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Review

The Critical Role of IoT for Enabling the UK's Built Environment Transition to Net Zero

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Abstract

The built environment contributes approximately 25% of the UK's total greenhouse gas emissions, positioning it as a critical sector in the national net-zero strategy. This review investigates the enabling role of the domestic smart metering infrastructure combined with other IoT systems in accelerating the decarbonisation of residential buildings. Drawing from experience gained from governmental and commercially funded R&D projects, the article demonstrates how smart metering data can be leveraged to assess building energy performance, underpin cost-effective carbon reduction solutions, and enable energy flexibility services for maintaining grid stability. Unlike controlled laboratory studies, this review article focuses on real-world applications where data from publicly available infrastructure is accessed and utilised, enhancing scalability and policy relevance. The integration of smart meter data with complementary IoT data—such as indoor temperature, weather conditions, and occupancy—substantially improves built environment digital energy analytics. This capability was previously unattainable due to the absence of a nationwide digital energy infrastructure. The insights presented in this work highlight the untapped potential of the UK's multibillion-pound investment in smart metering, offering a scalable pathway for low-carbon innovation for the built environment, thus supporting the broader transition to a net-zero future.

Keywords: net-zero target for the built environment sector; IoT for the built environment; domestic smart metering infrastructure; smart metering data; energy data and digitalisation; energy intelligence for the built environment

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1. Introduction

The UK has committed to decarbonise all sectors of the economy to reach its net-zero target by 2050 [1]. Specifically, the residential built environment contributes 20.8% of all carbon emissions in the UK [2]. In 1976, building regulations first outlined the minimum requirements for insulation and built quality [3] to support improved energy efficiency of homes. In terms of regulatory energy models, the UK government issued the Standard Assessment Procedure (SAP) in 1993, the Reduced Data SAP (RdSAP) in 2005, which is a simplified version of the SAP, and then the Energy Performance of Buildings Directive (EPBD) in 2006 [4]. These regulatory models created a basis for understanding

the energy performance of the new and existing building stock and often provide the basis for informing the UK's policy for the built environment [5].

However, the energy consumption of a building measured while in use has been found to be up to 272.9% greater than predicted by design calculations, though some of this discrepancy may be attributed to occupants' behaviour [6,7]. Moreover, measurements of building fabric performance on unoccupied buildings have found an underperformance of up to 140% when compared with the model [8]. This discrepancy, known as the building Energy Performance Gap (EPG), can be caused by a variety of factors such as climatic conditions, building quality, design changes or material substitutions [9–13].

Reliable testing and measuring methods are required to verify the effectiveness of the new building regulations by measuring rather than estimating a building's energy performance. However, collecting high-quality energy and outdoor climate data [14] was challenging before the existence of Internet of Things (IoT) technologies, especially at a large scale. Prior to the IoT era, measuring energy use in the built environment relied upon traditional metering. Low-frequency energy consumption data, such as annual or quarterly meter readings, was manually collected alongside mean temperatures from nearby weather stations for analysis purposes. These two measured quantities were used to estimate a building's energy performance. Later, energy performance estimates were improved in terms of accuracy by including indoor temperature using sensors and data loggers. However, field trials often consisted of small samples (test houses) due to the difficult nature of data collection and the cost of equipment, with larger trials relying on low numbers of data points assuming falsely that all homes exhibit a similar heating pattern as indicated in [15]. It also required multiple site visits to extract the data and troubleshoot sensing equipment, which could increase the project cost significantly. Furthermore, since testing for energy performance metrics has to take place during the heating season [16], equipment failure and faulty sensors could cause year-long delays, meaning there was a requirement to repeat the test during the following heating season. These difficulties restricted researchers to small numbers of test houses so as to maintain the test and to obtain good-quality data. The energy performance estimation methods used often utilised Heating Degree Days (HDDs), which assume that heating is required when the outdoor temperature falls below a certain threshold [17], or the Energy Signature model, which assumes the indoor temperature to be quasi-constant [18], while other methods assume a constant comfortable temperature at, e.g., 21 °C everywhere in the home. Although these initial methods had drawbacks when estimating a building's energy performance, they laid the foundation for the more advanced methods. These advanced methods require higher data quality, as well as additional measured quantities which are necessary for the more accurate estimation of a building's energy performance. The requirement for high-quality, remotely accessed data has been met through IoT-enabled monitoring systems.

Thus, until relatively recently, the desired metrics were coarsely estimated, rather than measured frequently, due to cost and technical difficulties associated with acquiring and accessing the data of interest. However, the smart meter rollout alongside the development of cost-effective and reliable IoT products and services has provided the built environment sector with the opportunity to measure rather than approximate the physical quantities which are necessary for developing highly accurate models for the built environment.

The three principal entities who are driving Great Britain's (GB's) smart meter rollout for homes and small businesses are the Department for Energy Security and Net Zero (DESNZ) [19], the Office of Gas and Electricity Markets (Ofgem) [20] and the Smart Data Communications Company (DCC) [21]. The Smart DCC is a licensed monopoly with the aim of managing the smart meter telecommunication network and also with a focus on the utilisation of smart metering data for the public benefit. DCC's license has been

granted by the government and is regulated by Ofgem. This national asset—which is a GBP 13.5 billion public investment—benefits energy suppliers and distribution system operators (DSOs) and assists several economic sectors in reaching their net-zero target [22]. The built environment is among the sectors that derive significant benefit from the utilisation of smart metering data for its decarbonisation [19].

At this point, it is important to clarify that the domestic smart metering infrastructure is deployed exclusively in GB, and not across the UK. Accordingly, this article uses the terms "UK" and "GB" with precision to reflect this distinction.

The smart metering rollout provides the built environment with the opportunity to access the imported (grid to home) and exported (home to grid) energy data of a building [23,24]. Until now, GB's smart metering infrastructure has been primarily used for billing, energy monitoring and integration of domestic renewable sources. However, it has the potential to deliver additional services. For example, the imported and exported energy data can be combined with other data quantities such as indoor (home) temperature and weather data accessed through IoT monitoring systems in order to develop accurate models for a building's energy performance and efficiency. Furthermore, the electricity meter (Figure 1) readings can be used for the identification of domestic appliances using pattern recognition methods, for assessing energy-saving products and services, and for other energy-related applications and services. Nevertheless, despite the growing use of IoT devices and smart sensors, approximating/estimating certain quantities cannot be fully avoided due to the complexity of a building's energy dynamics and its interaction with indoor activities and outdoor conditions such as occupant-driven ventilation [25] and solar gains [26].



Figure 1. Smart electricity meters rig installed in the Smart Meters > Smart Homes (SMSH) lab—the SMSH lab belongs to the Energy House Labs at the University of Salford. The photo originates from material that belongs to the Energy House Labs.

To support the development of energy-related innovative products, technologies and services for the built environment, the government has developed dedicated funding programs. Specifically, the Net Zero Innovation Portfolio (NZIP) is a GBP 1 billion funding scheme, initiated in 2021 by the DESNZ [27], in order to accelerate the transition to net zero by 2050 and enhance UK's green economy growth through the commercialisation and cost reduction of innovative technologies for decarbonisation; NZIP was launched as part of the government's Ten Point Plan for a Green Industrial Revolution [28]. The NZIP funding

scheme supported innovation across selected priority areas including the built environment [29–31]. The funding of the programme was awarded through open competitions encouraging collaboration among SMEs, organisations and academic institutes. Examples of the NZIP funding scheme include the Flexibility Innovation Programme (FIP) [32], which is a GBP 65 million programme focusing on the areas of systems' integration, data, digitisation and markets for flexibility, as well as the Heat Pump Ready programme, which is a GBP 60 million programme focusing on high-density deployment and optimised solution development for heat pumps [31].

Other governmental initiatives related to the decarbonisation of the built environment are (i) the Boiler Upgrade Scheme (BUS), which is a GBP 205 million programme for the decarbonisation of heat in buildings in England and Wales as part of the Warm Homes Plan [33,34]; (ii) the Transitioning to a net-zero energy system: smart systems and flexibility plan, which is a comprehensive strategy by the UK government and Ofgem focusing, amongst others, on supporting consumer energy flexibility, as well as removing the barriers and reforming the flexibility market [35]; (iii) the Social Housing Decarbonisation Fund (SHDF)—Waves 1, 2.1 and 2.2 [36], which is a GBP 1 billion scheme aiming to improve social homes in England in terms of their energy performance; and (iv) the Claiming Research & Development (R&D) tax relief aiming to support companies which are involved in R&D projects [37].

Similarly, in 2021, Ofgem launched the Strategic Innovation Fund (SIF) aiming towards a low-carbon gas and electricity network future. Ofgem is expected to invest GBP 450 million through SIF by 2028 [38]. Although SIF focuses primarily on electricity and gas networks, it also funds projects for the decarbonisation of heating in local communities such as in [39].

The insights presented in this article are grounded in knowledge and experience we gained through multiple governmental and commercially funded R&D projects, including SMIOTS (DESNZ/FIP) [40], Net Zero Terrace (Ofgem/SIF) [39], SEDR (DESNZ/FIP) [41], and THOM (DESNZ/Heat Pump Ready programme) [42].

Several review studies underscore the substantial impact of IoT on efficiently managing energy and reducing the energy consumption of the residential built environment sector. Notably, [43] offers a comprehensive overview of IoT energy-related applications for the built environment, including energy monitoring and management, alongside non-energy-related IoT-enabled applications such as air quality monitoring, security, and structural health monitoring. The article also identifies IoT implementation barriers, technical integration challenges, as well as technical and non-technical concerns including safety and confidentiality, the ecological impact, socioeconomic inequalities and limitations in the interoperability of IoT systems. Review articles [44,45] also provide in-depth analyses of IoT technologies for the built environment sector. In [44], an overview of IoT system architectures is provided with a focus on smart buildings' related applications. The article also outlines constraints associated with IoT technologies and offers insights and recommendations for built environment professionals. In [45], a detailed analysis of IoT in energy is provided, covering system components, communication protocols and applications. It also addresses key challenges, security threats, and emerging trends highlighting the Green IoT as a promising future direction for developing energy-efficient devices throughout their lifecycle.

This article distinguishes itself from existing review studies by focusing on the role of the UK's IoT national infrastructure as a key enabler for the decarbonisation of the built environment sector and for supporting grid stability. The domestic smart metering infrastructure serves as the national IoT backbone—central to the UK's energy transition and digitalisation strategy; thus, its utilisation for the decarbonisation of the built envi-

ronment sector further enhances its value and relevance. So, in this paper, the capabilities of the publicly available IoT infrastructure combined with commercially available IoT products and services will be explored to address current challenges and to assist the built environment sector in its journey towards the net-zero target.

Indicative examples of services and applications enabled by the domestic smart metering infrastructure are briefly presented in Section 2. In Section 3, an overview of the basic steps of data acquisition and access from the domestic smart metering infrastructure—which has the same features/key components as any other IoT system—is provided. In the same section, representative Key Performance Indicators (KPIs) for assessing energy-related interventions and field trials are presented, as well as four indicative built environment use cases. In Section 4, there is a description of some of the quantifiable and non-quantifiable limitations and challenges of IoT-enabled built environment projects. In Sections 5 and 6, certain privacy and General Data Protection Regulation (GDPR) aspects of the built environment's field trials are highlighted, closing with a summary section where potential future research and development directions are outlined.

2. Opportunities for the Built Environment Sector from the Domestic Smart Metering Infrastructure

The data accessing capabilities of the domestic smart metering infrastructure and the prevalence of IoT technologies have created opportunities to assist the built environment in its journey towards the net-zero target. Specifically, the Smart DCC infrastructure provides the consumer with the unique opportunity to access their electricity and gas meter readings [21,46].

The DCC infrastructure relies on a bespoke cybersecure network, fully managed and controlled by the Smart DCC and independent of other mobile networks or local broadband connections, as presented in Figure 2.

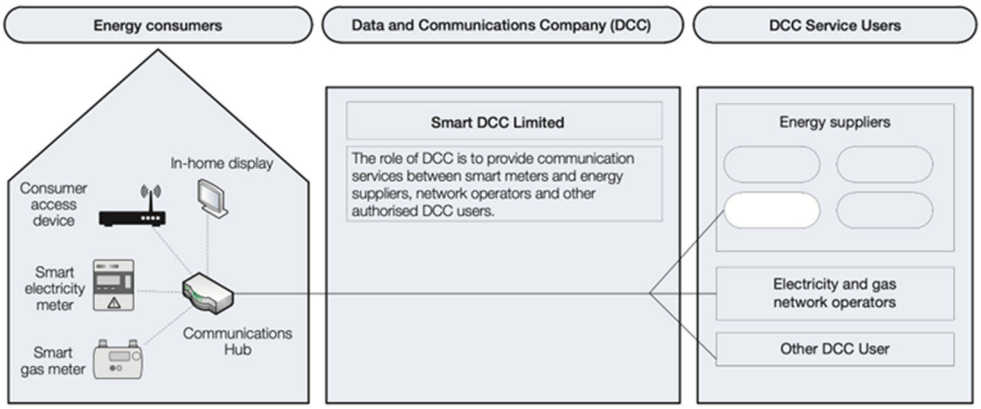


Figure 2. Overview of the end-to-end DCC system—figure adapted from [47]. The figure is retrieved from publicly accessible sources.

The following built environment-related products and services—enabled through the domestic smart metering infrastructure and other IoT systems—not only change the pattern of energy consumption but also create opportunities for new research questions to understand what might be considered an energy systems' transition [48].

2.1. Time-of-Use (ToU) and Other Tariffs for Load Shifting and Cost Saving

The increasing number of Electric Vehicles (EVs) alongside the electrification of heating (e.g., Air-Source Heat Pumps (ASHPs)) will soon result in an increase in both the total and peak electricity energy demands. Static and dynamic ToU tariffs could partially alleviate the peak-related issue by shifting the peak demand during time windows when the energy

need on the network is lower. Dynamic optimisation algorithms can utilise day-ahead dynamic ToUs, alongside weather forecasts and indoor temperature data, in order to reduce the peak energy demand as well as the cost, as consumption is shifted to lower-demand time windows when the energy cost is lower [49]. Dynamic ToUs are available through the Electricity Smart Metering Equipment (ESME), whereas the indoor temperature and outdoor/weather data, which are necessary for developing dynamic optimisation algorithms, can be accessed through IoT-enabled sensors.

2.2. Home Energy Management System (HEMS)

HEMSs monitor the energy consumption and generation of a household and manage the energy flows using pattern recognition and machine learning algorithms [50] in order to save energy and reduce the cost for the consumer. A HEMS accesses imported, exported and generated energy, indoor and outdoor temperature, and other IoT data in order to develop the relevant optimisation models.

The corresponding system for managing the energy consumption/generation of a large building is called a Building Energy Management System (BEMS), and a Community Energy Management System (CEMS) manages the energy consumption and generation at the community level.

2.3. Demand Side Response (DSR)/Energy Flexibility Services

Another area where the domestic smart metering infrastructure plays an enabling role is energy flexibility services, where high-energy-consuming appliances/devices such as EV chargers, ASHPs, and Heating, Ventilation and Air-Conditioning (HVAC) systems can communicate with the DSR Service Provider (DSRSP) over one or more Customer Energy Manager (CEM) systems. CEMs negotiate different scenarios and the DSRSP selects the optimum combination in order to assist the grid in maintaining its balance during time windows of higher demand [47,51]. Note that the appliances/devices in a DSR configuration need to have capabilities/technologies for data exchange/communication and for automatic control.

2.4. Assessment of a Building's Energy Performance

Smart metering data, alongside other IoT data, can be used to estimate a building's energy performance. The Heat Transfer Coefficient (HTC) is a data-driven indicator which is related to the Energy Performance Certificate (EPC) rating of a building and can be measured using smart metering alongside other IoT data when a property is either unoccupied via a co-heating test or occupied [18,52]. The assessment of a building's energy performance using the HTC is particularly useful as EPC ratings are often outdated (buildings are not assessed regularly) and may incorporate subjective information, whereas HTC is data-driven, can be 'real-time' and without subjective input in its estimation.

More details on the utilisation of IoT data for assessing a building's energy performance can be found in Use Case 3 (Section 3.4).

2.5. Assessment of Energy-Saving Products

Electricity and gas smart metering data, alongside other IoT data such as temperature and humidity, can be used to assess energy- and carbon-saving products, e.g., smart heating control devices [53].

More details on the use of IoT data for assessing/testing energy- and carbon-saving products can be found in Use Case 4 (Section 3.4).

2.6. Home Appliance Identification, Data Disaggregation and Grid Load Forecasting

The instantaneous power demand of a household—estimated through the aggregated electricity energy data accessed from the smart meter—can be used for applications such as load disaggregation using pattern recognition algorithms [54].

Furthermore, Artificial Neural Networks (ANNs) and other machine learning techniques, are used for the analysis and processing, both in real time and offline, of high volumes of energy data for managing the smart grid, energy consumption forecasting, fault detection diagnosis and other related areas [55,56].

More details on this application can be found in Use Case 1 (Section 3.4).

2.7. Data-Driven Policy Making on Fuel Poverty

Fuel poverty is a multi-dimensional concept, and its complexity may only be captured through a variety of indicators; the EU Energy Poverty Observatory uses primary and secondary data driven as well as subjective indicators [57]. Energy consumption data, accessed from the domestic smart metering infrastructure, combined with weather, occupancy and demographic data could form an additional data-driven indicator.

3. Data Acquisition, Access, and Analysis

Before analysing data from a domestic smart meter, as with any IoT system, a two-stage process must first be carried out. For the first stage, the quantity of interest is measured/acquired using meters/sensors, and for the second stage, the measured data is accessed [58]. This two-stage process requires a Communication Hub which collects the acquired data and then, usually, transmits it to a server for storing purposes.

Appropriate protocols are used for communication, data transmission and reception among the sensors and the hub(s), and transmission of the gathered data to the server. Then, the user can access the data from the server using an Application Programming Interface (API)/or other interfaces in order to undertake data processing and analysis [59].

In the following two subsections, the two-stage process of data acquisition and access is described, with a focus on the domestic smart metering system. However, the same process is common for all IoT systems.

3.1. Data Acquisition and the Domestic Smart Metering Infrastructure (SMETS1/SMETS2)

There are two types of smart metering equipment rolled out in GB, SMETS 1 and SMETS 2; SMETS stands for Smart Metering Equipment Technical Specifications. SMETS 1 corresponds to the first generation of smart metering equipment installed in GB and SMETS 2 to the second generation, which is technologically more advanced compared to the first generation, mainly in terms of communicating the meter readings to the energy supplier and the switching between energy suppliers [60–62].

The smart metering system consists of the following devices: the electricity smart meter or Electricity Smart Metering Equipment (ESME), the gas smart meter or Gas Smart Metering Equipment (GSME), the In-Home Display (IHD) and the Communication Hub (CH) usually fitted to the ESME.

The (a) ESME and the (b) GSME measure (a) the imported and exported (if the property has renewables) electricity energy and (b) the gas energy, respectively. The granularity of the data measured through the ESME is 10 s for the imported electricity energy and through the GSME is 30 min for the gas energy. The CH transmits the electricity and gas data, acquired by the meters, to the data collection entity, which shares the energy data with the Energy Supplier for billing as well as for data processing and analysis purposes. The IHD displays the electricity and gas consumption data to the consumer alongside additional information, such as the energy tariff, the corresponding energy cost and the

carbon footprint produced by the consumed energy. The ESME and CH, GSME and the IHD devices communicate over the Home Area Network (HAN), using the ZigBee smart energy protocol [63].

3.1.1. IoT Protocols for Applications Related to the Built Environment

The development of highly efficient communication protocols has played a key role in the extensive use of wireless sensors for energy-related built environment applications.

In the following table (Table 1), a brief overview of the most popular IoT protocols utilised for built environment applications, their advantages and disadvantages, and future trends in the field of IoT protocols is presented.

Table 1. Overview of IoT protocols.

Protocol	Description	Benefits	Challenges
ZigBee	The ZigBee protocol uses the 2.4 GHz band, also used by WiFi, and also supports sub-GHz ranges [64,65].	(i) ZigBee devices generally have lower power consumption. (ii) The ZigBee bandwidth size is appropriate for transmitting/receiving high volumes of data. This is an important parameter in configurations where the sensors need to communicate/interact with the hub frequently and transmit high volumes of data. (iii) ZigBee devices are usually less expensive as they do not need to be certified.	(i) Most Zigbee devices use the 2.4 GHz band and therefore penetration-related issues may arise, especially in urban environments and in buildings that have thick walls [66]. (ii) In field trials/set-ups, where high data granularity is required, data may be lost as the bandwidth spectrum could be congested with other networks which use the same frequency, e.g., WiFi.
Z-Wave	The Z-Wave protocol is well-known and widely used in the IoT industry. In Europe, the frequencies used by Z-Wave are 868.40 MHz and 869.85 MHz [67].	(i) Z-Wave devices consume less power [65]. (ii) Z-Wave uses lower frequency compared to, e.g., ZigBee, allowing better penetration of the signal through the walls. (iii) Z-Wave uses a different spectrum compared to ZigBee and WiFi, thus avoiding congestion with other networks. (iv) Z-Wave devices need to be certified, which can potentially improve the quality of the devices/data.	(i) The lower frequency used by Z-Wave devices results in lower data rates compared to ZigBee. Specifically, the maximum data rates which can be transmitted using the Z-Wave protocol are up to 100 kbps [67]. (ii) Z-Wave devices need to be certified, which increases the cost per device and can limit the variety of available devices.
Wireless M-Bus	The Wireless M-Bus is a less well-known protocol compared to ZigBee and Z-Wave. Like its wired counterpart, the Wireless M-Bus is often used for utility metering. The Wireless M-Bus uses the 868 MHz, 434 MHz, 169 MHz frequencies or any other sub-GHz frequency if the corresponding license is granted [68]. Wireless M-Bus meters, similar to the ZigBee and Z-Wave set-ups, require a central hub to transmit the acquired data and access any configuration-related information.	Like Z-Wave, which also uses lower frequencies, the Wireless M-Bus allows better penetration through walls and has a longer range if the 169 MHz frequency is used.	(i) If the polling rate is frequent (e.g., less than 15 min), an external power supply (instead of a battery) may be required. (ii) The Wireless M-Bus protocol is usually utilised for utility metering (electricity, gas and water) so regular battery life monitoring needs to be considered in case an external power supply is not available.

Table 1. *Cont.*

Protocol	Description	Benefits	Challenges
WiFi	WiFi-enabled IoT devices can take full advantage of all the features of WiFi. They can use different frequencies depending on the device's requirements. However, most IoT WiFi devices use 2.4 GHz instead of the 5.0 or 6.0 GHz frequency.	(i) Usually, a hub is not required, as a WiFi router is standard in almost all domestic properties. (ii) The WiFi bandwidth is adequate to transmit/receive high volumes of data.	WiFi-enabled IoT devices consume more power compared to the devices that use any of the aforementioned protocols, and thus there is need for external power supplies.

Note that ZigBee's Smart Energy Profile (SEP) is incorporated into the ZigBee Smart Energy Standard [64] and will be described in more detail in Section 3.2.3 where the smart metering cluster will be discussed.

3.1.2. An Emerging Connectivity Standard

The protocols described previously are generic with limited standardisation features; thus, sensors from different manufacturers may not be compatible with the same hub or may require third-party code to integrate. Sensor and hub incompatibility is one of the major issues in built environment field trials, where often a wide range of equipment/devices may need to be used for data collection. Consequently, multiple platforms are required to gather the data. The use of multiple platforms increases the system complexity as they may support different granularities and data formats; thus, aligning/merging data from various sources requires extra steps, sometimes affecting the data quality.

Matter is a recently developed home automation connectivity standard which operates in a platform-agnostic way and thus could resolve the aforementioned issue. It is an open standard developed by the CSA (Connectivity Standards Alliance) [69], which is a consortium that includes many large-scale companies. To ensure interoperability, Matter has standardised the messaging protocol that the devices use.

Matter can utilise Ethernet, WiFi, Thread and Bluetooth Low-Energy (BLE) technologies, so the device's manufacturer can choose to support one or more of these technologies. In most cases, BLE would be used for setting-up and configuration purposes, and with Matter over Ethernet, WiFi or Thread, the devices/sensors are connected to the hub which is responsible for converting these protocols to Matter as well as for device orchestration and control [70,71]. Matter has the potential to overcome incompatibility-related issues that affect built environment's field trials; however, as it is a recently developed protocol, it is not widely adopted and, consequently, its potential has not yet been fully realised.

3.2. Common Data Accessing Interfaces and the Smart Metering Cluster

The interfaces which are commonly used to access metering data are the REST and the MQTT APIs and are briefly described as follows:

3.2.1. The REST API

The REpresentational State Transfer (REST) is the technical architecture of a WWW server system and is the vehicle for users to interact with the data. Masse [72] explains how to design a RESTful API for data retrieval. Specifically, data request structures consist of the GET command, simple URLs, and HTTPS, with other parameters concatenated together, such as API keys, addresses, authorisation (user, password) and the response file type (JSON, XML). REST data requests also include other commands such as POST (to share a resource with the client), PUT (to update the state of a resource) and DELETE [73].

3.2.2. The MQTT API

Another popular interface for data access is the Message Queuing Telemetry Transport (MQTT)—primarily a messaging protocol—which is used in most operating systems such as Android and iOS. MQTT, as a messaging protocol, can handle poor network connectivity and it is popular for transmitting data from IoT-enabled sensors to databases, as it is lightweight, fast and efficient and, hence, requires low power. However, the MQTT as an access interface is unable to handle high-level queries that can be achieved with the REST API, such as extracting data with certain constraints, such as from date to date, filters, and other conditions.

Note that most built environment applications require several measured quantities, which are usually not acquired using the same IoT system. Consequently, the end-user would need to access the relevant data using numerous APIs depending on the number of data acquisition systems used for the project.

3.2.3. Accessing Smart Metering Data and the 0x0702 Cluster

In the case of domestic smart meters, energy data should ideally be accessed via the DCC infrastructure as illustrated in Figure 3; however, this approach presents practical challenges [58]. In most cases the end-user can access the smart metering data either through their energy supplier's portal [74], when suppliers provide data accessing services, or via a Consumer Access Device (CAD) using the product's REST and MQTT API as demonstrated in Figure 4 and in [75].

The CAD is a third-party product which communicates with the smart meter over the HAN [58], provided there is compatibility between the smart metering system and the CAD. The CAD accesses the measured data and stores it in a cloud server. The end-user can then retrieve the energy data in near-real time [76]. The data granularity available from the energy supplier's platform is usually limited to 30 min. However, if the task requires higher granularity, a CAD-based solution is preferred, as it can provide imported electricity data with granularity of up to 10 s.

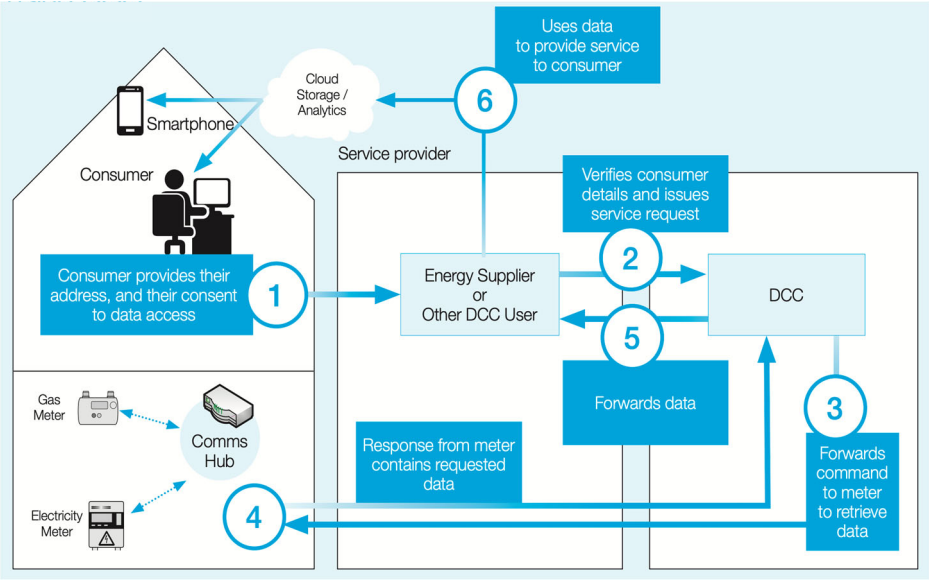


Figure 3. Accessing data directly through the DCC infrastructure [77]. The figure was retrieved from publicly accessible sources.

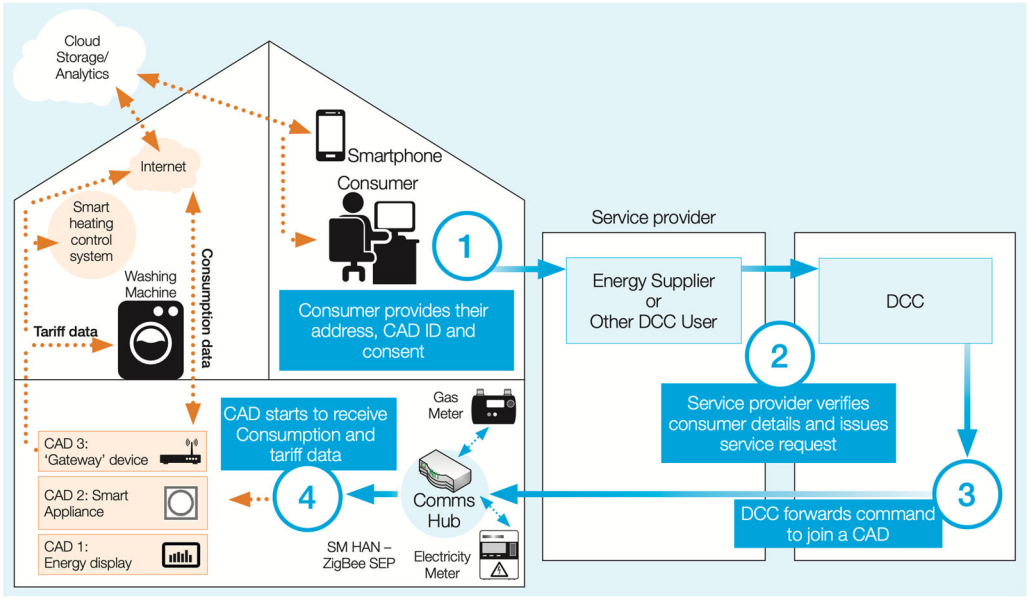


Figure 4. Accessing data through the DCC infrastructure using a CAD [77]. The figure was retrieved from publicly accessible sources.

The data accessed from domestic electricity and gas smart meters is organised into a standardised cluster, called the metering cluster with ID 0x0702, according to the ZigBee Smart Energy Standard [54,64], as presented in Table 2. The metering cluster is organised into four main sections: (i) formatting, (ii) reading information set, (iii) historical consumption and (iv) meter status, named after the attributes of each of the four sets. The purpose of the metering cluster is to ensure interoperability among the various smart energy devices/entities.

Table 2. Structure of the smart metering cluster 0x0702; ZigBee Smart Energy Standard/SEP.

Attribute Set Identifier	Attributes	Description
Formatting [0x03]	Demand formatting	Deciphers the number of digits and decimal location of the values of the demand-related attributes
	Multiplier/divisor	Multiplies/divides the received values in order to express them in the selected units; kWh and kW for the smart metering case
	MPAN	Meter Point Administration Number
	Smart meter serial number	Serial number of the smart meter
	Energy measurement unit	Electricity and gas in kWh
	Commodity	Electricity or gas
Reading Information Set [0x00]	Current summation delivered	Most recent aggregated value of energy delivered to the premise (value updates continuously)
	Current maximum demand delivered	Most recent value of maximum demand for energy delivered to the premise (value updates continuously)
Historical Consumption [0x04]	Current-day consumption delivered	Aggregated value of energy delivered to the premises since midnight local time (value updates continuously)
	Instantaneous demand	Most recent value of energy demand delivered to the premise (value updates continuously)
Meter status [0x02]	Status	Indicates erroneous conditions detected by the meter

For a detailed description of the 0x0702 smart metering cluster, see [54,64,78].

The following part explores how smart metering data can be leveraged in built environment projects that involve data processing and analysis. A general framework for conducting field trials in the built environment, along with relevant KPIs, is outlined, followed by a description of four representative use cases. These use cases either formed components of field trials or were field trials on their own.

3.3. Assessment of Energy-Related Field Trials

In this subsection, a general framework for preparing energy-related field trials for the built environment, alongside commonly used KPIs for evaluating the impact of energy-saving interventions, products, technologies or services tested in these field trials, is outlined.

Broadly speaking, field trials focusing on the decarbonisation of the built environment usually aim to assess real-world building energy performance or energy- and carbon-saving products, systems and services considering the dynamic interaction between them and the occupants, taking into account factors such as the weather conditions.

The initial stage of field trial preparation involves the selection of a representative sample of dwelling archetypes, geographic regions, and population demographics aligned with the trial's objectives, ensuring that the sample reflects diversity within the target population. Moreover, the household's baseline energy and other relevant quantities are usually required. These quantities can be measured using the domestic smart meters and/or third-party energy-measuring products, sensors for measuring temperature and humidity, as well as motion detection sensors for occupancy-related data, if necessary for the project. Occupant surveys may also be conducted to gather insights into household routines and thermal comfort preferences, helping to understand how the occupancy factor influences energy usage. Depending on the project, this data may be used to assess key aspects of the trial such as a building's energy performance and occupancy behaviour patterns. The baseline profile is then used to assess potential energy and cost savings derived from an intervention, service or product installed. These potential savings or improvements are usually quantified through relevant KPIs.

Commonly used KPIs for field trials focusing on the decarbonisation of the built environment sector, associated with the standards in [79–83], include the following:

(i) Energy Use Intensity (EUI): This indicator corresponds to the total energy consumption of a household over a year, typically normalised per unit of floor area. A reduction in the EUI after an intervention indicates energy and carbon savings.
(ii) Peak Load Demand: Refers to the maximum power demand placed by a building/household or energy system at any single point in time. This indicator captures the interval(s) of highest energy demand within a time window and therefore is particularly useful for energy services involving load shifting/demand-side energy management.
(iii) Heating and Cooling Load: Refers to the energy required to maintain the desired indoor temperature. This indicator is useful for evaluating the efficiency of domestic heating/cooling systems.
(iv) Carbon Footprint of a household: Corresponds to the total amount of greenhouse gas emissions resulting from the household's energy use. This metric is critical for assessing the environmental impact of energy-saving measures.
(v) Thermal Comfort: Reflects the degree to which indoor conditions meet the occupant's comfort standards. This indicator is related to physical as well as psychological factors.

(vi) Occupant Satisfaction: This indicator captures the occupant's feedback on aspects such as thermal comfort and indoor air quality. This indicator can combine subjective data (e.g., responses to surveys) with measurable data in relation to indoor conditions.
(vii) Cost Savings: Represents the financial benefit resulting from energy-related interventions to a household.
(viii) Return on Investment (ROI): Evaluates the profitability of the financial investment related to an energy-saving intervention. It is expressed as the ratio of the net profit to the investment cost multiplied by 100.
(ix) Thermal Comfort Equity: Refers to the principle that thermal comfort should be inclusive for all occupants irrespective of lifestyle differences, health conditions, etc. This indicator can be calculated through a combination of objective metrics and subjective feedback.

When combined, these and other KPIs provide a comprehensive view of how effective energy- and carbon-saving interventions are for decarbonising the built environment sector.

3.4. Built Environment Energy-Related Use Cases

In this subsection, four indicative built environment energy-related use cases are presented. The first two were components of broader field trials, while the latter two constituted field trials on their own. In the past, without the relevant IoT technologies, it would have been unfeasible for these and for other similar use cases to be mapped into field trials due to high cost, the frequent site visits causing disruption to the occupants, and various technical challenges.

Use Cases 1 and 2 focus on power consumption and residential space heating monitoring, respectively. Use Case 3 demonstrates how IoT enables the assessment of a building's energy performance and Use Case 4 focuses on assessing an energy-saving product.

3.4.1. Use Case 1—Power Consumption Monitoring

A relatively common use case in the built environment is to monitor the power consumption of selected, usually high-energy-consuming, domestic appliances/devices in order to associate the consumption with the occupants' lifestyle patterns.

Power consumption can be either measured using smart plugs (Section 3.4.1 (a)) or estimated through pattern recognition methods (Section 3.4.1 (b))

(a) Smart plugs—Measuring power consumption

Smart plugs can be used to measure the power consumption of appliances/devices of interest. The smart plugs should use an IoT protocol suitable for an environment where there might be thick walls, and relatively long distances among the smart plugs or between each plug and the hub. The frequency of the smart plugs' protocol should ideally be different to that of WiFi to avoid network congestion. So, smart plugs using the Z-Wave protocol would be appropriate for this use case.

The smart plugs' power consumption data would be uploaded via the hub to the cloud each time new readings are recorded. Subsequently, through an API, the data would be accessed from the cloud and then stored in a local database to be retrieved by the researchers for post-processing purposes as in Figure 5.

(b) Pattern recognition—Estimating the power consumption of specific devices

As mentioned in Section 3.2.3, the imported electricity data of a household can be accessed using a CAD. The accessed data can be used for identifying appliances/devices of interest using Non-Intrusive Load Monitoring (NILM) methods. For example, coefficients could be extracted from the frequency or time–frequency representation of the 10 sec

aggregated power consumption signal and then introduced to an ANN for identifying the appliances of interest [54].

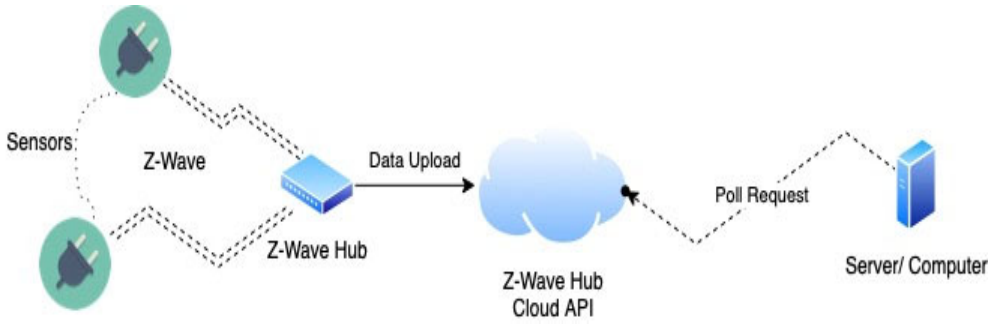


Figure 5. Accessing energy consumption data acquired through Z-Wave smart plugs.

3.4.2. Use Case 2—Residential Space Heating Monitoring

In 2023, 62.5% of the energy consumption in the EU's residential settings was for space heating [84] so it is important to monitor the associated energy consumption, especially during the heating season.

In GB, although accessing data from the GSME is usually possible, the data's low granularity of 30 min might be a barrier for meaningful data analysis [54,77]. So, heat meters need to be used to measure the output of heating systems—which can be either gas-powered or electrically powered—in order to acquire data of higher granularity.

There is a wide range of IoT protocols used for accessing the data acquired from heat meters, such as wired/Wireless M-Bus, wired Modbus, Long-Range Wide-Area Network (LoRaWAN) and Long-Term Evolution (LTE). LoRaWAN and LTE protocols are more appropriate for projects where the heating systems of a wider area, e.g., at the neighbourhood level, are monitored, whereas for projects where the heating systems monitored are located within the same building, the Wireless M-Bus [85] might be preferred.

3.4.3. Use Case 3—Building Energy Performance and the HTC

The predicted annual space heating energy use of a dwelling is typically ascertained from its EPC, which was gradually introduced in the European Union and UK under the EPBD [86]. In the UK, an EPC is calculated using the SAP methodology for a new-build dwelling and the RdSAP methodology for an existing dwelling. Both methodologies are based on the Building Research Establishment Domestic Energy Model (BREDEM). The thermal performance of the building's fabric is a key determinant of predicted space heating energy use in BREDEM-based models [87]. These models quantify the thermal performance of an entire dwelling using a metric called the HTC, which is defined in ISO 13789 as the "heat flow rate divided by temperature difference between two environments" [88]. The heat flow rate includes both thermal transmission through the building fabric and air infiltration. Thermal transmission in SAP is based on values specified by the designer, whereas in RdSAP, it is based on assumptions informed by a physical survey. Both methodologies allow air infiltration to be derived from air permeability measurements, although air infiltration can be assumed in the absence of measurement.

Studies have highlighted significant discrepancies between HTCs calculated using SAP and RdSAP input data and measured HTCs. For new-build dwellings, most studies performed to date have found measured HTCs to be greater than predicted HTCs calculated using SAP input data [8]. This underperformance is known as the building EPG and has been primarily attributed to issues related to the construction process. For existing dwellings, HTCs calculated using RdSAP input data typically overestimate fabric performance [89]. Therefore, since current EPC-based predictions of space heating energy usage

are not reliable, it is not possible to establish whether differences between measured and predicted energy use should be attributed to occupancy behaviour, issues with the space heating system, or the performance of the building fabric. Furthermore, the aforementioned discrepancies reduce confidence in the use of EPCs to identify which dwellings should be prioritised for a fabric retrofit.

Inputting measured HTC values into building energy use models could improve their accuracy and utility. However, ISO 17887-1:2024 is the only recognised standard for in situ HTC measurement and requires a dwelling to be unoccupied and heated electrically for a minimum period of 15 days [90]. Shorter test methods have been proposed, but the minimum period in which a dwelling must be unoccupied is overnight [91]. Such methods all require the installation of space heaters and monitoring equipment, and must be performed in the heating season. Thus, these methods are impractical and too expensive for mass deployment.

Cheaper and less obtrusive methods have recently been developed that enable the HTC of a dwelling to be estimated when a dwelling is occupied. These methods require smart meter energy data, indoor temperature measurements, weather data and, optionally, additional measured quantities; for an indicative list of the data required, see Table 3. In the UK, such methods are referred to as Smart Meter Enabled Thermal Efficiency Rating (SMETER) technologies. Initial trials of SMETER technologies suggest that data from the domestic smart metering infrastructure and IoT-enabled sensors can provide a reasonably accurate HTC estimate of a dwelling, thereby improving the prediction of space heating energy use [92]. The use of SMETER technologies is now being proposed to inform EPCs, assist with the sizing of heating systems [42], and assess the impact of building fabric retrofit measures [93].

Table 3. Commonly used quantities for estimating a building's HTC using SMETER technologies.

Data	Accessibility and Description
Energy consumption	The aggregated energy consumption data (electricity or gas) can be accessed directly from the domestic smart metering infrastructure (SMETS 1/2) or measured via current meters (knowing the voltage) through an IoT set-up.
Indoor temperature	The indoor temperature data can be accessed from IoT-enabled temperature sensors, Thermostatic Radiator Valves (TRVs), Thermostatic Controllers, etc.
Weather conditions	IoT-enabled weather stations can be purchased off-the-shelf. Alternatively, weather data can be accessed via the Met Office, or it can be purchased online from web-based providers. The quantities of interest are the temperature, solar radiation, wind speed and direction.
Occupancy presence	Occupancy presence patterns can be detected through motion detection sensors.
Occupant-driven ventilation	Opening/closing sensors are fitted in door and window frames to detect occupant-driven ventilation.
Building metadata	Building metadata can be retrieved from EPCs. EPCs can be purchased or some of them can be accessed free of charge via the Open Data Communities website of the Ministry of Housing, Communities & Local Government (MHCLG) [94].

3.4.4. Use Case 4—Assessment of Energy-Saving Products

The energy-saving capabilities of products or services are sometimes assessed in real conditions, through field trials, before reaching the market [95]. The households that

participate in the trials are usually divided into two groups, where one group, known as 'Experimental', consists of the samples (households) where the energy-saving product has been fitted, and the other group, known as 'Control', consists of the samples where the product has not been fitted.

In the case that the product for testing is, for example, a smart TRV, the energy consumption over a period of time as well as the indoor temperature of each home, the weather conditions, and potentially other quantities such as occupant-driven ventilation would need to be measured and combined. The energy consumption data could be accessed through the domestic smart meters and the other quantities through relevant IoT-enabled set-ups. Then, a statistical test (e.g., a *t*-test) would be conducted to reject or not the null hypothesis at a selected significance level [96]; the null hypothesis for this case would be the claim that the use of this product does not result in energy savings. It is important to note that, for any conclusions to be valid, the houses of the Experimental and Control groups participating in the field trial should have similar characteristics (be comparable) in terms of their building type, built-form, size, and energy performance. Should the Experimental and Control groups consist of houses of different built forms, sizes, etc., a matched-pair analysis should be preferred [96].

There is a plethora of factors which influence the outcomes of field trials such as data availability and quality and occupancy behaviour, also presented in Section 4. The level of uncertainty introduced by these factors needs to be incorporated into the relevant analysis.

To close, Table 4 outlines the four use cases presented in this subsection, stating the IoT technologies and the data required and also incorporating indicative actors, outcomes and KPIs associated with each use case.

In the following section, an overview of the more prominent limitations and parameters which need to be considered when planning IoT-enabled projects or field trials for the built environment sector is provided.

Table 4. IoT-enabled energy-related use cases for the built environment.

	IoT standards/Protocols and Other Technologies	Required Data	Primary Actors/Outcomes (Indicatives)	KPIs (Indicatives)
Use Case 1: Power consumption monitoring.	Z-Wave smart plugs, hub(s) and cloud services.	Power consumption.	Primary actors: occupant, energy supplier, DSO. Outcomes: Monitoring the power consumption of devices/appliances of interest to identify opportunities for energy flexibility services and energy-saving interventions.	EUI, Peak Load Demand, Cost Savings.
Use Case 2: Residential space heating monitoring.	Heat meters; wired/Wireless M-Bus, wired Modbus, LoRaWAN and LTE.	Thermal energy [97].	Primary actors: occupant, building manager. Outcomes: Monitoring of residential space heating to identify homes which need fabric retrofitting.	EUI, Thermal Comfort, Heating Load.

Table 4. *Cont.*

	IoT standards/Protocols and Other Technologies	Required Data	Primary Actors/Outcomes (Indicatives)	KPIs (Indicatives)
Use Case 3: Building energy performance and the HTC.	Domestic smart metering (SMETS 1/2) and IoT-enabled sensors.	Energy consumption, indoor temperature, occupancy presence, occupant-driven ventilation, weather conditions, building metadata.	Primary actors: occupant, energy assessor. Outcomes: Estimation of a building's energy performance to (i) inform EPCs, (ii) inform the sizing of heating systems and (iii) assess building fabric retrofit measures.	EUI, Carbon Footprint of a household, Thermal Comfort, Occupant Satisfaction, Cost Savings, ROI.
Use Case 4: Assessment of energy-saving products, e.g., smart TRV.	Domestic smart metering (SMETS 1/2) and IoT-enabled sensors.	Energy consumption, indoor temperature, weather conditions, occupant-driven ventilation.	Primary actors: energy consultant, researcher. Outcomes: Testing of the product to assess its energy-saving capabilities.	EUI, Thermal Comfort, Occupant Satisfaction, Cost Savings, ROI.

4. Quantifiable and Non-Quantifiable Limitations of IoT-Enabled Built Environment Projects

As described in the previous sections, IoT data of high granularity and quality has enabled the development of useful applications and services for the built environment sector. However, there are quantifiable and non-quantifiable limitations and parameters which need to be considered when planning IoT-enabled projects and field trials.

4.1. Quantifiable Limitations and Threats

4.1.1. Compatibility and Configuration

Identifying sensors and compatible gateways developed by different manufacturers could be a challenging task [98]. Similarly, configuring sensors and meters with generic gateways may sometimes be complicated and time-consuming.

4.1.2. Cost of Field Trials

Large-scale installations, required for field trials, may necessitate frequent site visits which are costly. Moreover, storage of high-frequency data also contributes to the total cost.

4.1.3. Data Loss and Data Manipulation

In field trials, data losses may occur due to trialists' dropouts and unexpected unplugging of sensors alongside faulty sensors and poor internet connectivity. The shortcomings of data losses are reflected in the corresponding data analysis. To minimise the effect of data loss, some analysts interpolate the missing data; however, interpolation in some cases may not be appropriate. As an example, interpolating space heating energy data (note that space heating energy is usually aggregated with domestic hot water energy) could be challenging due to the inherent unpredictability of occupant behaviour [16].

Furthermore, IoT systems may suffer from cyberattacks towards the network, the end-point devices, the cloud or the data acquired. As far as the data is concerned, these attacks may include data poisoning aiming to corrupt or manipulate the training data, affecting the artificial intelligence (AI) and machine learning (ML) models, and/or evasion attacks

resulting in incorrect outputs of the model due to manipulation of the input data [99,100]. Due to these cyber threats, protective measures need to be incorporated in the IoT system to ensure data integrity and to ensure that the model outputs are unaffected by potential malicious attacks.

4.1.4. Smart Metering Data Granularity and Access

As mentioned in Section 3.2.3, energy suppliers' portals may provide access to smart metering data; however, the 30 min data granularity available from a certain supplier's portal may not be adequate for the needs of a specific project. So, accessing smart metering data through a CAD would need to be considered in order to access the imported electricity data with the highest (10 s) granularity. Nevertheless, this solution would increase the project's cost and complexity and could potentially result in data losses due to, for instance, poor internet connectivity or equipment failure of the CAD.

Field trials can face further limitations caused by the lack of access to smart metering data due to, for example, Wide Area Network (WAN) connectivity issues, in which case alternative metering solutions such as current meters would need to be considered.

4.2. Non-Quantifiable Limitation

The most prominent non-quantifiable limitation in energy-monitoring field trials is the occupants' behaviour. Variables which are related to occupancy are the comfort temperature preference, heating schedules, ventilation habits, hot water usage, presence pattern, incidental gains from the usage of home appliances and others. Due to the nature of these variables, standardised methods for estimating them reliably have not been fully established, thus resulting in significant uncertainty margins [52].

5. Data Privacy and the GDPR

When choosing devices such as sensors and hubs for field trials, the privacy and security parameters are of utmost importance. Specifically, it is necessary to store the collected data safely to ensure that the data will not be shared without the participants' consent and to take all the necessary steps so that the data will not be compromised. To ensure privacy, it is safer to select a solution which involves local rather than cloud data storage and processing, as there is the potential risk for the cloud to be compromised as well as the danger that the stored data could be used by the cloud provider or third parties without the participants' and/or the field trial organisers' consent.

As an example, in the use case of power consumption monitoring using smart plugs (Use Case 1/Section 3.4.1 (a)), to avoid privacy and data security-related issues, the selected hub would need to be configured to minimise its interaction with the cloud as well as to avoid (i) the need to create 'users' to connect to the hub, (ii) the requirement of a smart device (e.g., smart phone) for setting-up purposes, (iii) the use of location-related data; thus, the data collected would be anonymised to ensure the participants' privacy.

Along similar lines, in relation to the GDPR for field trials, one of the key elements is the definition of personal data as described in the Directive 95/46/EC for the EU [101], the data protection legislation for the UK [102] and outlined in [103]. Specifically, three key issues are identified:

- Whether the data collected/accessed is related to an identified or identifiable natural person [104].
- Whether the data is anonymised. If it is, then it is not personal data.
- If any special categories of data, such as health or financial, are accessed/collected.

For the cases that it is required to relate data from multiple sources, a 'Chinese wall' needs to be established between the research/data analysis team and a trusted external part-

ner/administrator who would link the data from these sources and return it in anonymised codes' format to the research/data analysis team, thus limiting the GDPR risk.

For the data protection and sharing restrictions of a field trial, the Ethics Policy of the organisation which runs the field trial should also be adhered to. The Ethics Policy of the organisation should cover issues related to data privacy, the GDPR and the protection of the participants from any risk of harm from the research/field trial, following the guidelines for responsible research and innovation [105].

6. Summary and Future Trends

This article highlights the pivotal role of IoT for the decarbonisation of the built environment sector. It emphasises the importance of the national IoT energy infrastructure as the key enabler for a wide range of digital energy applications and services that support this transition.

IoT technologies have provided the sector with the ability to measure and remotely access the quantities of interest in order to develop highly accurate models as well as reliable energy-related services and applications. By integrating energy data from smart meters with data from other IoT systems, a diverse range of applications and services can be developed. These include assessing the energy performance of both new builds and the existing housing stock, enabling the delivery of energy flexibility/DSR services for grid stability, assessing energy-saving products, optimising energy management, load forecasting, and informing policy making.

Until now, domestic smart metering infrastructure has been used primarily by energy suppliers for billing purposes, introducing smart tariffs to the market, and integrating domestic renewables into the grid. Even though the infrastructure serves the purpose it was created for, it could be utilised to deliver additional benefits. Specifically, third-party entities could use the smart metering platform in a secure manner, thus enabling the significant expansion of its services and generating added value to the original investment. For example, opening the HAN would allow researchers and developers to connect sensing devices to measure various quantities of interest such as indoor temperature, and then use this data for intelligent local control of domestic Low Carbon Technologies (LCTs) to support energy flexibility services [40].

In summary, IoT technologies are the key enablers for upgrading the UK's housing stock and developing services and applications for monitoring and managing domestic energy use. Improving the energy performance of residential buildings and optimising energy usage would play a key role in the incorporation of the built environment sector into smart city and smart grid planning and, alongside the other economic sectors, would contribute to the 2050 net-zero target.

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Abbreviations

The following abbreviations are used in this manuscript:

SAP	Standard Assessment Procedure
RdSAP	Reduced Data SAP
EPBD	Energy Performance of Buildings Directive
EPG	Energy Performance Gap
IoT	Internet of Things
HDD	Heating Degree Days
GB	Great Britain
DESNZ	Department for Energy Security and Net Zero
Ofgem	Office of Gas and Electricity Markets
DCC	Data Communications Company
DSO	Distribution System Operator
SMSH	Smart Meters > Smart Homes
NZIP	Net Zero Innovation Portfolio
FIP	Flexibility Innovation Programme
BUS	Boiler Upgrade Scheme
SHDF	Social Housing Decarbonisation Fund
R&D	Research and Development
SIF	Strategic Innovation Fund
KPI	Key Performance Indicator
GDPR	General Data Protection Regulation
ToU	Time-of-Use
EV	Electric Vehicle
ASHP	Air-Source Heat Pump
ESME	Electricity Smart Metering Equipment
HEMS	Home Energy Management System
BEMS	Building Energy Management Systems
CEMS	Cluster/Community Energy Management System
DSR	Demand Side Response
HVAC	Heating, Ventilation and Air-Conditioning
DSRSP	Demand Side Response Service Provider
CEM	Customer Energy Manager
HTC	Heat Transfer Coefficient
EPC	Energy Performance Certificate
ANN	Artificial Neural Network
API	Application Programming Interface
SMETS	Smart Metering Equipment Technical Specifications
GSME	Gas Smart Metering Equipment
IHD	In-Home Display
CH	Communication Hub
HAN	Home Area Network
SEP	Smart Energy Profile
CSA	Connectivity Standards Alliance
BLE	Bluetooth Low Energy
REST	Representational State Transfer
MQTT	Message Queuing Telemetry Transport
CAD	Consumer Access Devices
MPAN	Meter Point Administration Number
EUI	Energy Use Intensity
ROI	Return on Investment
NILM	Non-Intrusive Load Monitoring

LoRaWAN	Long-Range Wide-Area Network
LTE	Long-Term Evolution
BREDEM	Building Research Establishment Domestic Energy Model
SMETER	Smart Meter Enabled Thermal Efficiency Rating
TRV	Thermostatic Radiator Valve
MHCLG	Ministry of Housing, Communities & Local Government
AI	Artificial Intelligence
ML	Machine Learning
WAN	Wide Area Network
LCT	Low Carbon Technology

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