallel demonstration. Therefore, this section summarizes the challenges of modeling and demonstration of energy systems.

7.1. *Energy Systems Integration (ESI)*

Integrating various energy vectors including heat, electricity, gas, and transportation has been proven to increase energy system flexibility, maximize integration of renewables while simultaneously reducing negative impacts on the environment (Hosseini, Allahham, Vahidinasab, et al., 2021a, p.106481) (Hosseini, Allahham, Walker, & Taylor, 2021b, p.119968). ESI therefore plays a critical role in the race to achieving NZC targets. The following sections describe different integrated energy system models and demonstrators that have been designed to evaluate decarbonization pathways in the UK.

7.2. *Whole energy systems modelling*

A review of the different models developed in the literature to evaluate the decarbonization scenarios of the energy systems is presented. The objectives of scenarios can be economic (reducing the operational costs) and/or environmental (reducing the carbon emissions), and/or technical (increasing the energy system reliability, security, and flexibility). Modelling of energy systems is affected by the interactions between the different energy vectors considered in the system, and the model can be formulated as an optimization problem or an operational analysis model.

7.2.1. *Operational analysis models*

Operational analysis models of energy systems mainly focus on analyzing and predicting how the energy system may behave for the given decarbonization scenarios. The decision variables of these models are the voltage magnitude and angle for each bus and the gas pressure at the different nodes. The constraints are mainly the active and reactive power balances at the buses and the gas flow balance at the gas nodes (Hosseini, Allahham, Vahidinasab, et al., 2021a, p.106481) and (Hosseini et al. 2021b, 119968).

7.2.2. Optimisation models

These can be operational or planning optimization. Operational models aim to identify the optimal operating set-points of the facilities included in energy system. Planning models investigate the evolutions of the energy systems being analyzed over a long-term period, such as new investment in generation facilities, transmission lines, transmission pipelines, storage facilities, and coupling components (Hosseini, Allahham, Walker, & Taylor, 2020, p.110216). Co-planning of power and natural gas networks can be proposed at the system level (Khan 2006) and at local/distribution level (Observer 2008). The optimization planning models are generally composed of mathematical formulations that include an objective that usually is to minimize capital and operational expenditures (CAPEX and OPEX, respectively) during the period of study; and constraints that include the equations defining the energy flow in the networks, the technical limits, renewable targets, budget and risk limits.

Optimization models can be bottom-up energy system models (Böhringer and Rutherford 2008, 574–596), such as MARKAL and TIMES models (Pfenninger, Hawkes, and Keirstead 2014, 74–86). On the other hand, there are the top-down models, or the macroeconomic models, which try to outline the economy as a whole (on a national or regional level) to estimate the economic impact of a change in energy and climate policies (Farrokhifar, Nie, & Pozo, 2020, p.114567). Using macro-economic data, these types of models are usually used to analyze the relationship between the energy supply, demand and prices in the market. The top-down and bottom-up models can be soft/hard linked or fully integrated (Helgesen, Lind, Ivanova, & Tomasgard, 2018, p.196–212), to capture the economic comprehensiveness of top-down models and the detailed representation of bottom-up models (Böhringer and Rutherford 2008, p.574–596)

Decarbonization of the heating sector has been studied using bottom-up models which are briefly described as follows:

7.2.3. UK TIMES Model (UKTM)

The UKTM is a techno-economic model, showing various aspects of the UK holistic energy system, including fuel processing and transport, electricity generation, as well as all final energy demands (Daly and Fais 2014). This bottom-up least-cost optimization model is used to study future energy scenarios, making it a versatile tool for analyzing heat decarbonization pathways and determining the most economic investment decision. In particular, it provides a range of heating technologies (district and residential) for meeting current and future heat demands.

In (Li, Keppo, and Strachan 2018), information from a nationwide survey on residential heating technologies were used to create a new modeling framework in which heterogeneous household (HH) preferences for heating technologies were integrated into the UK TIMES model and decarbonization was examined. This was accomplished by developing HH based on characterizing influential factors and applying it to the objective function of the UK TIMES model to determine the choice of heating technology, with variable adoption rates to reflect changes in preferences for new heating technologies. This study discovered that, without taking into account HH preferences, the energy system model adopts as many gas heaters as possible over the next few decades, with a dramatic increase in the share of heat pumps near the end of the time horizon. However, such a rapid transition is driven by the cost-cutting approach and does not appear plausible in light of the surveyed households' preferences. Because the survey indicates that households are heterogeneous and that household adoptions of heating technologies are influenced by the technologies that these households currently have, abrupt changes in the technology mix are unlikely to occur in a short period of time. The updated model incorporates household preferences, resulting in a more gradual and smoother development of heating technologies than the standard model. This demonstrates how the residential sector could gradually decarbonize as consumers shift from one technology regime to another, as described by observed preferences. However, relying solely on household preferences for individual heating technologies implies costs that are high enough to trigger investments in district heating and conservation to reduce the need for house-specific heating technologies in the considered scenario. The addition of district heating increases the system's flexibility for heat decarbonization. Even if the penetration of low-carbon heaters, such as heat pumps, is slower than expected, district heat networks can further decarbonize residential heating by switching to low- or zero-emission fuels, such as biofuels or hydrogen produced through carbon capture and storage.

7.2.4. Energy system modelling environment (ESME)

This is an integrated techno-economic optimization model designed for a UK integrated energy system and is used to analyze combinations of low-carbon technologies, in order to help achieve the UK's carbon reduction targets. ESME is a Monte Carlo model which considers the uncertainty in future energy prices and performance of energy technologies (Scamman et al. 2020, 1869). The model was used in (Pye, Sabio, and Strachan 2015, 673–684) to explore the impact of uncertainties in the whole energy system on decarbonization, with heat decarbonization achieved by the adoption of heat pumps and district heating options. More precisely, this study reveals that the heating provision is unaffected by system uncertainties, and CO_2 prices deliver similar levels of heat pump uptake and district heating in both 2030 and 2050 across most simulations.

7.3. Whole energy system demonstrators and test house facilities

The demonstrators described in this section have been developed in order to analyze future energy scenarios that will pave the way for decarbonization of the various sectors, including heat, transport and electricity. In addition, demonstrators of energy systems are important to collect the real-time data and consequently build the baseline energy demand profiles, and to assess the performance of the different decarbonization technologies and solutions.

7.3.1. Whole energy system demonstrators

7.3.1.1. InTEGReL. Integrated Transport Electricity Gas Research Laboratory (InTEGReL) demonstrator located at North East England is a partnership between several representatives from academia and industry. InTEGReL offers collaborations between academia, industry, and government to work closely together and commercialize research ideas to tackle energy system transition challenges such as heat decarbonization. The intention is to understand the interactions between different energy networks, including gas, electricity, district heating, as well as to carry out the control and management of whole energy system through IoT infrastructure there (IDEALHY InTEGReL 2021). An overview of the facilities and elements of this demonstrator is presented in Figure 8 (IDEALHY project 2021).

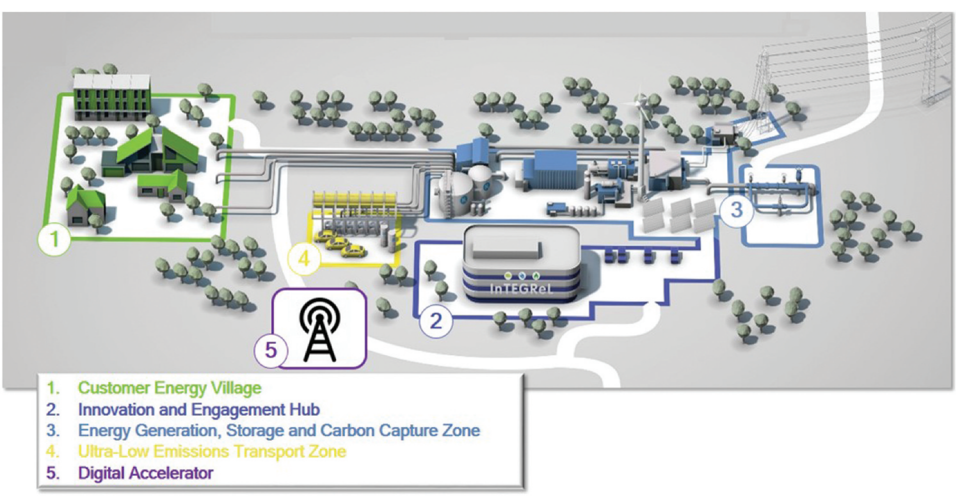

Figure 8. Schematic of the elements of the InTEGReL demonstrator.

In relation to heating decarbonization, the unique capabilities and opportunities of the InTEGReL site allow to blend the hydrogen and the natural gas. This blended gas is then used to meet heating demand. Furthermore, InTEGReL site includes the UK's first homes with appliances fueled entirely by hydrogen. These homes provide the public with a glimpse into a potential emission-free home of the future. Data collected by smart meters from these homes will be available for research purposes.

7.3.1.2. SEND. Smart Energy Network Demonstrator (SEND), is the "living laboratory" of the campus of Keele University, which provides several capabilities including energy forecasting and generation, storage, distribution, and energy balancing to be implemented intelligently across different players in their energy system. The aim of SEND is to improve energy management, reduction of the reliance on fossil fuels and energy waste, and to foster innovative approaches to energy management and use. SEND is able to demonstrate IoT-home control capabilities and the ability of blending hydrogen into the private NG network at Keele University. The facility and the big data generated at SEND will pave the way for new research, demonstration, and innovation partnerships with local, regional and international businesses, inventing new products, services and knowledge, to facilitate implementing a sustainable and low carbon economy and jobs, in line with the UK Government "Net Zero" targets ("The Smart Energy Network Demonstrator," 2021). This makes it an extremely versatile and powerful tool for analyzing decarbonization pathways that will greatly enhance heat decarbonization in the UK.

7.3.2. Test house facilities

7.3.2.1. Salford Energy House. Salford Energy House (SEH) is a Victorian "hard to retrofit" two-bedroom terraced house, which is built inside a fully metered environmentally controlled chamber. Hence, it is possible to replicate any kind of weather condition (wind, rain, temperature, solar). SEH is suitable for whole building energy system research since (i) any kind of retrofit option (door, windows, heating system, appliances, furnished or unfurnished) can be investigated; (ii) most of the variables required for energy studies are metered (environmental sensors, heat output of every heat appliance, total electricity, gas, and water consumption, walls' U values, metered sockets, thermographic image and building's heat flux); (iii) the behavior of the occupants as well as the effect on neighboring houses can be replicated (Alzetto et al. 2018, 35–41; Farmer et al. 2017a, 404–414; Ji et al. 2014, 1–11; Ji, Lee, and Swan 2019, 224–234). It is therefore possible to use the test house to analyze the impact of factors such as energy digitization and occupant behavior on household heat decarbonization.

7.3.2.2. SPECIFIC. SPECIFIC is a research center based at Swansea University. The aim of SPECIFIC is to develop products and technologies for decarbonizing heat and power in buildings. The center has a number of demonstrators including (i) Solar Heat Energy Demonstrator (SHED): SHED is an active building and is built to research several areas including large-scale solar heat storage, third-generation PV and photovoltaic thermal (PVT) studies, electrical storage systems, and inter-seasonal heat storage; (ii) Active homes: A set of 16 innovative, eco-friendly off-gas grid homes, which are retrofitted with energy-efficient material and renewable technology to study active carbon emission reductions from homes. Fuel poverty, renewable electricity generation and storage are also other areas of research; (iii) Active buildings: A combination of three buildings (The Pod, Active Office, and Active Classroom), which are off-grid energy-positive buildings that also share energy and information among them. The heat and power is provided by PV and PVT panels mounted on the roof and on south-facing walls (About specific ikc 2016) ("Active Office: The UK's first energy-positive office space," 2018) ("The Active Classroom: An award-winning, energy-positive building," 2016), ("The POD: Proving the Buildings as Power Stations Concept," 2020) ("Active Homes NEATH," 2020) (Burford et al. 2016a, 500).

7.3.2.3. Living laboratory at Dundee Botanic Gardens. This is small Passivhaus standard, self-sufficient studio, built in 2011, to investigate energy positive and sustainable buildings, and occupant behavior toward reduced energy consumption. The main research areas investigated at this demonstrator include: (i) overheating issues; (ii) research on building material, resources, and energy technologies; (iii) energy generation on site, storage and optimized utilization; (iv) whole building sustainable energy system research; and (v) research on innovative intelligent energy management and control algorithms (Burford et al. 2016a, 500).

This living-laboratory provides a facility for assessing and communicating the performance and impact of passive environmental design, carbon-negative renewable generating technologies, power storage and human spatial-environmental interactions. The activities taken place in this laboratory aim to address the following research question: ”How can we design future self-sufficient buildings to help save the planet’s valuable resources and how can this be achieved within a northern regional climatic and cultural context?.” Consequently, the data available from this laboratory used to assess passive design, sustainable technologies, monitoring environmental performance and people/spatial/environmental interactions (Burford and Robertson 2016, 3–13; Burford et al. 2016b, 500; Reynolds, Rodley, and Burford 2013, 168–174). Furthermore, the laboratory allows to engage with industry to foster innovative technologies and solutions toward net-zero target. This engagement can be through: upskill industry in sustainable construction practices, upscale regional sustainable technologies, and initiate debate on the role that architecture, people, energy conservation and ecology have in addressing the climate crisis.

7.3.2.4. Building research establishment (BRE) innovation parks. BRE innovation parks are a network of parks located in the UK, Canada, Brazil and China, to inform the sustainable development at a global scale and promote innovative materials, resources, technologies and solutions to tackle the pressing target of Net Zero carbon by 2050. The lessons learnt from BRE have led to useful tips for those working on the Code for Sustainable Homes (Skandamoorthy and Gaze 2013, 397–421). In the field of energy, the Building Research Establishment (BRE) determined that using renewable energy, either generated communally or through micro-generation at each house, is necessary for meeting high codes. All the homes incorporated some form of micro-generation, with photovoltaics emerging as the most preferred option. It is possible to use larger wind turbines, biomass and CHP when energy is generated collectively.

The Centre for Smart Homes and Buildings (CSHB) within BRE is a hub for government, industry, and academia collaboration, which fosters the utilization of smart services and products in the built environment through IoT markets. Also, the Smart Home Lab is developed by BRE to facilitate collaboration in relation to the technologies and products for smart homes which can lead to reduction of energy consumption and hence carbon emission, health and wellbeing of the energy user, and to support the more flexible and intelligent management of energy supply and demand (Bre innovation parks network 2020; The centre for smart homes and buildings 2020).

7.3.2.5. Creative Energy Homes at the University of Nottingham. A set of seven living labs (3) and occupied houses (4) benefiting from real data that are designed to investigate several areas including energy-efficient technologies and smart products, retrofit challenges, micro-smart grids, demand-side management, energy storage, and acceptance of the occupants of the innovative energy solutions. The research areas investigated at these Creative Energy Homes include demonstration of energy transition of the society to Net Zero carbon feature in an affordable way, knowledge transfer between academia, industry and the general public, exploring different building codes, user satisfaction and comfort, research on RES for buildings at the domestic scale, research on the level of uncertainty of energy use within buildings, intelligent and efficient control and management of building energy consumption, and impact of occupant behavior on energy consumption. The houses are fully instrumented with sensors for occupancy, environmental conditions, total energy and water consumption and utilization, building fabric energy performance, and contribution from RES generation (Creative energy homes 2020).

In this project, a trial has been conducted to investigate the feasibility of using ground-source heat pumps for domestic applications. This trial showed that it is necessary to evaluate the entire system, including the ground loops, household hot water systems and radiators, and operating conditions in order to achieve the target system efficiency. Ground source heat exchanger stacked concrete foundations were investigated as an alternative to the original design. Heat pump performance was examined, as were changes in temperatures in piles of foundation and in the surrounding earth. The seasonal climatic influence on ground temperature was used to compare the changes in the test plot's temperature to those seen naturally. Ground temperature change was found to follow predicted seasonal patterns and was unaffected by the heat pump's seasonal performance factor (SPF), which was determined to be 3.62 (indicating high efficiency) (Wood, Liu, and Riffat 2010, 4932–4940). Post-occupancy evaluations were conducted in all six homes to gather reliable data on how each room was utilized in the building. As a result of the usage of radio frequency identification (RFID) in this study, a novel methodology was developed that was utilized to analyze the data in order to improve future house designs and maximize space utilization (Gillott, Holland, Riffat, & Fitchett, 2006, p.273–288). These findings were further supported by research that employed wireless technologies to monitor energy use in real time and uncover connections between occupant occupancy and energy consumption (Gillott et al., 2006, p.273–288). One of the most important findings that came out of this study was that performance evaluations of residential buildings should include monitoring of occupancy (Gillott, Rodrigues, & Spataru, 2010, p.77–87).

7.4. Summary of the challenge of modelling of energy systems

Energy system decarbonization is analyzed using energy system models, which are generally techno-economic in nature and can therefore be applied to determine the financial implication of decarbonization. The review of the literature on modeling of energy networks reveals that the following challenges must be considered: (i) limited or entirely absent representation of consumer behavior (Daly and Fais 2014); (ii) interactions between heating systems and other parts of the energy system, e.g the electricity system, may result in aggregating the housing stock and therefore having a low temporal resolution for the entire energy system; and (iii) spatial resolution is a particular issue in modeling heat energy systems, especially in cases where demand density and costs can possibly lead to entirely different decisions (Daly and Fais 2014). Considering these challenges requires different modeling approaches and types to represent the energy networks, and the heat model which examines (i) the energy efficiency and storage measures, (ii) the impact of consumer behavior (including willingness to pay and comfort levels), (iii) individual building characteristics, (iv) policy incentives, and (v) regional suitability of low carbon heating technologies. These models can then be co-simulated or linked to adequately address the challenges of heat decarbonization at modeling levels.

8. Recommendations for future research and demonstration

The above review of the literature on the challenges of fair transition of energy system toward 2050 "Net Zero" carbon target reveals the following areas still need further research and demonstration to pave the way for a fair transition, so that all the groups of the society benefit from the emerging opportunities and advantages.

8.1. Hydrogen production, storage and transportation

While the production of hydrogen through electrolysis or from biomass stocks is a very well-established practice, the most important practical challenges for hydrogen are:

- **Upscale hydrogen production** The economic hydrogen production must be at scale to close the gap between retail prices of hydrogen and equivalent fossil fuels. Within multiple future energy scenarios suggested by major UK utility providers, hydrogen is to play a major role in future energy systems (UK National Grid assigns H_2 a value of between 21% and 59% of end-use energy use by 2050 (National Grid 2020, 1–166)).
- **Incentivize the private sector to be involved in hydrogen production through appropriate policy** The most prominent need for H_2 success is successful policy backing to allow H_2 to realize its full production potential through more confident private sector innovations.
- **Enable Hydrogen to take part of flexibility market** While H_2 will be particularly indispensable to heavy transport, shipping and aviation, in a highly electrified economy it will be able to unite power, heating and transport vectors and as such requires real-time (and predictive) controls in an integrated energy system to enable H_2 to bring about substantial real-time, diurnal and seasonal flexibility to energy systems.
- **Encourage innovation to boost thermodynamic efficiencies of the main components in the hydrogen supply chain** The energy density of hydrogen in gaseous form and under atmospheric and moderate pressures is quite low. This makes liquefaction or pressurization to 400+ bars necessary for transport and seasonal storage that can penalize the round-trip efficiencies of H_2 production and usage. This requires process intensification, advanced thermal management and inter-cooling processes to boost the overall thermodynamic efficiencies of integrating H_2 into energy systems.

8.2. Retrofit research and demonstration

Very few sources of literature were found that reported on a real-world demonstration of retrofit scenarios and its techno-economics. This emphasizes the fact that there are challenges associated with field trials of retrofit options. As a future research priority, the techno-economic-environmental impact of building retrofit on the utility networks and their interactions and interdependencies, as well as on the whole energy system can be considered. This presents a great opportunity to observe and evaluate the incorporation of smart appliances and new material, technologies and products into the whole energy system through IoT, and the associated AI and ML techniques. But more importantly, this connects the micro and macro components of an energy system to shed light on whole system dynamics as a function of small changes at household levels. This can further provide a basis for making well-informed decisions for both individuals and the policy makers for optimized use of the limited budgets considered for housing stock retrofit

8.3. Fair transition and fuel poverty

The main challenges facing the fair transition and fuel poverty can be summarized as follows:

- **Develop inclusive energy efficiency and retrofit plans** The literature on fair transition in relation to the groups vulnerable to fuel poverty showed that a just energy systems transition has three aspects of recognition justice, procedural justice and distributional justice. The research and demonstration of the impact of retrofit on vulnerable groups and those in fuel poverty need to carefully consider all three aspects in order to ensure the energy efficiency measures and plans are inclusive and deliver benefits. Further, research and demonstration are needed to ensure energy efficiency measures and retrofit plans impact positively on the livelihoods of the people struggling with fuel poverty.
- **Consider the social and emotional aspects of the engagement of the vulnerable groups** The social aspect of fair transition in relation to fuel poverty suggests that the emotional livelihood of the energy users impacts their engagement with the energy measures and the uptake of new solutions. It also showed any disruption to the current energy practice can influence the experience of energy use. Given the potential for hydrogen for the decarbonization of homes and the possible shift in the fuel poverty experience, the social and emotional aspects of the

engagement of vulnerable groups with hydrogen require further investigation. This is essential in order to further understand whether emotional engagement helps or hinders hydrogen-related solutions during a fair energy system transition.

8.4. Digital energy and IoT infrastructure

Instrumentation of energy consumers with smart meters and sensors will give the energy consumers full visibility over their energy consumption. However, some challenges can be found, which are:

- **Enhance the consumer digital capability** The baseline consumer digital capability required to enable the consumer to identify and participate informedly in potential energy schemes, is still an area of research to be investigated.
- **Consider the impact of digital inclusion** Energy digitalization may give more benefits to affluent groups of society than other groups. Evidence of the impact of digital exclusion on vulnerable consumers can be considered as a research gap to consider.

8.5. Modelling energy system for heating decarbonisation

There are several areas that are still needed to be considered by the energy research community in order to further investigate and tackle the challenges of modeling and demonstration of buildings and energy networks. These areas include:

- **Consider the retrofit scenarios** Impact of building retrofit scenarios on the operational analysis and planning of buildings and networks interactions analysis is still an area of research to be investigated;
- **Consider the social dimension** Social acceptability, behavior change, and vulnerability analysis of building retrofit options are important factors to consider in the operational analysis and planning of buildings and network interactions analysis. This analysis can be scaled up to a community level;
- **Consider the implications of cyber-physical systems on buildings operation** The IoT, big data, ICT and cyber security implications must be considered during the operational analysis and planning of buildings and IENs;
- **Assess the role of buildings in the flexibility market** The role of the buildings as flexibility providers to the energy networks needs to be investigated. This investigation must consider different factors such as family size and land use in the buildings/homes.

9. Applicability of future recommendations designed for the UK for the other European countries

Achieving net-zero carbon emissions by 2050 is a significant challenge, not only for the UK but also for all European countries, particularly in the decarbonization of the domestic heating sector. This section aims to demonstrate the applicability of the recommendations for future research and demonstration, presented in Section 8 for the other European countries.

9.1. Hydrogen production, storage and transportation

The methods of residential building heating vary considerably across European nations, shaped by diverse factors such as national resource availability, economic capacities, and technical infrastructure (Salite, Miao, and Turner n.d., p.1–33). To assess the applicability of the recommendations provided in Section 8 to other European countries, it is crucial to examine the heating methods employed in the residential buildings within these countries, with particular attention given to countries sharing similar weather conditions as the UK.

In Norway, the primary heating source for buildings is electricity, accounting for approximately 85% of the total, while district heating (DH) powered by fuel (60%), biofuels (24%), and electricity (10%) are used in around 11% of buildings (International Energy Agency 2017b, 1–165; Kerr and Winskel 2021, 5–18). In Sweden, DH is the predominant heating method for domestic buildings, accounting for 50%, followed by electric heating (29%), biomass systems (18%), and small fractions of natural gas (1%) and oil boilers (1%). Approximately 75% of district heat in Sweden is derived from biofuels and waste, with a small portion relying on fossil fuels (International Energy Agency 2019, 1–165; Karolyte 2017, 1–6; Kerr and Winskel 2021, 5–18). In Finland, residential heating comprises 36% district heating, 33% electric heating, 16% biomass, and 9% oil. Fossil fuels (coal, peat, gas, and oil) contribute to 54% of district heat, while biofuels account for 32% and waste generation for 7% (International Energy Agency 2018b, 1–166). Denmark's residential buildings rely on district heating for nearly half of their heating needs (Danish Energy Agency 2021, 1–60). Approximately 60% of district heating in Denmark is fueled by biofuels and waste, with coal and gas each contributing to about 20% (International Energy Agency 2018a, 1–165). Notably, the Scandinavian countries consider district heating as a key element in the decarbonization of heat, with biomass being the primary source for low-carbon district heating.

In Germany and the Netherlands, the primary method of heating residential properties is through a gas grid. In Germany, approximately 53% of properties rely on gas heating (International Energy Agency 2020, 1–165), while in the Netherlands, this figure is as high as 95% (Sahni et al. 2017). These countries, with a significant dependence on gas-based technologies for home heating, now need to transition from gas to a low-carbon alternative. One potential solution is the utilization of low-carbon hydrogen as a replacement fuel. Both the Netherlands and Germany have released their hydrogen strategies (Dutch Ministry of Economic Affairs and Climate Policy Ministerie van Economische Zaken en Klimaat, The Netherlands 2020), which highlight the viability of hydrogen for residential heating.

In France, the heating supply for buildings is composed of 42% gas, 21% oil, 15% electricity, and 12% biofuels and waste (Sahni et al. 2017). France has plans to phase out fossil fuel and direct electric heating, aiming for 38% of heating to be sourced from renewables by 2030 (Sahni et al. 2017). In 2018, the French government launched a Hydrogen Deployment Plan, which supports experimental projects to explore the feasibility of producing hydrogen from surplus renewable energy for injection into the existing gas grid (known as 'power to gas') (de L'hydrogène and de Déploiement 2018).

Given this review about the way of heating the residential sector in many European countries and the governmental plans, we can state that the recommendations presented in Section 8.1 can be generalized for the countries which use largely gas-based technologies for heating such as Germany, Netherlands, and France.

9.2. Retrofit research and modelling energy system for heating decarbonisation

Extending beyond the UK, retrofitting residential dwellings has attracted significant interest across European countries. This can be attributed to the prevalence of aging buildings throughout (European Commission 2019). Notably, approximately 35% of the entire building stock in the EU is over 50 years old EC2019, with a substantial 57% of buildings in the UK predating 1965 (Ministry of Housing, Communities & Local Government 2019). Moreover, a staggering 75% of dwellings in Europe are categorized as 'energy inefficient,' with only a marginal 0.4–1.2% of the stock undergoing renovation each year (European Commission 2019).

It is worth noting that the emphasis on dwelling retrofit is more pronounced in Western and North-Western Europe, including the UK, compared to Southern Europe. This disparity can be attributed to the climatic differences, as West and North-West Europe experience cooler temperatures, resulting in a greater demand for space heating during the winter months. Consequently, the research literature has primarily focused on dwelling retrofit in Western and North-Western

Europe. The focal points of this research primarily revolve around energy efficiencies and interconnected factors, such as energy performance, heating, power and control technologies, indoor environmental quality, and retrofit practices (Ruggeri, Gabrielli, and Scarpa 2020, p.1–37). After the introduction of the European Energy Performance Building Directive in 2010, which mandated Energy Performance Certificates and energy demand reduction (European Commission 2019, 2020a), a well-established research framework has emerged to monitor and model energy performance, to enhance energy efficiency. Building upon this research direction, the recommended research directions outlined in Section 8.2 remain relevant for other Western and North-Western European countries. Pursuing these research directions presents an opportunity for academics to provide valuable insights to decision-makers regarding suitable retrofit options. This can be achieved through data-driven analyses utilizing information collected from demonstration projects. Furthermore, researchers can assess the holistic impact of these retrofit options on the entire energy system, considering technical, economic, and environmental aspects. By following these research directions, researchers can effectively contribute to evidence-based decision-making processes in the domain of retrofitting. The recommendation presented in sections 8.2 and 8.5 support the future research directions in the European countries for developing the aforementioned data-driven approaches.

9.3. Low carbon transitions, digitalisation, and fair transition

Low carbon transitions create new injustices and vulnerabilities, while also failing to address preexisting structural drivers of injustice in energy markets and the wider socio-economy (Sovacool et al. 2019, 1–38). Four European low-carbon transitions were examined in (Sovacool et al. 2019, p.1–38) from the different aspects of energy injustice. These European transitions have been promoted as templates for low-carbon policies around the world. It has been found that low-carbon transitions are disruptive and contested. In addition, analysis shows that this disruptive nature can have profound impacts on certain groups of people. The dimensions related to recognition justice show that transitions can create new vulnerabilities or worsen existing ones, especially among the poor, the rural, those with disabilities, those with mental health concerns, and large families (Sovacool et al. 2019, 1–38) (Sovacool et al. 2019, 1–15). Hence, research must identify and calculate the benefits and non-benefits of low-carbon transitions, and their effect on vulnerable groups.

The impact of digitalization in different European countries has been investigated in (Sareen 2021, 1–10). It has been found that digitalization can exacerbate existing inequalities, but equally offers opportunities to enable inclusive smart energy transitions.

(Dillman and Heinonen 2022, 1–14) addressed the gap of absence of social assessments of the hydrogen economy around the world through a normative energy justice assessment across the hydrogen economy value chain. Results in (Dillman and Heinonen 2022, 1–14) show that potential injustices could arise from unjust decision-making, socially irresponsible development, and the poor sharing of ills/benefits on the consumption end.

It has been noticed in (European Commission 2020b, 1–30) and (Catrin 2020, p.1–25) that there is a lack of long-term evaluation of European energy renovation programs that includes measuring the social impact. The potential reduction of energy poverty is usually not quantified in advance. Future energy renovation programs must be designed to reduce the social risk of adverse outcomes, such as unaffordable rents after retrofitting, higher energy bills after new heating and payment arrangement, or lack of focus in the community (Catrin 2020, 1–25; European Commission 2020b, 1–30; Manjon, Merino, and Cairns 2022, 1–14).

It can be noticed from the review of the relationship between the energy transition, digitalization, housing retrofit, and hydrogen integration on one side, and the energy poverty and social injustice on the other side, that the recommendations for future research directions presented in the sections 8.3 and 8.4 can be applied not only in the UK but also in the other European countries.

10. Conclusions

One of the key challenges to meet the UK 2050 "Net Zero Carbon" target is to decarbonize the domestic heating sector. To explore this a critical review of the main challenges of energy systems transition in five interconnected fields was presented. These included integration of hydrogen in energy systems, retrofit of housing stock, enhancements through IoT and digital energy, a fair energy system transition and modeling and demonstration of energy systems. Overall, it was found that a greater confidence is emerging in both research and commercial sectors that suggests within a decade, green hydrogen at scale can be produced at retail prices close to fossil-based heating solutions. More precisely, the hydrogen cost for home heating could be 1.7 times the cost of natural gas cost at the end of the decade (Lowes and Rosenow 2023). End-user acceptability of hydrogen requires greater examination, and it is not yet clear if hydrogen-based heating solutions can be brought into energy systems in a way that can enhance the well-being of (and economically benefit) all, but including the most vulnerable societal groups. If natural gas networks are exploited to support a fully or partially H_2-based heating solution, greater penetration of IoT and digitalization is key to enable big data analytics on energy system carbon intensity, to enable greater demand side responsiveness and to improve returns on investment. Finally, retrofitting existing urban fabric remains a costly, location-specific and cumbersome challenge marred by socio-political barriers for which limited real-world demonstrators were found. Validated results on the techno-economic impact of a new generation of retrofit material and solutions would be invaluable in (i) de-risking their adaption at scale and (ii) creating validated urban energy models to optimize wider smart energy systems using bottom-up real-world data.

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