UK Building Thermal Performance from Industrial and Governmental Perspectives

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Abstract
Current policies have implied that improving thermal performance of the built environment would be included in a strategy to reduce the greenhouse gas emissions in the UK and meet the national targets of the Climate Change Act by 2050. However, the perceptions of the industrial stakeholders in this matter have not, to date, been clear. This study aimed to uncover stakeholder perspectives on thermal performance of the built environment and investigate whether their perspectives aligned well with the national policies. Focusing on attributes of the built environment, technology and innovation, barriers and reflections on reality, technical feedback was gathered from experienced industrial stakeholders via a one-day workshop and emails. The analysis showed that despite being familiar with the national policies, the perspectives of the industrial stakeholders did not fully align with the national policies in most aspects. However, the industry had no objection to employing low carbon technology alternatives in the future. The study concluded that consultation with industry should be carried out continuously to assist in the formation of future national policies to significantly improve the thermal performance of the built environment. Future research should be extended to comparing the stakeholder viewpoints and national policies from environmental and economic perspectives on a European/global scale.

Keywords: Building; built environment; thermal performance; energy efficiency; national policy; stakeholder perspective

1 Introduction
The built environment is a significant component of world energy consumption and CO_2 emissions. It includes residential, commercial (e.g. offices, warehouses, factories and hotels) and non-domestic buildings (e.g. hospitals and schools). In 2016, the construction and use of buildings consumed 36% of total final global energy consumption and contributed 39% of energy-related CO_2 emissions [1]. When buildings perform poorly, more energy will be consumed and more CO2 will be released, leading to lower building sustainability and unfavourable life quality.

Over the years, building research and development (R&D) has continued to improve and therefore created a better understanding of the built environment. The R&D trend in the UK can be understood by referring (in chronological order) to the literature. In 1990, Pimbert and Ruyssevelt [2] monitored the performance of super-insulated and control houses located in London and analysed the opinion of the occupants. Based on simulation and life cycle costing, Gorgolewski *et al*. [3] examined the performances of thermal insulation, ventilation control, double glazing and sunspaces for high-rise buildings. To enable prediction of energy demand load profile, Yao and Steemers [4] applied thermal resistance network theory and developed a thermodynamic model.

Since 2010, more research has been reported. For instance, Palmero-Marrero and Oliveira [5] scrutinised the effects of louver shading devices and compared building performances in the UK to those in Spain, Portugal, Mexico and Egypt. Using a modelling approach, Kendrick *et al*. [6] evaluated thermal performance of residential houses whilst Wang *et al*. [7] addressed energy consumption and overheating issues of industrial buildings. Focussing on office buildings, Korolija *et al*. [8] developed a model for parametric analysis which considered built form, design, occupancy and control. In studying the thermal comfort of the occupants, Barbhuiya and Barbhuiya [9] determined indoor temperature, lighting level and energy consumption of a non-domestic building. In scrutinising energy demand of 96 houses, Bagdanavicius and Jenkins [10] estimated electrical power required for the use of ground source heat pumps to supply space heating and hot water. Meanwhile, Herbert *et al.* [11] investigated the potential of expanding energy schemes in London i.e. to supply heating and cooling with ground source heat pumps. Shahrestani *et al*. [12] characterised the performance of heating, ventilation, air conditioning and refrigeration systems that could be considered for UK building application. These were based on energy consumption, indoor air quality, thermal comfort and CO_2 emission.

Using a learning algorithm, Papafragkou *et al.* [13] developed a model to categorise domestic buildings in line with thermal performance and occupant behaviour. In regard to retrofitting residential buildings, Cuce and Cuce [14] carried out experiments to understand energy loss caused by non-insulated walls. To enable thermal upgrades and facilitate behaviour change among building occupants, Jones *et al*. [15] analysed data on social housing, occupant behaviour and perception which were collected from household survey and building audit. By matching energy efficient measures with occupant types, Marshall *et al.* [16] modelled lower energy demand scenarios for households. The scenarios included households with single or double incomes, with or without children. To close the gap between modelled and measured building performances, Marshall *et al.* [17] adjusted the input parameters of modelling with data measured from building fabric tests. By exploring and developing a multi-agent system for intelligent control, Jiang *et al.* [18] dealt with thermal comfort and energy efficiency of commercial buildings simultaneously. Also for commercial buildings, Alam *et al.* [19] compared insulation measures in terms of potential savings in energy and emission and time required for recovering investment.

By considering both embodied and operational energies, Azzouz *et al.* [20] assessed the environmental impact of a large office building in London aiming to optimise building design at an early stage. Recently, Sousa *et al*. [21] reviewed the housing stock energy models deployed in the UK covering accuracy, transparency, computational efficiency, sensitivity to design parameters and usability. Also, Gupta and Kotopouleas [22] bridged the gaps between designed and measured thermal performances of 188 Passivhaus and non-Passivhaus dwellings. This was carried out by reviewing the air permeability, wall/roof thermal transmittance and heat loss data.

As shown by the literature above, residential, commercial and non-domestic buildings have been studied using various approaches including modelling, experiments and surveys. Whilst modelling is the most commonly applied approach in the literature, only [2] and [15] took account of stakeholders' perception. As a whole, the literature has spanned a range of aspects from building thermal performance, opinion of occupants, energy consumption, energy demand prediction, thermal comfort, use of technology, occupant behaviour, energy loss and efficiency, payback, emission and environmental impact to comparison between designed, measured and/or modelled data. The wide range of aspects are in agreement with the definition of a high performance building by [23]. The definition covered energy and thermal efficiency, cost effectiveness, safety, security, accessibility, functionality, productivity, aesthetics and sustainability. Nevertheless, it is impossible to present such a broad scope in any single research study.

As such, this study aimed to provide insights into stakeholder perspectives and national policies regarding building energy efficiency and thermal performance in the UK. The objectives were to consult experts in the field about thermal energy challenges, identify future needs and investigate strategies required to rise to the challenge for the built environment. As buildings cannot function without applied energy, this study is relevant to all building stakeholders regardless of how much an individual knows about such concepts. The study is crucial to ensure R&D is carried out instead of presenting theoretical studies that would never be applied by industrial stakeholders and occupants in their daily lives at work or at home. This would not only meet current needs but also benefit the end-users pragmatically.

Unlike previous literature, legislations and national policies were considered substantially in this study. Stakeholders' perspectives were taken into account to reflect the reality and human elements, in addition to building attributes, use of technology and innovation and potential barriers. For this reason, this study is original and the outcome is manifestly worth-noting, unless the research community intends to deny these factors within the building sector. The study has disclosed stakeholders' perspectives on a wide range of topics (see Section 3), which affect national and international communities significantly. These topics have been investigated individually but they have not been analysed together taking account of stakeholders' perspectives. The outcomes could assist in deciding the direction of long-term strategy planning as well as future R&D.

In line with the specific focus and coverage of this article, UK evidence is presented as background in Section 2. Ways to implement the methodology in this study is explained in **Section 3**. Feedback from the stakeholders for each focus area is reported in **Section 4**. Discussion based on relevant national policies and future outlook (in line with the stakeholders' feedback and national policies) are presented in **Section 5** prior to drawing conclusions in **Section 6**.

2 Background: The current state in the UK

The built environment has a large share of the UK's net wealth value. In 2017, it was estimated to be worth approximately £7 trillion, of which infrastructure, domestic, non-domestic and commercial buildings constituted £1.10 trillion, £5.9 trillion, £883 billion and £147 billion respectively [24]. Also in 2017, there were 23.1 million households in England [25] and the number was expected to grow more rapidly. This was indicated in [26], which reported that economic and population growth would increase building development even higher in the future.

Growth in the building sector should be planned carefully through legislation to monitor its impact on the environment and economy. Since 1990, the building sector has been the fourth largest sector contributing to greenhouse gas (GHG) emissions in the UK (where the other three main sectors are industry, power and transportation). In 2016, the building sector accounted for 30% of the total UK GHG emissions in which the total quantity rose by 9% compared to the previous year [27]. Progress made in reducing GHG emissions from the residential sector over the period 2008 to 2012 stalled whilst it hardly began for commercial and public buildings [27]. To meet the targets of the *Climate Change Act 2008* i.e. reducing 80% of the UK carbon emissions by 2050 compared to the 1990 level [28], buildings must become more energy efficient in feasible, practical and affordable ways [29].

In reaching the goals, improving energy performance of the built environment in terms of technical systems and building fabric could reduce current dependency on energy supply. Space heating accounted for 80% of the total energy consumption in domestic buildings in 2016 [30] which was mainly supplied by gas boilers and radiators. As for commercial buildings, 161 TWh energy was used per year for electricity and non-electrical usages, which accounted for 53% and 47% respectively, mainly because of lighting and space heating [30].

The huge share of energy spent on space heating for both domestic and commercial buildings showed the potential for reducing GHG emissions in the built environment. This could be achieved through the improvement of thermal performance and decarbonisation of heat supplies [27] and the thermal performance of the buildings themselves (e.g. insulation/glazing).

The UK Government was concerned that the rise in electrical consumption in commercial buildings and the increase in electricity costs would have a direct impact on local businesses and industries, which in turn would affect the UK's economy [31]. Legislation and guidelines were provided as part of Building Regulations. For instance, Part L detailed how to

(i) achieve carbon emission reduction and energy efficiency targets for new dwellings [32, 33]; and
(ii) (ii) retrofit existing buildings [34, 35] by considering the building's fabric requirements, minimum efficiency of technical systems, and the use of high efficiency system alternatives.

Meanwhile, Part F described the requirements and means to achieve ventilation in domestic and non-domestic buildings [36]. Both Parts L and F were supported by [37, 38], which provided technical system installation guidance and control system recommendations. British Standards were also introduced to

(i) cover heating systems on general aspects [39], space heating [40] and hot water [41]; and
(ii) estimate the impacts of building automation and control systems (BACS) as well as technical building management (TBM) on energy performance and use [42].

To mitigate GHG emissions of the built environment, the following national strategies were proposed recently:

- keeping up with the demand by escalating new housing development [26];
- providing high quality houses [29];
- enabling clean and affordable energy [29, 43];
- stimulating investment in smart energy systems and advanced construction [29];
- improving energy efficiency across business, industry, homes and transportation [43];
- reducing power cost for households and businesses [43]; and
- improving resource efficiency with reduced waste and pollution [44].

The UK regulations focused on improving the thermal performance of the built environment by the use of insulation materials potentially aided by decarbonisation of heat supplies and higher efficiency of heating systems. However, besides the strong focus on the energy performance, thermal comfort and building sustainability should also be taken into consideration. The Grenfell Tower tragedy was one example of a retrofit project which became *one of the most unimaginable tragedies* in the UK in many years [45]. How the tragedy was perceived by the industrial stakeholders was unclear. Achieving high performance for new and existing buildings would be a challenge for the UK Government and the stakeholders. Therefore, how to motivate initiatives among the stakeholders would be crucial. The use of hydrogen as a potential energy vector for future heat supply in buildings was recommended by the Committee on Climate Change, see [27]. Prior to this study, it was not certain whether the stakeholders were prepared for the switch in the near future.

3 Methodology

A framework, as shown in Figure 1, was designed and applied which outlined ways of methodology implementation for this study. The study aimed to consult experts in the field about the thermal energy challenge for the built environment, forecast future need and identify strategies required. The scope and focus of the study were illustrated in Figure 2. A one-day workshop was designed and run to receive feedback from a representative sample of industrial stakeholders who have primarily dealt with the issues on a daily basis.

Invitations were sent to 633 experienced industrial stakeholders across the UK specialising in energy, mechanical, project or sustainability engineering. These included engineers, consultants, managers and (technical, managing, deputy managing or associate) directors. The 33 industrial stakeholders who attended the workshop were divided into 11 random groups of 3 to participate in the 4 interactive sessions. Prior to the workshop, the questions to be addressed by the attendees were designed and refined via meetings and email communication. The focus areas covered attributes of the built environment, technology and innovation, barriers and reflections on reality.
During the workshop, a web-based audience response system, Poll Everywhere, was adopted to effectively capture real-time responses from the attendees. The workshop discussion was focussed around three keynote presentations:

(i) the gap between actual and achieved performance;
(ii) the critical need to consider ventilation; and
(iii) approaches to retrofitting.

For Sessions 1 and 2, attendees discussed the pre-defined questions in groups and submitted their feedback to the system within the allocated time. Also, barriers to the uptake of energy efficiency identified by Building Performance Institute Europe [46] were shown. Based on the UK's current context, the attendees were asked to organise the barriers in the order of prominence. At the end of both Sessions, attendees were invited to suggest additional questions/issues that should be addressed on the day. All attendees were then asked to choose the questions that should be addressed in Session 3, which formed an additional focus area i.e. people. This was followed by open discussion on the reflections on reality in Session 4.

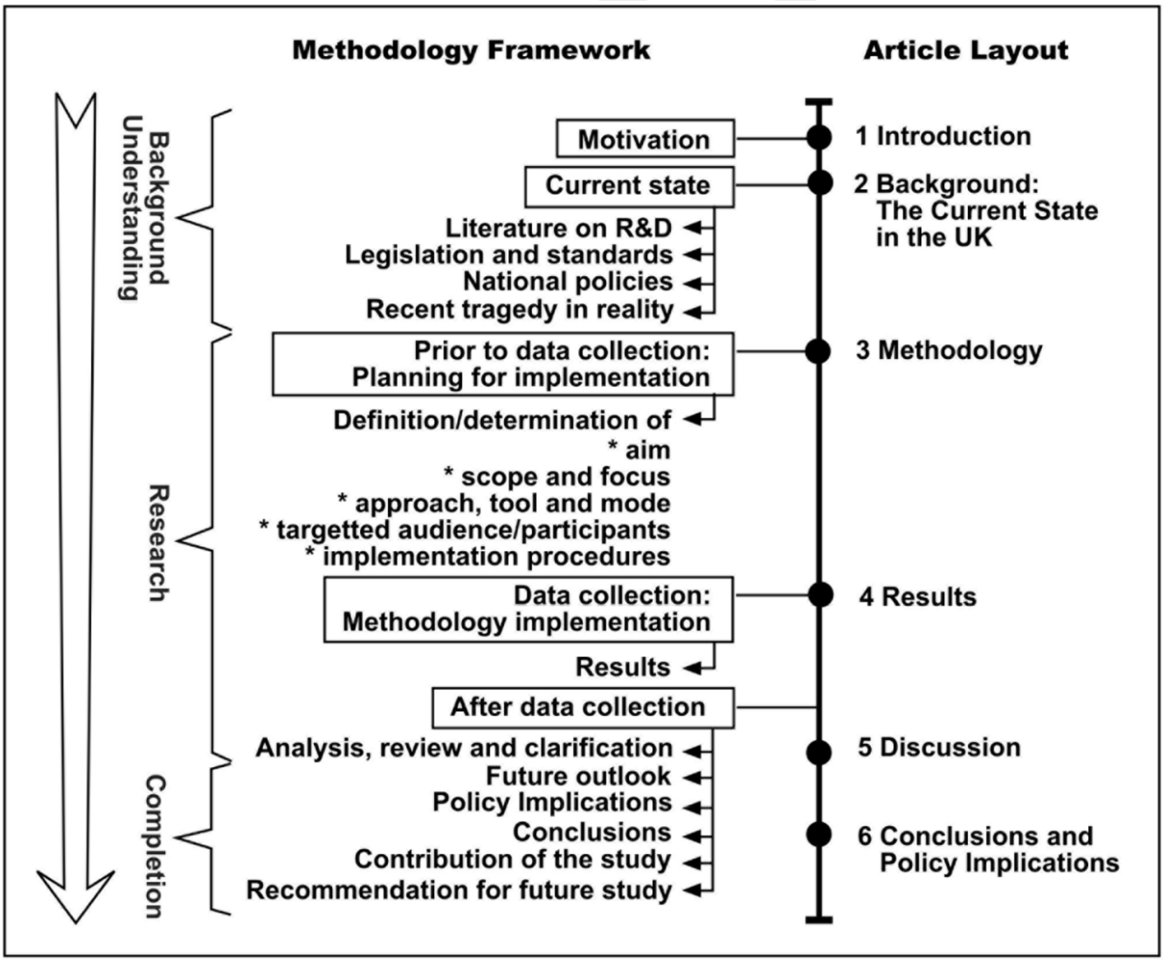

Figure 1: Methodology framework applied for the study matching up with the layout of this article.

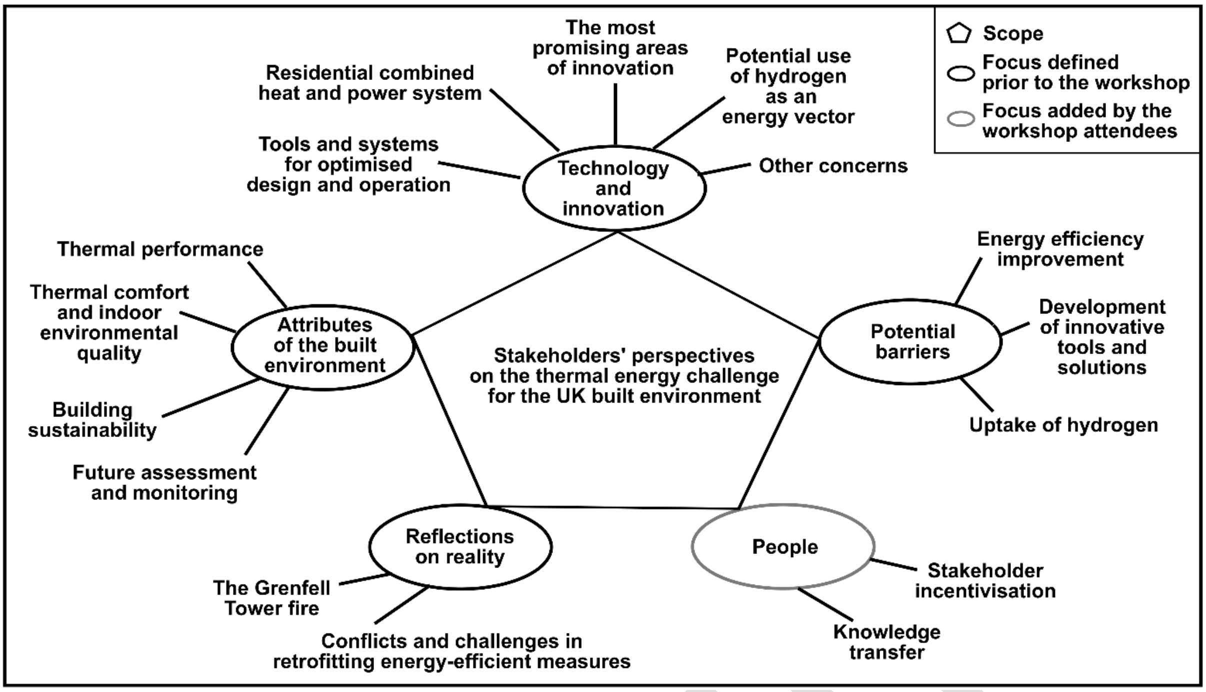

Figure 2: Scope and focus of the study.

The four-session design was crucial to stimulate active involvement, facilitate brainstorming and expedite the response of the attendees. The sessions complemented each other by enabling individual specific focus areas discussed in both small and open group discussion. Table 1 summarises the questions discussed and participatory modes implemented for each session during the workshop. The feedback was reviewed and clarified by the attendees after the workshop.

Table 1: Focus, questions and participatory modes designed and carried out during the workshop.

Session and focus	**Question**	**Participatory Mode**
Session 1, Attributes of the built environment	• Focussing on building fabric and/or technical systems, what areas of research would be needed to ensure high thermal performance and faster and more cost-effective deep renovations? • What approaches should be developed further to improve thermal comfort and indoor environmental quality? • What tools and/or initiatives should be employed to stimulate improvement in building sustainability? • What form of energy performance assessment and monitoring should be developed in the future? • What other questions should be asking? • What other issues would be relevant?	Small group discussion, followed by web-based audience response
Session 2, Technology and innovation	• What tools and systems should be developed to optimise the design and operation of existing heating and cooling systems? • Is residential combined heat and power system still a desirable solution? • What are the most promising areas of innovation in renewable thermal energy, thermal energy storage,	Small group discussion, followed by web-based audience response

	district heating and cooling systems, and hybrid energy systems? • Is there the potential for the increased use of hydrogen as an energy vector in the building sector? • What other questions should be asking? • What other issues are relevant to this topic?	
Sessions 1 and 2, Potential barriers	• Organise the barriers in descending order of prominence in the UK's current context: I Awareness of potential/benefit – insufficient knowledge about energy, cost and carbon savings from different measures II Professional skill shortages – lack of skilful contractors (for effective installation) and architects (who are familiar with low energy renovation design) III Competing investment priority – staff and equipment versus energy costs IV Information barrier – do not fully comprehend the effectiveness of technologies V Institutional bias – more familiar with supply-side investments than demand-side projects VI Multi-stakeholder issue – difficult to reach a decision for multi-owner buildings VII Structural issue – aging buildings and the landlord-tenant dilemma VIII Payback expectations – against proposals that required more than 5 years to pay back the investments IX Access to finance – required for investing energy efficiency measures X Financial incentive – to undertake energy retrofit investments XI Regulatory and planning – fragmentation, delay and gaps in the regulatory action of public planning • What are the main barriers currently preventing the development of innovative thermal energy tools and technological solutions? • What are the barriers to the use of hydrogen as an energy vector in the building sector?	Web-based audience response and group discussion
Session 3, People	• Should education and training be provided to improve the knowledge of building stakeholders? • How to incentivise people to use alternative technology?	Small group discussion, followed by web-based audience response
Session 4, Reflections on reality	• Deep renovations of buildings – how has Grenfell Tower moved the goalposts? • What are the conflicts and challenges in retrofitting energy-efficient measures?	Open group discussion

4 Results

4.1 Attributes of the Built Environment

4.1.1 Thermal Performance

Focussing on building fabric and/or technical systems, thermal performance of the built environment could be enhanced by effective design, monitoring and control. As a key factor, buildability (or constructability) must be the design focus as it would determine the easiness of building construction at a later stage. In applying different elements and components, details of the junctions between them should be clearly shown to the builders. Research areas required for effective monitoring included

(i) the development of rapid measurement tools;
(ii) the advance on the feedback loop for monitoring air tightness; and
(iii) the acquisition of more real-time, large-sample data.

Such data would be useful (with minimum variations) in analysing and validating occupant behaviour. With real-time performance, the options of using different materials could be compared. Altogether, these were necessary for better understanding in controlling real-time energy performance and avoiding overheating. In addition, they enabled deep renovations to be tailored to existing buildings in a faster, more appropriate and cost-effective way. From a social-technical perspective, research should be carried out to identify barriers and skill gaps among the workforce prior to providing training.

4.1.2 Thermal Comfort and Indoor Environmental Quality

The space and thermal condition in either a living or working environment should be more flexible to enhance the thermal comfort i.e. whether occupants would feel cold or hot. Other approaches included

- monitoring CO_2 levels and temperatures with user interfaces;
- developing high-level parameters and control mechanisms which were easy to understand; and
- integrating fabric measures (e.g. insulation and air-tightness) more effectively with building services (e.g. heating and ventilation).

The indoor environmental quality could be improved by installing and operating a fresh air filter. The regulations, in particular [36] should be reviewed regularly. Assessments of indoor air quality and thermal comfort have not been sufficiently performed. The situation could be improved by carrying out relevant assessments as recommended in the Regenerative Ecological, Social and Economic Targets (RESET) Standard and Building Research Establishment Environment Assessment Methodology (BREEAM) Framework. Incentives should be made available to enhance the practice.

4.1.3 Building Sustainability

As the key to building sustainability, the roles played by individual stakeholders were crucial. For instance, regulatory compliance would be met by the architects, builders and suppliers during construction by providing accurate estimates for energy use, fuel-cost-based efficiency rating and CO_2 emissions in line with [32, 33]. In addition, modular buildings as applied by the architects could result in continued development. Technical support and training provided by the suppliers and sustainability consultants within design and construction teams could raise sustainability awareness. Key performance indicators (KPIs) determined by the researchers and survey carried out among the occupants could reveal current energy management practice. Advanced tools included

- internal relative humidity and vapour pressure; and
- dynamic moisture equilibria through building fabric.

These tools would be required for a better understanding and management of moisture risk in buildings. Incentives including tax breaks, stamp duty, green landing deals and subsidies which could further stimulate building sustainability.

4.1.4 Future Assessment and Monitoring

A few suggestions were given in relation to the form of energy performance assessment and monitoring to be developed in the future. Conventional energy modelling methods could be improved by

(i) developing an incentivised system;
(ii) implementing a dynamic approach;

(iii) taking account of the life cycle of buildings;
(iv) adopting smart meters; and
(v) applying the concept of whole-building testing.

Better assessments would be required to manage the moisture risk and incorporate behaviour factors more effectively. A more robust monitoring protocol could generate high quality data and enable the development of assessment models with improved and more flexible defaults. Similar to the SAP, the National Calculation Method (NCM) for the Energy Performance of Buildings Directive (EPBD) should be updated and calibrated regularly. Also, the International Performance Measurement and Verification Protocol (IPMVP) should be integrated more effectively.

4.2 Technology and Innovation

4.2.1 Tools and Systems for Optimised Design and Operation

A number of tools and systems that could optimise the design and operation of existing heating and cooling systems were suggested. This was vital to manage the energy performance of the built environment. To enable design freedom, standards should be established based on performance. Simplicity, smartness, user-friendliness were the common quality desired for both controls and systems. Incentivised control based on real-time demand should be taken into account. For example, heating systems could be controlled based on demand by operating thermostatic radiator valves (TRVs) or local zone temperature sensors. Smart devices such as smart heating and cooling controllers and water control devices could lead to more efficient operation. Also, systems should be robust, integrated and independent of pre-defined users' behaviour. Nevertheless, building occupiers as well as facility management team members should be engaged, educated and trained to use the systems more effectively.

4.2.2 Residential CHP Systems

CHP systems for domestic households were a relatively new technology if compared to other conventional technologies. How industrial stakeholders perceived the application of CHP in the UK's residential buildings was discussed. It was reported that CHP was appropriate for

(i) existing large-scale applications which were currently not efficient and
(ii) district heating networks due to cheaper gas prices when compared to electricity.

However, the use of residential CHP was not desirable because of expensive costs required for installation, operating, maintenance and insurance. In addition to space and air quality requirements, there were technical difficulties in sizing the system and connecting to the grid without suffering from large distribution losses. From a technical perspective, the application would require sufficient operating hours to ensure a steady base load. It would also require a thermal storage (or a battery) system to provide reliable power supply. It was reported that almost all existing domestic CHP systems have not performed as promised. As the application involved a carbonised network, decarbonisation of the grid was also a concern. It was thought biofuel and hydrogen would be the alternatives in the future.

4.2.3 The Most Promising Areas of Innovation

The most promising areas of innovation were identified from the perspective of industrial stakeholders. These included renewable thermal energy and storage, district heating and cooling systems, and hybrid energy systems. Despite being widely researched, recovery of (low grade) heat, photovoltaic (PV) thermal and passive smart materials would remain as the focus of future technology. Producing useful, efficient heat from low grade sources could be more advantageous if innovative technology was integrated appropriately into energy systems. The adoption of low-carbon technology was also an important driver. For instance, by combining low-carbon heat pumps with conventional boilers, bivalent local heating systems with seasonably variable flow temperatures would have the potential to improve not only the coefficient of performance (CoP) of the heat pumps but also the overall efficiency of district heating systems. Codes of practice should be established and adopted to improve the quality of heat network performance and other measures. Examples included demand side response and flexible living. To transform solar PV into renewable electricity, improved battery technology and electricity storage would be required for intermittent power storage.

4.2.4 Potential Use of Hydrogen as an Energy Vector

Hydrogen could be produced by various sources. They included renewable (i.e. solar, wind, hydro, geothermal and biomass), non-renewable (i.e. natural gas, coal, oil and nuclear), and (thermochemical, electrochemical and biochemical) processes. There was the potential for the increased use of hydrogen as an energy vector in the building sector to store surplus energy and transfer it over space and time. Theoretically, when hydrogen was produced from PV systems integrated into the built environment, it could be transferred to a nearby CHP system and used for power generation. With proper technical modification, equipment which was operated by natural gas could be run by hydrogen, or vice versa. Apart from discussing the potential use of hydrogen as an energy vector in general, the industrial stakeholders were less enthusiastic about switching to hydrogen in the near future. This was mainly because of uncertainties and challenges involved in the technology uptake. Currently the UK Government does not recognise the use of hydrogen as an energy vector in the building sector. Investigation into fuel cell (hydrogen) domestic CHP has been carried out (for instance Intelligent Energy in Glasgow) but without success.

4.2.5 Other Concerns

To cover any concerns the industrial stakeholders might have, additional questions and issues therein were collected at the end of Sessions 1 and 2, as shown in Table 2 There were a broad range of concerns such as covering cost, future-proof design, ethics, communication, drives, metrics, transition, technology etc. The UK Government's proposal to phase out fossil fuel heating (as in [43]) was not envisaged by the workshop attendees.

Table 2: Additional questions and issues raised by the stakeholders during the workshop.

	Interactive Session 1	**Interactive Session 2**
Additional questions	• What is the proportion of energy cost in all energy-related costs e.g. maintenance, operation etc.? • How to measure decision makers' drivers (e.g. environmental quality, built quality, robustness, health and wellbeing)? • Should new builds be designed as future-proof instead of meeting current standards only? • What drivers are important to different people in terms of building design and use? • How to incentivise people to use alternative technology? • What is the impact of contracts on the entire process? • How can ethics, communication and training be improved?	• What are the agreed standard set of metrics to compare innovative technologies e.g. capital, operational cost, size per output, energy and carbon efficiency? • How should people be educated about the new technologies? • How to move from the current state to deriving hydrogen from water using renewable electricity instead of fossil fuels? • By taking transition and technology into account, is disruptive new technology appropriate for energy supply? • Why are systems still not being monitored to show the facts not theory and spin? • How will future distribution networks connect to buildings to deliver power for electric or hydrogen cars and what are the storage possibilities that should be looked at for energy?

	• How to ensure sufficient time is given to designers to do their job? • Should the building regulations be updated and reviewed? • Is there sufficient work force which is trained to a required level in respect to energy efficiency? • Can design engineers spend more time working alongside the building during the commissioning phase? • How to make energy performance more user friendly and understandable for building users? • Should a comparison/scale of energy performance be carried out? • Should education and training be provided to improve the knowledge of building stakeholders? • Is there legislation that can be amended or introduced? • How does energy performance vary across building types and with common occupancy patterns? • What do real occupancy patterns look like and can any generic ones be discerned? • How can the UK Climate Impacts Programme (UKCIP) predictions and scenarios for future climate be integrated into the performance prediction procedures, in order to take account of likely performance over the whole life of the building in a warming climate?	• Is carbon capture feasible or a waste of time? • Can network efficiency be improved by technology/manufacture of community generation/utilisation systems? • Why is alternative technology not being employed yet? • How to convince the decision makers who reject the adoption of alternative technology while taking into account the conflict of interest in energy industry? • How can people be incentivised to use alternative technology? • How could public members get financial support to uptake technology? • Why is the energy industry so slow to change if compared to other industries? • How can the infrastructure be powered to implement it?
Additional issues	• Inclusion of operation and maintenance drivers into design process e.g. minimum faults, easy maintenance, operation frequency and cost • Role for energy suppliers which is currently missing • Review of the design and build process	• All-electric buildings • Decentralised thermal storage for dwellings

	• Impacts on domestic properties, industrial and other commercial buildings	

4.3 Potential Barriers

4.3.1 Energy Efficiency Improvement

As shown in Figure 3, how the attendees perceived the barriers to improvement of energy performance of the built environment in the UK was analysed. In line with the total number of barriers, an 11-point Likert scale (in which 1 representing the least important barrier whilst 11 representing the most important barrier) was adopted. Some patterns were observed:

- Focussing on the 2 most/least important aspects which hindered the building's energy efficiency improvement in the UK, each barrier was recognised by at least one group i.e. 9.1% of the attendees. Such results indicated that none of the barriers was absolutely important nor not-important at all.
- Professional skill shortages (labelled as II in Figure 3) were recognised by 9.1% and 36.4% of the attendees as the most and the second least important barriers respectively when compared to the other barriers.
- In relation to the multi-stakeholder issue (labelled as VI in Figure 3), 45.5% perceived it as the second most important barrier, if not the most important one. In contrast, 18.2% felt that the multi-stakeholder issue was the second least important barrier amongst all.
- Awareness of potential/benefit (labelled as I in Figure 3) was ranked as the second most and the least important barrier by 27.3% and 9.1% of the attendees respectively.
- Institutional bias, access to finance and financial incentive (labelled as V, IX and X respectively in Figure 3) were identified as the least important barriers by 27.3%, 18.2% and 18.2% respectively.

Looking on the bright side, the diverse range of responses implied that there were no unshakable views among the stakeholders in the UK. Therefore, there was opportunity to improve the energy efficiency of the built environment in the UK, although it would be challenging to overcome the barriers before any negative perception rooted deeply in the community.

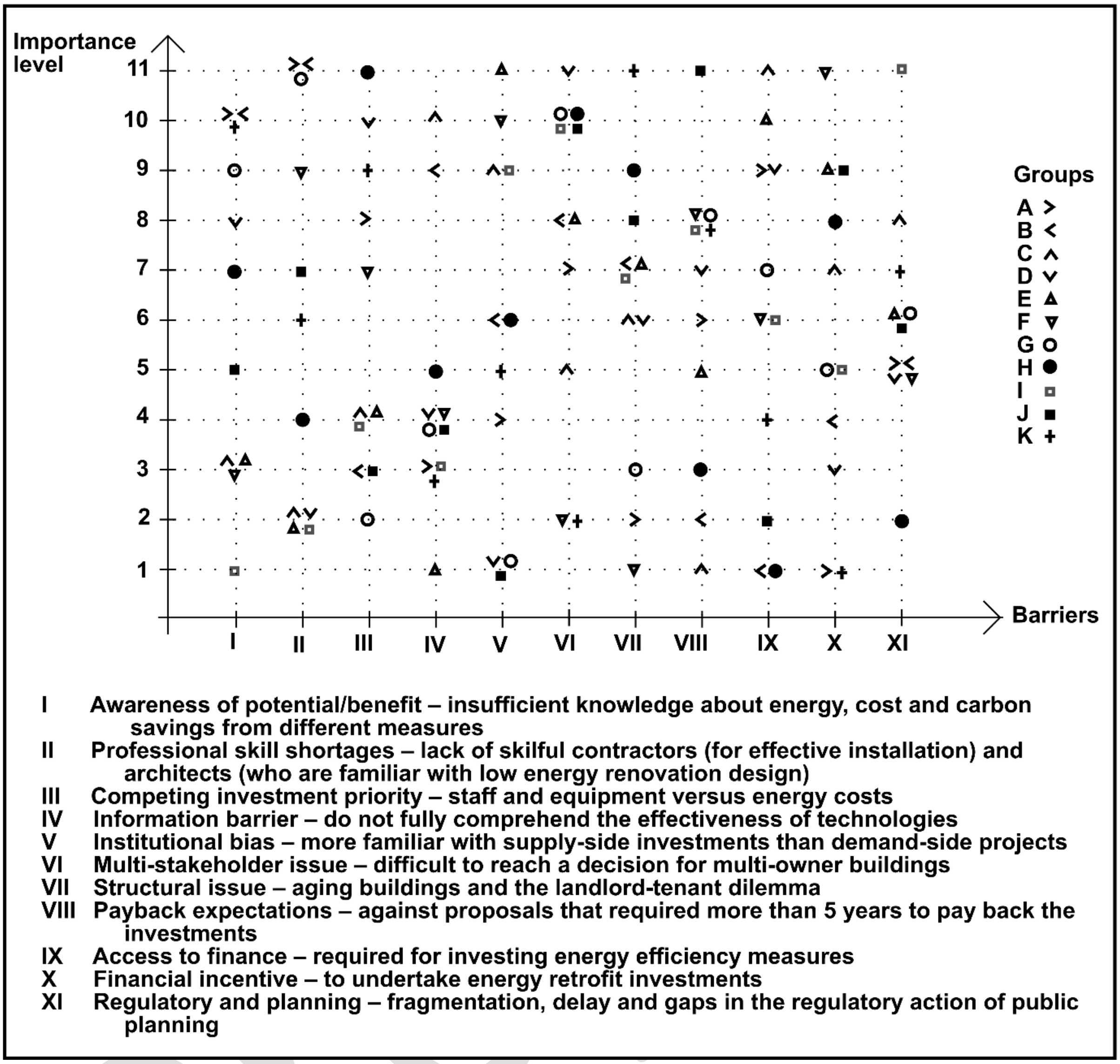

Figure 3: Importance level of the barriers to energy performance improvement for the built environment in the UK as perceived by the workshop attendees.

4.3.2 Development of Innovative Tools and Solutions

The development of innovative thermal energy tools and technological solutions could not show any competitive advantages over conventional technologies. A number of main barriers currently preventing the development of innovative tools and solutions were identified. These would invariably come with complex control systems and integration, which must be proven in a pilot study prior to commercial applications. However, the pilot study would seldom take place for various reasons, which resulted in the absence of innovation in technology.

As the UK energy market was monopolised by the Big Six energy suppliers (which offered both gas and electricity nationwide), developing the tools and solutions would involve a huge capital cost. This cost could be further increased if sufficient subsidies, incentives and funding were unavailable from the UK Government. Furthermore, such development would require in-depth discussion among highly-skilled personnel from multidisciplinary professions (e.g. material scientists, thermal/civil engineers, commercial lawyers, and health and safety officers, to name a few). However, opportunities for the personnel to exchange their ideas were not commonly available.

The situation would be worsened when neither an education nor training programme was provided to transfer the knowledge to the building occupiers. It would also be challenging to implement innovative technologies in the rental sector as the landlords would be reluctant to pay for the cost.

4.3.3 Uptake of Hydrogen

The uptake of hydrogen, which was a dangerous gas, as a new energy vector for the built environment might appear sceptical to society despite its potential. In fact, hydrogen might not be completely clean, depending how it was produced. If compared to PVs, a system operated by hydrogen would be less efficient. The infrastructure, knowledge and understanding of the application were still lacking. As such, transporting and storing a large volume of hydrogen would not be easy. Before it could be widely used, government support, which was currently unavailable, would be required to cover the expensive cost involved in realising such infrastructure change.

4.4 People

4.4.1 Knowledge Transfer

Knowledge was necessary to enable building operators to effectively manage the energy performance of the built environment. However, building operators (as well as other stakeholders) were restricted from in-depth understanding due to the lack of real-time data, actual costs, non-technical user guides and frequently asked questions (FAQ). To ease understanding, complicated systems should be simplified, control systems should be compared to alternative systems, and system tolerance should be highlighted. The evidence trail of efficiency could be available provided a simple guide on how to fit a cheap monitoring device was in place. Building owners should be encouraged to monitor and increase energy efficiency of their buildings. Both facility and technical managers should acquire sufficient level of knowledge about mechanical and electrical systems. It could be more pragmatic if facility managers were mandatorily required to get involved from the design phase through the consecutive phases such as installation, construction and commissioning. To assist designers and contractors to effectively apply the concept of energy efficiency in their daily tasks, regular training should be provided by the specialists. Tax breaks and business rate cuts were examples of incentives to stimulate the knowledge transfer among building stakeholders.

4.4.2 Stakeholder Incentivisation

Building stakeholders could be motivated to use alternative technology via various ways. Financial incentives could make alternative technology more affordable. Some examples were

- (i) direct support to ensure funding for new technology;
- (ii) reduced stamp duty on new homes that installed alternative technology;
- (iii) adjusted stamp duty for existing buildings to make Essentially, Energy Performance Certificates (EPC) more carbon sensitive;
- (iv) increased fuel tax which could be offset by lower income tax or a similar system to tax brackets e.g. increased electricity cost with usage; and
- (v) subsidies combined with regulation, e.g. the Merton Rule.

Removing risks, providing infrastructure to ensure the possibility of the uptake and assuring aftercare support to allow easy access to maintenance and repair specialists would appeal as compelling drivers in this regard.

The stakeholders could be educated and trained to compare conventional and alternative technologies in terms of monetary value. This could be done by taking account of (capital and running) costs and savings achieved via alternative technology applications. The full-life-cycle cost comparison could provide proof of performance. A UK Government sponsored educational/training programme should be made available, perhaps via social media as a means to reach out to the wider audience. Besides, housing regulations enforced by the UK

Government (e.g. the minimum energy efficiency standards set for the EPC as required for the sale of letting of buildings) would be imperative to ensure compliance among all stakeholders.

4.5 Reflections on Reality

4.5.1 The Grenfell Tower Fire

The Grenfell Tower fire was a red herring in relation to the question of deep renovation of buildings. The use of external cladding during deep renovation of domestic properties was proven thermally effective for minimising heat loss of low rise houses. However, there was a severe reaction to the Grenfell Tower fire which has had a major impact on the use of external cladding in the UK's high rise buildings. Whilst cost, aesthetics, weather resistance and effectiveness were key factors in external cladding, fire safety should be of paramount importance. After examination of the primary causes of the fire spreading, the continuous use of insulating cladding was debated by building stakeholders. As insulation was required for better energy performance, incombustible insulation materials could be used together with a compatible cladding system. This was required by the current regulations in the UK but not apparently complied with in some respects in the Grenfell Tower.

4.5.2 Conflicts and Challenges in Retrofitting Energy-Efficient Measures

The majority of the existing buildings in the UK were built before the enforcement of Building Regulations in 1965. The Regulations were assessed and became stricter over the years which resulted in different thermal performances across the built environment in the UK. There was a need to retrofit existing houses to meet the Climate Change Act's targets for an 80% reduction in greenhouse gas emission by 2050 based on the level in 1990. Some measures e.g. low-cost heat pumps and substantial renewable energy systems were suggested. However, it was uncertain whether UK houses were prepared for retrofitting despite the growth of electricity and thermal renewable energy to dominate domestic energy use. In fact, integrating energy-efficient measures into existing buildings could be challenging. For instance, converting homes from electrical to thermal energy would face technical issues such as hot water supply (via solar thermal, perhaps). This could have a knock-on effect on the local capacity of the grid which might subsequently require the employment of batteries. Meanwhile, determining the right size and location of heat pumps would be required prior to employment. Nevertheless, all houses should have a whole-house retrofit plan in a medium term. Such plan would consider the interactions between measures at the corners, junctions, edges and interfaces, which could be updated regularly.
On the other hand, some attendees argued that a fabric-first approach which chose the most ideal components and materials as building fabric should be adopted for optimum energy performance. The claim was made based on the belief that retrofitting energy efficient measures e.g. PV into buildings would in effect cover up the problem i.e. poor building energy efficiency.

Cost would be a prime consideration. As energy-saving technologies could not increase house prices significantly, they did not align with the objectives of housing developers. From the perspectives of developers, profitability was based on cost reduction (instead of energy saving) and sales of the houses. Unlike some continental countries, incentives, subsidies and/or tax breaks for retrofitting energy-efficient measures were not available in the UK. Thus, energy-efficient measures e.g. substantial renewable energy systems were less affordable and rarely fitted to the UK houses. The added value of the energy-efficient measures was not realised by property owners as well as first-time buyers. However, lower energy bills could bring more financial benefits to the property owners if they were reflected in a lower interest rate for highly energy efficient homes.

5 Discussion

Whether the industrial stakeholders and the UK Government were on the same page about issues discussed among industrial stakeholders (as reported in Section 4), if relevant, were analysed. This was uncovered by taking a closer look at relevant existing UK policies. The potential use of the findings in this study for real applications and a future outlook are presented to close the analysis.

5.1 Attributes of the Built Environment

5.1.1 Thermal Performance

In relation to design standards in the UK, building energy performance requirements were measured in terms of fabric energy efficiency and CO2 emission rates. These were not taken up by the industrial stakeholders during the workshop. In brief, fabric energy efficiency and CO_2 emission rates denoted energy demand in kWh and CO_2 in kg for 1 m^2 of floor area in a year respectively. As governed by [32, 33], the minimum energy performance requirements for new buildings should be determined by calculating Target Fabric Energy Efficiency (TFEE) for dwellings and Target CO_2 Emission Rate (TER) for all building types. In addition, during the design phase of new dwellings, the Dwelling Fabric Energy Efficiency (DFEE) and the Dwelling CO2 Emission Rate (DER) must be calculated to determine their actual energy performance.

Before commencing any construction work, builders would be required to produce specifications using the Standard Assessment Procedure (SAP2012). They would also be required to highlight the design features which were critical for compliance. According to [32], a new dwelling which was entirely constructed to the specifications would not only meet TFEE and TER but also result in DER and DFEE that were lower than TFEE and TER. Still, there was room for improvement as DER and DFEE were currently calculated based on inputs provided by the builders. Thermal bridges in the insulation layers which were formed during the installation phase would affect the actual energy performance of a building.

For commercial buildings, the use of building monitoring with control systems and energy meters to achieve the TER was highlighted in [33]. For instance, automatic meter reading and data collection were required. Also, centralised switching of appliances were highly recommended for buildings with a floor area larger than 1000 m2. Nevertheless, some buildings were exempt from the energy efficiency requirements, as clarified in [35]. They included

- protected buildings (due to designated environment, architecture or historical merit);
- religious buildings;
- industrial sites;
- workshops;
- non-residential agricultural buildings;
- temporary buildings;
- residential buildings which were rarely in use; and
- standalone buildings with a floor area larger than 50 m^2.

5.1.2 Thermal Comfort and Indoor Environmental Quality

A number of conventional building service technologies were presented in [37, 38], which might be applied to provide thermal comfort to the occupants. In [37, 38], installation guidance for relevant technologies was made available by the UK Government. They covered (i) gas- and oil-fired space and water heating, underfloor heating, community heating, solar water heating, mechanical ventilation, heat pumps and micro-combined heat and power (CHP) systems for domestic buildings; and (ii) boilers, heaters, heat pumps, CHP systems and community heating for non-domestic buildings. How to calculate energy requirements and efficiencies of these technologies was detailed in [39]. The impact of control systems on the energy performance of the built environment was identified in [42], which recommended providing building services with controls as a minimum improvement. The guides were fundamental for stakeholders to comply with energy efficiency requirements set for the systems as stated in the Building Regulations.

Ventilation was a possible alternative to control thermal comfort but it was not controlled by Building Regulations, as clarified in [36]. The Regulations only suggested sufficient/acceptable levels of ventilation, indoor moisture and pollutants for dwellings and non-dwelling buildings based on performance. Ventilation should be controlled (manually or automatically) to maintain reasonable indoor air quality and reduce energy consumption. In summer, over insulation of the building fabric could result in building overheating and therefore increase demand for indoor comfort i.e. comfort cooling. Minimum energy efficiency ratios and control systems were recommended for cooling comfort in [37]. In addition, two of the approaches recently proposed in [43]were relevant and echoed in [44]. They were (i) the reduced energy demand requirement set for new builds as a part of high environmental standards; and (ii) the upcoming clean air strategy to clearly project how fossil fuel heating could be phased out for improved air quality.

5.1.3 Building Sustainability

The UK Government have recognised that building sustainably was a major factor in resolving housing shortage issues in the UK. They have proposed to build the right homes in the right places, in a shorter time, for a diversified market with help and advice offered to potential residents.

As presented in [26], modular (also referred to as prefabricated, factory- or system-built) and custom-built homes would be promoted. As published in [32, 33], new buildings could comply with the energy efficiency requirements by meeting the following criteria:

- DER for dwellings or BER for non-dwelling buildings was lower than TER (and DFEE was lower than TFEE for non-dwelling buildings).
- Energy efficiency standards were achieved reasonably by individual fabric elements and the fixed building services.
- Passive control measures were applied for indoor temperature control.
- Buildings performances were consistent with DER, BER and DFEE (whichever relevant).
- Provisions should be in place to enable energy-efficient operation.

The same energy efficiency requirements would apply to modular buildings (which had more than a 2 year planned service life) as well. Special considerations should be made provided

(i) 70% of the external envelope of the modular buildings were built prior to the enforcement of [32, 33]; or
(ii) the modular buildings were frequently moved from one location to another in less than 2 years.

The UK Government expected housing developers to not only focus on design and quality but also invest in the research and skills base to build new homes rapidly, as indicated in [26]. This would enable the industry to be steered towards productive, efficient, innovative and sustainable construction.

5.1.4 Future Assessment and Monitoring

The need of future assessment and monitoring was verified by the update of the EPBD announced by the European Commission in July 2018 (see [47]). Under the newly revised directive, building occupants in the Member States would have to (i) install control systems and devices that regulate indoor temperature; and (ii) follow the schemes established for regular inspection of heating systems. Taking Brexit into account, it was not certain whether the UK Government would transpose the new provisions into legislation. However, there was no indication such provisions would not be considered. Meanwhile, IPMVP provided a framework to building occupants outlining how to quantify energy consumption that could be avoided when a particular energy conversion measure (ECM) was implemented. It involved developing a plan for measurement and verification and reporting the possible savings of an ECM. In the UK, IPMVP was not enforced by legislation. Consequently, an ECM would only be implemented for measuring and verifying the potential savings when an energy project was under consideration. It was recommended to be applied in conjunction with other appropriate indicators and techniques [48].

5.2 Technology and Innovation

5.2.1 Tools and Systems for Optimised Design and Operation

Tools and systems for optimised design and operation were presented in [37,38] where installation and minimum energy performance requirements were covered. These included heaters, ventilation systems, boilers, heat pumps and micro-CHP systems. According to [32, 33], the use of high-efficient system alternatives must be considered during the design phase and analysed from technical, economic and environmental perspectives. Suggested alternatives included cogeneration and systems driven by renewable energy sources such as decentralised energy supply systems and district heating and cooling networks.

5.2.2 Residential CHP Systems

The UK government was in favour of residential CHP systems, contrary to the negative attitude of the stakeholders. According to [38], CHP systems should be the lead heat source to supply at least 45% of the annual heat demand of community heating which were used in conjunction with boilers. The use of thermal storage was also recommended to meet the energy demand during peak periods. In [44], the Government recognised the need to improve air quality by regulating air pollutants emitted by small scale diesel generators and medium sized combustion plants. As such, the impact of CHP systems on the air quality should be investigated. As such, the impact of CHP systems on the air quality should be investigated.

In addition, considering the alternatives was encouraged for buildings which were about to undergo any renovation, as stated in [34]. However, the employment of such alternatives would be expensive and very likely infeasible in most cases. It was worth-noting that such alternatives were not mandatorily required by Building Regulations. As a result, conventional measures such as boiler seasonal efficiencies and window opening allowances would be chosen to meet the energy efficiency requirements. To support improvement in energy efficiency performance, voluntary building standards for commercial buildings would be explored by the UK Government, as recently indicated in [43].

5.2.3 The Most Promising Areas of Innovation

The use of low-carbon heat sources could reduce TER significantly, as fuel factors (which were required in the calculation of TER) were dependent on heat sources. As pointed out in [32], Building Regulations were technology neutral and the installation of low and zero carbon systems was not mandatory. However, the need of innovation and development could not be denied. In [29], the UK Government recognised innovation, modern infrastructure and skilful personnel as 3 of the 5 foundations necessary for the UK to remain as a great place for business investment. Clean growth was identified as 1 of the 4 grand challenges, in which the UK was aspired to become a global leader in developing, manufacturing and commercially applying low-carbon technologies, systems and services. Relevant areas included (but not limited to) smart energy systems, advanced construction, fuel switching and improved energy efficiency. The UK Government promised to enhance living and working environments with *high quality housing and clean, affordable energy*.

5.2.4 Potential Use of Hydrogen as an Energy Vector

The feedback of industrial stakeholders (i.e. hydrogen use in the building sector was unrecognised by the UK Government yet) was valid. In reviewing hydrogen economy for building application, [49] pointed out that hydrogen could be produced from

(i) natural gas reformation using solid-oxide or polymer electrolyte membrane fuel cells;
(ii) photocatalysis where hydrogen was separated from hydrocarbons or water by sunlight; or

(iii) system integration with a gas boiler, a heat pump driven by gas or a microalgae bioreactor.

Nevertheless, [49] also reported that hydrogen use in buildings was restrained by technical complexity, capacity and high capital costs. This was in agreement with the current UK context. In fact, hydrogen and fuel cell opportunities was explored, for instance in 2006, see [50]. Also, economy development and future infrastructure design of hydrogen energy in the UK were investigated between 2009 and 2015, as confirmed by [51]. None was fruitful nor leading towards implementation. More R&D and support from the UK Government were required should the nation wish to employ hydrogen energy in future.

5.3 Potential Barriers

5.3.1 Energy Efficiency Improvement

Energy efficiency is pertinent to energy consumption, emissions, performance and sustainability. In brief, enhanced energy efficiency leads to lower energy consumption, reduced emissions, higher performance and improved sustainability. The strategies recently formulated by the UK Government were more proactive which provided financial motivation for energy efficiency improvement. The UK Government proposed to tackle thermal performance of the built environment by improving home energy efficiency and rolling out low carbon heating. As recently presented in [43] to the UK Parliament, £3.6 billion would be invested to upgrade one million homes through Energy Company Obligation (ECO). Energy performance standards would be strengthened to improve energy efficiency of all commercial buildings and homes, regardless of whether they were new, existing, privately rented or owned. Heat networks across the country would be developed to phase out fossil fuel heating in all homes (which were off the gas grid). Also, new boilers with improved standards and control devices would be used. Meanwhile, £184 million would be made available for developing new energy efficiency and heating technologies whilst £20 million would be spare for early stage clean technology development. The Renewable Heat Incentive would be reformed where £4.5 billion would be spent to support low carbon heat technologies in homes and businesses. As indicated in [43], the UK Government would require mortgage lenders to support energy-efficient properties by developing and providing green mortgage products with enhanced repayment schemes.

5.3.2 Development of Innovative Tools and Solutions

Constructing new buildings that could operate more efficiently and improving building performance were part of the UK Government's new strategy, as clearly indicated in [29]. This would transform the UK building sector and result in lower emissions. In appreciating the role of research and innovation, R&D tax credit rate was raised up to 12% [52]. A total budget of £170 million was made available for a national building construction programme [53]. The allocation would be used to develop an innovation hub, establish an active centre and support relevant R&D projects. The envisaged solution was to integrate low-cost energy generation, management and storage into new buildings more efficiently at building level. It was further supported by industry's committed match i.e. £250 million in total. Calls, for instance [53, 54], were announced for research proposals on innovations in the built environment. The targeted innovations included

(i) smart meters;
(ii) low carbon heating technologies;
(iii) building thermal efficiency; and
(iv) smart heating systems.

5.4 People

5.4.1 Knowledge Transfer

In line with [43], the UK Government recognised the need for knowledge transfer via training and education. This was necessary in expediting the national clean growth plan for building construction. In establishing a National Retraining Scheme, £64 million was made available for training and reskilling. In addition, £406 million was allocated for education to reinforce science, technology, engineering, and maths skills [52]. The long-established Construction Industry Training Board (CITB) was involved to provide opportunities for staff training, skills development and apprenticeships.

5.4.2 Stakeholder Incentivisation

Any forms of incentivisation by the UK Government such as stamp duty and lower tax would be valuable but they were currently unavailable. Nevertheless, costing and profit dilemma faced by building developers was acknowledged in [26]. The current UK market was highly dominated by big construction companies. Therefore, the UK Government would attempt to diversify the market and support more small and medium innovative building developers. The following strategies were proposed in the new policy:

- supporting a joint working group among lenders, valuers and the building industry to
  (i) develop a stronger evaluation approach used in measuring the performance of various technologies,
  (ii) ensure the availability of mortgages across a range of tested construction methods, and
  (iii) facilitate good decision making;
- investigating how the planning system could operate effectively to enable the development of modern construction methods; and
- creating new opportunities to apply modern construction methods and support the delivery of high quality, energy efficient homes through an Accelerated Construction Programme and the Home Building Fund.

The Home Building Fund would provide short- and long-term loans (which were worth £1 billion and £2 billion respectively) to building developers and regeneration specialists. The funding should be used to deliver new homes, prepare construction sites and develop infrastructure necessary for the housing projects.

5.5 Reflections on Reality

5.5.1 The Grenfell Tower Fire

The overly complicated and sloppy process of demonstrating compliance might be the cause of negligence. A quick practical solution would be to move away from fire safety engineering (which demonstrated theoretical compliance) towards a more prescriptive approach to compliance. Besides, changing cladding materials, would cause boundary issues for architects and developers due to the increased thickness for equivalent performance. If materials such as clay panels were embedded with phase change materials (PCMs), they might be flammable or toxic under certain circumstances. The existing building regulations on thermal performance could not be met unless a relaxation was temporarily put in place. If necessary, more regulations to cover any flammable materials and check on thermal performance and moisture in buildings should be introduced. The Grenfell Tower fire has not changed the goalposts but reinforced the need for compliance.

5.5.2 Conflicts and Challenges in Retrofitting Energy-Efficient Measures

Legislation should play a stronger role to mitigate the effects of global warming. Grants and tax breaks should be made available as a reward to property owners who incorporate energy-efficient measures. . The UK Government could enforce legislations to improve the situation. If energy efficiency initiatives were introduced, measures should be taken to prevent contractors installing stick-on solutions with insufficient technical knowledge or accountability. The reflection was made in particular on the creation of thousands of inexperienced installers under the UK Renewable Heat Incentive (RHI) scheme in 2011 due to insufficient number of qualified installers. Also, research on the built environment currently funded by the UK and the EU funding bodies were of different technology readiness levels. The former was closer to the technology development instead of system launching and operation. In the UK, preference should be given to industry-led projects with contributions from R&D.

5.6 Future Outlook and Potential for Real Applications

As experienced personnel in the field, the workshop attendees were familiar with the national policies related to thermal performance of the built environment. This was evidenced by their references of relevant regulations and practice. However, the comparison between their feedback and relevant national policies showed no close alignment in most aspects. A number of future needs and development were advocated by the stakeholders, as highlighted below:

- real-time effective performance control using advanced measurement tools and based on better understanding of occupant behaviour;
- CO_2 level and temperature monitoring with user interfaces;
- user-friendly high-level parameters and control mechanisms;
- modular buildings for improved sustainability;
- improved modelling methods with dynamic, life-cycle based, incentivised systems which incorporated smart meters and whole-building testing;
- heat recovery, PV thermal and passive smart materials; and
- performance-based standards.

The workshop attendees had legitimate concerns about pilot studies, funding, dialogue among different professions and innovative technology uptake, as evidenced by [43]. A few new funding opportunities were provided by the UK Government. Still, the industrial stakeholders were keen for the offer of other forms of incentives. These included tax breaks, stamp duty, subsides etc. and technical support e.g. training and educational programmes. These indicated no objection to the industry employing low carbon technology alternatives in the future. To enable commercial applications in UK buildings, development of low carbon technologies integrating renewable resources, hybrid systems, efficient processes and tools should be expedited. Environmental impact assessment and economic analysis should also be carried out.

Provided existing barriers were overcome, the employment of such innovative technologies could become mandatory in the near future. This would significantly reduce greenhouse emissions emitted by UK buildings. The use of hydrogen as an energy vector for heating buildings in the UK was not certain. Still, its potential should be explored and investigated via feasibility studies, technology development and demonstration prior to drawing any conclusion. Future national policies should be drawn up in consultation with industrial stakeholders. This would significantly improve the thermal performance of the built environment and rise to the challenge of meeting the national Climate Change Act's targets.

By consulting industrial experts in the field, the findings of this study uncovered current and future needs of building thermal performance in the UK. The study bridged communication gaps among building stakeholders. The findings were crucial for real applications to awaken researchers to the actual needs of the UK building sector. This could avoid R&D studies that have no or minimal benefits to building end-users. UK resources could be allocated more strategically to maximise the benefits of R&D to the society. The investigation of strategies required to rise to the challenge could be used in real applications by all building stakeholders. For instance, the findings could help to further shape the national and organisational strategies in creating a cleaner and more sustainable future for the sector.

6 Conclusions and Policy Implications

In relation to thermal performance of the built environment in the UK, it was argued that the stakeholder perspectives and their alignment with existing national policies were not clear. To uncover such missing information, this article reported the feedback received from experienced industrial stakeholders during and after a live-response-based interactive workshop. Topics such as selected building attributes, technology and innovation, barriers and reflections on reality were discussed. The industrial stakeholders perceived the future needs to be

(i) real-time effective performance control;
(ii) CO_2 level and temperature monitoring with user interfaces;
(iii) user-friendly high-level parameters and control mechanisms;
(iv) modular buildings;
(v) improved modelling methods (with dynamic, life-cycle based, incentivised systems);
(vi) heat recovery;
(vii) PV thermal,
(viii) passive smart materials; and
(ix) performance-based standards.

The analysis was complemented by highlighting relevant national policies. Whilst considering high-efficient system alternatives was currently a must (but their application was not mandatory), future strategies were envisaged by the UK Government:

(i) exploring voluntary building standards to improve energy efficiency performance of commercial buildings;
(ii) expecting housing developers to invest in research skill base; and
(iii) becoming a global leader in developing, manufacturing and commercially applying low-carbon technologies, systems and services.

The analysis on the barriers and people aspects showed that although there were no unshakable views among the industrial stakeholders, it would be challenging to implement innovative technologies. The barriers could be overcome with significant motivation via various forms of knowledge transfer and incentivisation. The reflections on the Grenfell Tower fire reinforced the need to strictly comply with Building Regulations. Meanwhile, reflections on the conflicts and challenges in retrofitting energy-efficient measures indicated the need of industry-led projects with contributions from R&D in addition to financial incentives. As such, challenges, future needs and strategies to improve thermal performance of the built environment in the UK were addressed. The study showed that despite the absence of close alignment between stakeholder perspectives and national policies, there was no objection to employ low carbon technology alternatives in the future.

To strategically improve thermal performance of the built environment, industrial stakeholders should be closely consulted in forming future national policies. The study was important and would be beneficial to the building sector in the UK. The findings had not only provided insights but also assisted both the industrial stakeholders and the policy makers in their daily practice and long-term strategy planning. The stakeholder perspectives and national policies should be analysed from environmental and economic perspectives in future study. Industry consultation should be continuously engaged in forming future national policies. Also, the findings and analysis presented in this article were valid in the UK context only, which could be further explored in future study on a European or global scale.

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