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Review

Building energy metering and environmental monitoring – A state-of-the-art review and directions for future research

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ABSTRACT

Buildings are responsible for 40% of global energy use and contribute towards 30% of the total CO_2 emissions. The drive to reduce energy consumption and associated greenhouse gas emissions from buildings has acted as a catalyst in the increasing installation of meters and sensors for monitoring energy use and indoor environmental conditions in buildings. This paper reviews the state-of-the-art in building energy metering and environmental monitoring, including their social, economic, environmental and legislative drivers. The integration of meters and sensors with existing building energy management systems (BEMS) is critically appraised, especially with regard to communication technologies and protocols such as ModBus, M-Bus, Ethernet, Cellular, ZigBee, WiFi and BACnet. Findings suggest that energy metering is covered in existing policies and regulations in only a handful of countries. Most of the legislations and policies on energy metering in Europe are in response to the Energy Performance of Buildings Directive (EPBD), 2002/91/EC. However, recent developments in policy are pointing towards more stringent metering requirements in future, moving away from voluntary to mandatory compliance. With regards to metering equipment, significant developments have been made in the recent past on miniaturisation, accuracy, robustness, data storage, ability to connect using multiple communication protocols, and the integration with BEMS and the Cloud – resulting in a range of available solutions, selection of which can be challenging. Developments in communication technologies, in particular in low-power wireless such as ZigBee and Bluetooth LE (BLE), are enabling cost-effective machine to machine (M2M) and internet of things (IoT) implementation of sensor networks. Privacy and data protection, however, remain a concern for data aggregators and end-users. The standardization of network protocols and device functionalities remains an active area of research and development, especially due to the prevalence of many protocols in the BEMS industry. Available solutions often lack interoperability between hardware and software systems, resulting in vendor lock-in. The paper provides a comprehensive understanding of available technologies for energy metering and environmental monitoring; their drivers, advantages and limitations; factors affecting their selection and future directions of research and development – for use a reference, as well as for generating further interest in this expanding research area.

Abbreviations: AFDD, automatic fault detection and diagnosis; AMI, adavanced meetering infracture; AMR, automatic meter reading; ASHRAE, American Society of Heating, Refrigeration and Air-conditioning Engineers; BAS, building automation system; BEMS, building energy management system; CT, current transformers; CRC, carbon reduction scheme; CSR, corporate social responsibility; DMPR, disjoint multi path based routing; EMCS, energy management and control system; EPBD, Energy Performance and Buildings Directive; ESOS, energy saving opportunities scheme; IAQ, indoor air quality; ICT, information and communication technologies; IEA, International Energy Agency; IECC, International energy Conservation Code; IoT, internet of things; M2M, machine to machine; MID, Measuring Instrument Directive; NDIR, non-dispersive infrared; PLC, power line carriers; PRT, platinum resistance thermometer; RFID, radio frequency identification; RHI, renewable heat incentive; RTD, resistance temperature device; RTE, real-time ethernet; RTU, remote terminal unit; SCADA, supervisory control and data acquisitions; SIM, subscriber identity module; SME, small and medium-sized enterprise; SMS, short message service; SSL, security socket layer; TCP, transmission control protocol; VOC, volatile organic compound; VPN, virtual private networks.

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Contents

1. Introduction

Globally, Heating, buildings account for 40% of total energy used and contribute towards 30% of the total CO_2 emissions [1,2]. Buildings are the largest consumer of energy in the European Union, accounting for up to 40% of the total energy consumption and approximately 36% of the greenhouse gas emissions [3]. Buildings' share of CO_2 emissions is higher in some countries; e.g., the sector represents 50% of the total of 570 $MtCO_2e$ emissions in the UK in 2013 [4]. Energy is used in buildings for heating and cooling, hot water, lighting and appliances, and the majority of this energy come from the burning of fossil fuel, which amounted to 81.23% of global energy consumption in 2011 [5]. Associated GHG emissions from the burning of fossil fuels have been attributed as the extremely likely cause of anthropogenic climate change [6]. According to the International Energy Agency (IEA) [7], global greenhouse gas emissions are rapidly increasing and it will be difficult to limit the long-term rise in global average temperature to 2 °C below pre-industrial levels. Addressing the issue of global climate change and reversing the trend of rising energy consumption is essential to reduce the impact of climate change to a 2 °C rise in global average temperature [7]. The building sector, therefore, plays a significant role in mitigating the impacts of climate change – first, through reducing the demand; i.e. energy conservation, and second, by maximising the use of renewable energy – both aimed at reducing GHG emissions [8].

Developed and developing countries alike are faced with the challenges of decarbonisation of their respective building stocks over the next 30–40 years [9]. Proposed measures for decarbonisation include but not limited to increasing the share of low- and zero-carbon buildings; smarter and more efficient energy systems and behavioural change among consumers. Gathering data on and evaluation of energy and environmental performance are at the heart of decarbonisation strategies to enhance energy efficiency and to reduce energy use in buildings. Advanced metering and control, and environmental monitoring technologies have a significant role to play in data-driven energy efficiency measures. There is also an increase in energy-related building legislations and regulations around the world, including stringent energy efficiency requirements that act as a motivator for increased level of metering, sub-metering and automated control, especially in non-domestic buildings. As an example, the European Energy Performance of Buildings Directive (EPBD) also requires EU members to encourage intelligent metering and active control systems in new or renovated buildings through building regulations [10]. In the USA, the Energy Policy Act of 2005 has metering requirements for federal buildings. Most US States, cities and districts have adopted the International Energy Conservation

Code (IECC) [11], with enhanced requirements for metering and control.

Building energy metering and environmental monitoring give stakeholders valuable information regarding how buildings are performing. Knowledge gleaned from analytics can also be used to improve the performance further. A comprehensive energy metering and environmental monitoring system has the potential to get all stakeholders (tenants, building owners, energy managers) on board to take energy-efficiency measures [12]. Energy metering can also help in identifying cost-cutting opportunities by detecting inefficiencies; benchmarking buildings internally and externally; improving load planning and energy usage; and managing demand to minimise exposure to system reliability and price volatility risks [12]. There is currently a myriad of metering and sensor technologies that are available on the market with varying degrees of sophistication and functionality. Choosing a correct metering and sensor solution for a building is a challenging and non-trivial task as it depends on different factors. These factors need to be considered to ensure the metering and monitoring solution can meter and monitor the relevant quality (power consumption, gas consumption, air-temperature, etc.). Therefore, it is important to be aware of different factors that influence the selection of these technologies. In future, smart buildings infrastructure will support bi-directional communication standards, which will allow continuous interaction between the utility, the consumer and the controllable electrical load [13]. According to Ras [14], a highly reliable communication will be required to transfer a high volume of data. Therefore, communication and network technologies will play a significant role in the integration of smart buildings and grids.

The increasing installation of energy meters and environmental monitoring sensors has acted as a catalyst towards the drive to reduce energy consumption and associated green gas emissions. This papers reviews drivers for installing these technologies; including social, economic, environmental and legislative. The recent developments in policy are pointing towards more stringent metering installation requirements and in future these requirements will become mandatory. The selection of metering and environmental solution can be a challenging task due to recent developments on accuracy, robustness, data storage, miniaturisation, ability to connect using multiple communication protocols, integration with BEMS and the Cloud. Different factors that influence this decision making process are also covered in this article. Different widely used communication protocols including low-power wireless (e.g. ZigBee) are also reviewed in the paper. Data protection and privacy is a main concern for both end users and data aggregators. Other challenges including cost, interoperability, lack of ICT infrastructure are also reviewed. In this paper, it is aimed to provide necessary information to energy managers, academic researchers, energy suppliers, owners, tenants, manufacturers, and technicians. The rest of the article is structured as follows. Section 2 details social, economic environmental and legislative drivers for energy metering and environmental monitoring. This section also highlights some of the legislations that are currently in place in different countries. In Section 3, classification of metering and monitoring devices is presented along with their working principle, types and cost comparison between different widely available meters and sensors. Section 4 details various factors that needs to be considered while selecting a metering and monitoring solution. The following section outlines widely used communication and network technologies along with their advantages and limitations. Section 6 focuses on the directions for future development and challenges including interoperability, security, cost, MEMS sensor technology and lack of ICT infrastructure. Concluding remarks are presented in the end.

2. Drivers for energy metering and environmental monitoring

There are many existing drivers for the installation of meters and sensors in buildings, but the overriding driver is usually to enable better management of energy within the building and ultimately identifying and achieving potential energy and cost savings and to verify savings that have been achieved [15]. More specific drivers are summarised below. However, there is a considerable overlap between these drivers and often it is difficult to assess which driver takes precedence over others.

2.1. Mitigating climate change and enhancing energy efficiency

In order to limit the projected global temperature rise to 2 °C, the IEA has proposed four emissions reduction policy solutions, of which the policies related to specific energy efficiency measures have been found to yield in greater savings – about 49% of the total emissions savings identified in the World Energy Outlook 2013 report [7]. In Europe, energy efficiency within the overall energy systems and infrastructure has been recognised as one of the five closely related and mutually reinforcing dimensions of the EU Energy Union agenda, aimed at reducing energy consumption to reduce pollution and preserve domestic energy sources [16]. In recent years, the overarching drive towards greater energy efficiency has resulted in renewed interests in heating and cooling as distinct areas of focus [17], in recognition of their share (50%) in the European Union's final energy consumption [18].

Electric and thermal smart energy grids with distributed and dynamic generation, transmission and distribution of energy are increasingly being seen as essential for the transition towards low carbon energy systems [19,20]. Data-driven control and management are the basis for smart energy grids that relies on the collection, aggregation and analysis of high resolution energy usage data from consumer premises, as well as the grid itself [20]. Advanced metering infrastructure (AMI); i.e. smart meters are the backbone of smart grids enabling wider integration of energy and information and communication technologies (ICT). AMI and associated technologies enable realtime, two-way communication between suppliers and consumers – thus creating more dynamic control and interaction of energy flows. It is expected that all 26 million households in England, Wales and Scotland will be fitted with smart meters by 2020 [21]. On the other hand, energy efficiency measures is a broad term and can include different strategies or initiatives within buildings. Chalmers [22] has discussed mitigation technology options including using daylighting, high-performance building envelope, efficient lighting, building automation and control system, smart meters and grids. Studies in the USA have also suggested that building efficiency measures that rely on sensors and meters, such as building energy management systems, lighting control, automatic fault detection and diagnosis (AFDD) and demand control ventilation, can reduce energy use by 5% up to 60% [23]. Therefore, it is evident that metering and sensing devices will play an important role to mitigate climate change.

2.2. Compliance with regulations and legislations

Recognising the need for tacking climate change, many governments have introduced legislation aimed at reducing greenhouse gas emissions. Different countries have implemented a range of legislations that are summarised in Table 1; with either having specific energy metering and controls requirements or indirectly encouraging building owners/users for their wider application in buildings. In Europe, most of the legislations have been introduced in response to the EU Directives, specifically the Energy Performance of Buildings Directive (EPBD 2002 [24] and 2010 [25]) and the Energy Efficiency Directive (2012). EPBD 2002 introduced building energy

Table 1
Energy legislation and regulations in different countries.

Country	Instrument	Building type	Metering requirements and drivers	Control requirements and drivers
JP	CCREUB (1999)	Commercial	None	Requires *proper controls* for HVAC, lighting, hot water and lifts
EU	EPBD 2002/91/EC (2002)	All new and refurbished buildings	Energy certification encourages the installation of smart meters and sub-meters	None
USA	Energy Policy Act (2005)	All Federal	Meter electricity where practicable, hourly interval data collected daily by 1 October 2012	None
UK	The Companies Act (2006)	GHG emissions[a]	Data collection requirements encourage installation of smart meters	None
USA	Energy Independence and Security Act (2007)	All Federal	Provide equivalent metering as EPA 2005 for natural gas and steam	None
UK	The Energy Performance of Buildings (Certificates and Inspections) Regulations (2007)	All (with exceptions)	Data collection requirements for DECs encourage installation of smart meters. Sub-metering may be required in some buildings (e.g., on campuses, multi-use or with excluded energy uses) to calculate accurately DEC rating	Controls will improve energy performance (EPC) asset rating and *in-use* DEC rating
UK	Carbon Reduction Commitment (2007)	Electricity and gas supplies	Reporting requirements plus 10% uplift on use of estimated data encourage roll-out of smart meters to ensure timely and accurate data collection	Control measures that reduce energy use will reduce carbon allowance purchase costs.
USA	International Energy Conservation Code (2009)	All[b]	None	Thermostatic control of HVAC systems including zone control. Minimum 7-day time control. Automatic shut-off of supply and exhaust dampers when systems/spaces not in use. Demand control ventilation of spaces greater than 50 m^2
USA	Seattle Energy Code (2009)	New and refurbished (excluding single family homes)	End-use metering of HVAC systems, lighting, plug and miscellaneous loads plus new systems for buildings >1858 m^2. Automatic daily data acquisition and 36 months data storage. Energy displays for building managers	As IECC 2009 plus: Humidistat control for each humidity control system. Optimum start control for systems with design air capacities exceeding 2000 CFM. Speed control of supply fans for AHUs with cooling capacity
JP	Energy Conservation Law (2009)	All	No specific metering/control required but buildings >2000 m^2 must submit an energy conservation report to the local authority before any new construction or major alteration, to demonstrate compliance with law and to implement recommended improvements. Local governments offer incentives such as relaxed height and size restrictions for energy efficient buildings to encourage inclusion of greater energy efficiency measures. [31]	
EU	EPBD 2010/31/EU (2010)	All	*Encourage* the use of intelligent metering systems for new or renovated buildings	*Encourage* the installation of active control systems such as automation, control and monitoring systems that aim to save energy
UK	Building Regulations Part L2A and L2B (2010)	All	Assign end-use categories (heating, lighting, small power, etc.) to 90% of building energy use. Separately monitor the output of any renewable energy systems. Include automatic meter reading &data collection capability in buildings over 1000 m^2	Separate zone control for areas with different solar exposure, occupancy or use type. Prevent simultaneous heating &cooling. Demand led control of central plant (default to off)
EU	Energy Efficiency Directive 2012/27/EU (2012)	General EE[c]	Free and simple customer access to real-time and historical energy consumption data through more accurate individual metering. Introduce energy audit obligations for large energy organisations including annual energy reporting	Set and achieve energy efficiency targets. Renovate 3% of central government buildings and procure energy efficient buildings, products and services
UK	Energy Saving Opportunities Scheme (2013)	Private organisations	No regulatory requirement but the need for reporting encourages the roll-out of smart meters to ensure timely and accurate data collection	Audit reports likely to include controls recommendations
UK	UK Smart Metering Implementation Plan (2014)	Small non-domestic &domestic	Roll-out of *smart meters* on smaller non-domestic and domestic electricity supplies by 2020 including wireless communications ability and real-time data collection and visualisation	None
AUS	Building Energy Efficiency Disclosure Act (2014)	Commercial	No specific requirements but sub-metering enable exclusion of tenant energy use from *Base Building* energy rating on Building Energy Efficiency Certificate that is required when office space is leased.	No specific requirements but reductions in energy use from good controls will improve the *Base Building* energy rating
AUS	National Construction Code vol. 1 (2014)	Commercial and multi-occupancy dwellings	Individual gas and electricity metering for all buildings with a floor area exceeding 500 m^2 (includes campus site). Sub-metering of main energy end-uses in buildings >2500 m^2	Timer control of main HVAC plant. Independent thermostatic control of zones with differing thermal characteristics and occupancy requirements. Occupancy linked control of *room conditioners*. Provision of an *outdoor air economy cycle* in air conditioning systems. Use of variable speed fans when variable air supply rates are required

[a] GHG emissions.
[b] Adopted in 46 US States, District of Columbia, NYC, Puerto Rico and US Virgin Islands.
[c] General Energy Efficiency.

labelling, and EPBD 2010 included specific requirements for metering and controls while the Energy Efficiency Directive also required the provision of smart meters to all customers and the creation of energy audit regimes for businesses.

In the UK, sub-metering and control requirements are included in the Building Regulations Part L while building energy labelling is covered by the Energy Performance of Building Regulations 2007. The UK Smart Metering Implementation Plan covers the roll-out of smart gas and electricity meters to all homes and businesses by the end of 2020. The Energy Saving Opportunities Scheme (ESOS) will require large private sector enterprises to conduct energy audits on a sample of their buildings by 5th December 2015 and every four years after that [26]. In 2010, the UK government also introduced the Carbon Reduction Commitment (CRC) energy efficiency scheme independently of any EU directives. This was originally intended as a carbon trading scheme for large and non-intensive energy users and was not included in the EU Emissions Trading Scheme. However, now it is a simpler carbon allowance purchase scheme where participants must purchase and surrender carbon allowances annually to cover carbon emissions from their electricity and gas supplies. As detailed in Table 1, the reporting regime does encourage the wider use of automatic metering to aid data collection and implementation of energy saving strategies to reduce carbon emissions.

In the USA, the Energy Policy Act 2005 and the Energy Independence and Security Act 2007 introduced metering requirements for federal buildings. Most of US states, cities and districts have adopted the International Code Council's International Energy Conservation Code (IECC) as their basis for building energy regulations and have also introduced enhanced requirements. These various legislations are summarised in Table 1 including one example of enhanced regulations in the USA. The Australian Building Energy Efficiency Disclosures Act allows commercial landlords to exclude tenant energy use if separately metered, to produce a "Base Building" energy rating. This act encourages sub-metering of tenant energy consumption, as the improved energy rating can be a useful marketing tool. Like UK and USA, Australian building regulations also have very stringent and specific requirements for sub-metering and controls. In Japan, legislations and regulations on building energy use is less prescriptive with regards to sub-metering and controls and only relies on voluntary compliance in many cases. However, compliance rates are quite high, and the requirement to provide an energy conservation report demonstrates that compliance with the Energy Conservation Law encourages the use of controls and also to have some degree of sub-metering. With regards to control, in the Japanese Commercial Building Code it is only stated that *a proper control system* should be adopted for controlling a range of energy supplying plant. Table 1 lists more details on different regulations.

2.3. Feedback on energy consumption and cost reduction

Researchers have done an extensive amount of research on providing feedback to users on their energy consumption and energy savings that can be achieved through feedback and it was concluded that feedback can reduce energy consumption. Darby [27] has reviewed three types of feedback for residential sector i.e. direct feedback (providing real-time meter readings), indirect feedback (billing) and inadvertent feedback (a by-product of technical, household or social change). It was found that energy savings from direct and indirect feedback were in the range of 5–15% and 0–10% respectively. Therefore, metering solutions are better options for providing feedback to occupants. We acknowledge that most of the studies conducted on providing feedback and its effect on energy savings are performed on residential buildings, and fewer studies were carried out on non-domestic buildings. Also, the impact of occupants behaviour on energy consumption in non-domestic buildings in less when compared to claimed 20% reduction in energy use [28]. The reasons for this variation is actual and simulated energy savings in non-domestic buildings as reviewed in Cox et al. [29]. The evaluation of behavioural initiative in non-domestic buildings is poorly understood because of the variety of organisational processes and lack of sub-metering. Employers can also provide feedback to their employees by displaying energy metered data on a plasma screen in a communal area inside their building. A UK trial of advanced energy meters in small and medium-sized businesses (SMEs) between 2004 and 2006 demonstrated that SMEs can identify an average of 12% carbon savings by using advanced metering [30]. The report concluded that low-cost metering services provided by automated systems could be effective in reducing energy use and if implemented on UK level can potentially save £ 650 million [30]. Shaikh et al. [1] have also mentioned that sensor based intelligent building automation systems could deliver average 30% reduction in building energy use worldwide.

2.4. Corporate social responsibility

Many companies promote their actions on energy efficiency through corporate social responsibility (CSR). The UK retailer Marks and Spencer's *Plan A* is a good example and includes concrete measures such as the use of automatic meters to validate energy efficiency savings for its UK operations, requirements for suppliers to report energy data and achieve savings and the introduction of an Eco-Factory standard for vendors. This standard includes requirements for sub-metering major energy end-uses and report them daily and to introduce controls for heating and cooling systems and electrical motors. 53 of Marks and Spencer's top 100 suppliers had achieved this rating by the end of 2013, and 85 had adopted temperature control measures [32,33]. Similarly, the international bank Santander gives prominence to energy metering and control measures in their CSR reports. This includes the roll-out of smart electricity meters and gas loggers to track energy performance and installation of controls for HVAC and lighting [34]. Therefore, it can be concluded that policies on a government level as well as corporation level are currently in place and are currently being implemented.

3. Classification of metering and monitoring devices

Fugate et al. [35] proposed three categories for building sensors and meters for measuring and sensing different building performance parameters, occupants comfort perception and machinery characteristics. Temperature, occupancy, humidity, CO_2 and air quality sensors are used to sense occupant comfort and activity. On the other hand; building energy meter, sub-metering, plug-load measurements, natural gas meters, and other sources of energy meters are used to measure energy consumption. Measurements of machinery characteristics can be done by using refrigerant temperature, machinery electrical current, machinery vibration, and return and supply airflows sensors. The focus of this article will only be on devices used for the measurement of primary energy (electricity and gas), thermal comfort, indoor air quality (IAQ) and lighting and occupancy control.

According to Fanger [36], the evaluation of the thermal environment requires the knowledge of six quantities: four physical parameters (air humidity, air temperature, mean radiant temperature and air velocity) and two subjective (clothing thermal insulation and metabolic rate). These parameters have to be measured or estimated to evaluate and monitor thermal comfort [37]. While subjective quantities are generally estimated according to benchmarks for specific activities and types of buildings, physical ones can be directly or indirectly measured [38]. The sensors used to evaluate thermal comfort, sensors used for daylighting control or occupancy detection serves different purposes. These sensors are installed in building to make sure that occupants have comfortable indoor air conditions, minimise energy consumption during unoccupied periods, provide detailed building energy consumption information, provide input for security, fire alarm system, etc.

In the following sections, each parameter has been characterised on the basis of the main sensing technologies used for metering and monitoring purposes, with a description of their operative principles, advantages, and disadvantages. Then for each parameter the main commercial products exploiting the above sensing technologies have been characterised on the basis of their main meteorological parameters (such as accuracy and operational range), usage and cost. The sensing and metering considered in this article are commercially available electronic devices that measure and record data for further analysis and not only individual the sensing components.

3.1. Electricity metering

Electricity meters operate by continuously sensing the instantaneous values of current and voltage to provide a measurement of energy used (and possibly power demand). The oldest and most common type of electricity meter is the electromechanical watt-hour meter (a 2-phase inductive motor). It is composed of an electrically conductive metal disc whose rotational speed is proportional to the power passing through the meter. The disc is influenced by two sets of coils properly connected to generate magnetic fluxes proportional to the load current and the line voltage respectively. This produces eddy currents in the disc that exert a force in proportion to the active power. Contemporary a permanent magnet produces an opposing force proportional to the rotational speed of the disc. The interaction between the two forces results in the disc rotating at a speed that is proportional to either the power or the rate of energy usage [39]. In the first mechanical meters the energy data had to be acquired using direct dial readings; modern ones, instead, can rely on encoders and other registering mechanisms to produce electronic or pulse output [40]. Although electromechanical meters represent the majority of the currently installed meters in both residential and commercial buildings, the future of the utility industry is represented by electronic (solid-state/digital) advanced meters, which do not require moving parts and are capable of storing and managing data. The most conventional current and voltage sensor circuits are typically current and voltage transformers. Due to their higher accuracy, data storage and communication capability and the consequent possibility to manage energy and power data, electronic meters are gradually replacing the old electromechanical models. Different types of current sensors consist of resistive shunt and Hall-effect circuits [41]. Furthermore, advanced meters have led in recent years to the development of automatic meter reading (AMR) solution and services [42]. Next generation meters (called smart meters) will make full use of AMR's features, enabling the creation of automatic meter infrastructure (AMI) with bidirectional communication between the meter (consumer's side) and the utility provider [14,43].

The accuracy of these devices depends on their application and the metering class they belong to (as will be discussed in coming sections). Typical accuracy values for meters in Europe are in the range of between ±0.5% to ±2%. The price of these devices is mainly dependent on their communication protocol, ease of deployment and AMR compatibilities and range between $300–700.

3.2. Gas metering

Gas consumption must be adequately measured to comply with European and local codes. Several types of gas meters are currently present on the market; though diaphragm, rotary and turbine ones are the most commonly installed. The diaphragm gas meter is divided into two or more chambers formed by movable diaphragms. The chambers alternately receive and expel gas, expanding and contracting the diaphragms; the linear motion of the diaphragms is converted into rotary motion using cranks and the gas-flow information is thus transferred to a counter mechanism. Rotary meters are used when high gas-flow levels and higher accuracy are required. This type of meter consists of two rotors that spin in precise alignment and let a specific quantity of gas pass at each complete turn. The gas flow information correspondent to each rotation is then recorded using electrical pulses or mechanical counters. In turbine gas meters a rotor with helical vanes freely rotates with low friction around an axis parallel to the flow and thus to measure the gas flow speed. Volumetric flow and speed are linked by the continuity equation and are characterized by linear proportion once that the internal meter area is known. The information is then transmitted electronically or mechanically to a counter. Turbine gas meters require the non-turbulent flow condition to work properly [44].

All of the three types of meters described above use dynamic mechanisms to measure the gas flow. Although dynamic meters (and, in particular, diaphragm meters) represent the near totality of flow meters used by distribution companies. However, their construction simplicity and low cost is often accompanied by wear problems, high-pressure losses and inability to indicate instantaneous flow rate value [45]. In recent years, many static methods for the measurement of gas flow have gained popularity both in the commercial and research fields. Among the static devices, ultrasonic flow meters have shown significant results regarding accuracy and non-intrusiveness [45]. They typically use narrow-band piezoelectric transducer arrangements to interrogate the flow of gas in a pipe [46] and use variation to velocities of the sound pulse in the acoustic path between transducers to measure the gas flow [47]. Other static gas flow meters are the fluidic meters that are based on fluidic dynamic oscillation principle [48] and those that use the Coriolis effect [49].

Like electricity meters, gas metering has also experienced a broad development of smart models and functionalities in recent years. Although the measurement principles of the meters do not change, smart meters contain electronic devices that convert the pulse information into an energy consumption reading and then storing the reading or send it to a server, enabling forecast and energy consultancy services [50]. Due to a large number of traditional meters that are already installed, many manufacturers have also developed AMR solution to be directly connected to the pulse output of traditional meters. In this way, the conventional meter can be upgraded to a smart meter in a simple, quick and non-invasive way. An example of such upgraded smart meters was developed by Smart Metering Systems Plc. [51], that can be connected to a gas meter in a non-invasive way to provide half-hourly consumption reading using GPRS at communication medium. Table 2 summarises different types of gas meters currently widely available in the market for both domestic and non-domestic sectors. The cost of gas meters depends mainly on the measuring technology, pulse output option, AMR compatibility and measuring range. Generally, static methods-based meters are more expensive than dynamic ones.

3.3. Air temperature

Air temperature can be defined as "the temperature of the air surrounding the human body, which is representative of the aspect of the surroundings that determines the heat flow between the body and air" [37]. The range of techniques used for the measurement of temperature are wide and can rely on many phenomena,

Table 2
Summary of gas metering technologies.

Type	Use	Measuring range	Output	AMR compatible	Approx. price (US$)
Diaphragm	Residential	up to 7 m^3/h	Odometer counter	√	125–185
			Pulse		150–265
	Commercial	11.33–28.32 m^3/h	Odometer counter	√	400–550
			Pulse		500–650
Fluidic	Commercial	up to 28.32 m^3/h	Pulse	√	2000
		up to 84.95 m^3/h	Pulse	√	2600

such as thermoelectricity, fluorescence and spectral characteristics, a temperature-dependent variation of the resistance of electrical conductors, thermal expansion, etc. [52].

For the measurement of air temperature, however, most of the sensors are based on mechanical and electrical operative principles. Mechanical devices are in general cheap and reliable but are usually used for direct control purposes and/or visualisation rather than for metering and monitoring. The most common example is the domestic room thermostat, where the output is the temperature-dependent physical displacement of a bimetal to operate directly a switch [53]. Another example is the mercury-in-glass or liquid-filled thermometer, where the temperature information can be only visualised on a graduated scale [37]. Electrical sensors, instead, have the capability to convert the measured value into a digitally encoded signal for direct communication for control and measurement purposes. Electrical devices are mainly based on thermoelectric and electrical resistance principles. Thermocouples are the most widespread example of thermoelectric devices and are commonly used because of their low cost, simplicity, robustness, temperature range and size and because there is no requirement of the power supply. As a matter of fact, their functioning is based on the See-beck effect, that is the production of an electromotive force in a circuit of two dissimilar conductors experiencing a thermal gradient [52]. Resistance temperature devices (RTD), instead, use the dependency between temperature and electrical resistivity of a conductor. Although any conductor could, in theory, be used as an RTD, practical considerations of cost, reliability and manufacturing constraints limit the choice to copper, gold, nickel, platinum and few other semiconductors [52]. Examples of RTDs used in the building sector are platinum resistance thermometer (PRT) and thermistor. The former can rely on great accuracy, reliability and stability, but has the disadvantage of the high cost and the very high time response. The latter, which consists of a semiconductor (usually a mixture of oxides of nickel, manganese, iron, copper and others [52], whose resistance is sensitive to temperature, is cheaper and has good accuracy, but has problems of drift and requires proper calibration [53].

Approximate range of values of sensing parameters, cost and relevant information of air temperature sensors are reported in Table 3. Prices of different sensors are taken from datasheets and user manuals of some of the main manufacturers. It is evident that thermocouples are cheap and can measure a wide range of temperatures, but have low accuracy (system errors of less than 1 °C can be difficult to achieve). PRTs have higher accuracy (though it would require a 4-wire connection) and stability than thermocouples, but longer response time and cost are the drawbacks of these types of sensors. Thermistors are the most accurate and sensitive type of sensors for temperature reading. They have shorter response time as compared to RTDs but nearly have same response time when compared with thermocouples.

Table 3
Summary of air temperature, air humidity, mean radiant temperature, air velocity, CO_2, CO and VOC concentrations sensors.

Measured parameter	Type of sensor	Accuracy	Response time	Comm tech.[a]	Use	Approximate price (US$)	Measuring range
Room temperature	Thermistor	±0.1–0.5 °C	10–30 s	Wired Wireless	Direct visualisation BMS HVAC	20–70	−50 to 180 °C
	Thermocouple	±0.8–4 °C	10–80 s	Wired Portable	BMS HVAC	10–50	−100 to 300 °C
	PRT	±0.25–0.6 °C	3–8 min	Wired Wireless	Direct visualisation BMS HVAC	35–100	−50 to 100 °C
	Capillary thermostat	–	5–12 min	Closed control	HVAC	20–60	−35 to 65 °C
Relative humidity	Capacitive polymer	±2–4.5% RH	10–50 s	Wired Wireless	Direct visualisation BMS HVAC	50–200	0–100% RH
	Ceramic resistance	±2–5% RH	10–50 s	Wired Wireless	Direct visualisation BMS HVAC	40–150	10–90% RH
Mean radiant temperature	Globe-thermometer	±1–3 °C	8–30 min[b]	Wired Portable	Thermal comfort tests	40–150	20–120 °C
Indoor air velocity	Hotwire	±2–5% of reading	0.2–5 s	Wired Wireless	HVAC Airflow control Thermal comfort test	50–180	0.05–20 m/s
CO_2 concentration	NDIR[c]	±30–80 ppm	30–50 s	Wired Wireless	Air-flow control	200–500	0–2000 ppm
CO and VOC concentration	MOSFET[d]	±50–100 ppm	<60 s	Wired Wireless Portable	Air-flow control	200–500	400–2000 ppm CO_2 eq.

[a] Communication Technology.
[b] Adjustment time.
[c] Non-dispersive infrared.
[d] Metal–oxide–semiconductor field–effect transistor.

3.4. Mean radiant temperature

The mean radiant temperature is defined by ISO 7726 as "the uniform temperature of an imaginary enclosure in which radiant heat transfer from the human body is equal to the radiant heat transfer in the actual non-uniform enclosure" [54]. It also suggested by ISO 7726 [54] that it can be calculated from the temperature of surrounding surfaces and their orientation with respect to the body (subject) [37]. However, besides calculation methods, ISO 7726 proposes a comprehensive series of methodologies and instruments for the indirect measurement of the mean radiant temperature and globe thermometer is widely used among them. This type of instruments has low cost and high traceability but also have high response times (that limit real-time measures) and overestimation of radiative contribution related to horizontal surfaces (floors and ceilings). Other usable instruments are contact and radiation thermometers and unlike globe thermometers both these devices can evaluate the asymmetry of the radiant temperature [54] within a room. However, to provide a reliable measurement, contact thermometers need significant attention regarding contact resistance evaluation, while radiometers require the knowledge of the emissivity of the surface to be measured. Finally, the most accurate sensors are the net radiometers, but their usage in the building is usually limited due to their high cost and the need for multiple sensors [55]. Most of the available devices in the market used to measure radiant temperature are globe thermometers. These types of probes for the measurement of mean radiant temperature are part of expensive portable instruments that are capable of the measurement of all the parameters that define thermal comfort.

3.5. Indoor air velocity

Air movement around the subject (occupants) can increase/decrease heat flow from and to the body and hence body temperature [37]. Indoor air velocity plays a significant role in the definition of thermal comfort conditions [36,56]. Indoor air velocity can be considered as "the mean air velocity intensity over an exposure time of interest and integrated over all directions" [37]. This means that any measuring device must be able to measure the effective velocity whatever the direction of the air is.

A commonly used principle is to calculate the air velocity from the cooling (or heating) produced by air moving across the instrument. The kata thermometer [57], for example, is an alcohol thermometer with a large bulb that is heated and exposed to the environment. Although these thermometers provide average practical values of air velocity, they are inadequate for significant fluctuations and cannot be used for recording and computer analysis purposes [37]. Another type of sensors, which also belongs to the same category and are widely used in the building sector, are hot wire anemometers [58]. These devices measure the cooling capacity of air moving across a 'hot' wire and relate this to the air velocity using the value of air temperature within the environment [59]. Compared to kata thermometer, hot wire anemometers measure fluctuations in the air temperature and measurements can be easily recorded for later analysis. They are, however, directional in response and can be inaccurate in low air velocities due to the natural convection of the hot wire [37]. An improvement of the hot wire anemometer is the low-speed hot sphere anemometer. It consists of two sphere/sensors: an electrically heated sensor that registers the air velocity and a cold sensor that measures the air temperature to allow for the correction of the heated sensor temperature. With respect to the hot wire anemometer, the hot sphere sensor is omnidirectional and, therefore, it is the most practical device that can be used for the measurement of indoor air velocity [60].

Air flow can be also measured by using more advanced (and thus expensive) sensors with directional sensitivity, like ultrasonic and laser Doppler anemometers. The former consists of 2, 4 or 6 prongs (about 100 mm apart) that emit a sonic signal in 1, 2 or 3 directions respectively. The velocity of the air in one direction influences the time of flight of pulsed sound waves between the corresponded prongs. As a consequence, pulsing two ultrasonic signals in opposite direction between each set of prongs and comparing the time of flights of the out signal and the back signal, it is possible to calculate easily the air velocity [61]. In the latter, the velocity measurement is measured by focusing a laser beam onto the measuring point and recording the frequency shift of the light scattered by moving particles [61]. These instruments are mostly used to room air velocity measurement both in laboratories and in field applications [62], their high cost, size and sensitiveness have limited their commercial development. There are other sensors that are based on principles involving pressure measurements (like Pitot tubes) or rotating element immersed in the air-flow, but sensors based on these principles are suitable for air speed measurement only when flow direction is determined, such as in air ducts. Their use for indoor air velocity measurement is therefore very limited.

3.6. Relative humidity

Humidity is defined as the water vapour content in the air or other gases. It is generally measured in terms of absolute humidity, dew point or relative humidity (RH) [63], but all three measures can be calculated from each other if the air temperature is known. One of the oldest used instrument for determining relative humidity is the whirling hygrometer (or sling psychrometer). Whirling hygrometer consists of two thermometers that are turned by vigorously swinging the handle and exposing the thermometers to rapid air movement. The bulb of one thermometer is placed in direct contact with the room air to measure dry-bulb temperature. The bulb of the other thermometer is covered with a silk or muslin sleeve that is kept moist to record the wet bulb temperature. The atmospheric humidity is determined by calculations, steam tables, or using a psychrometric chart (considering the difference in reading between the two thermometers) and, therefore, the use of these devices for monitoring purposes is very limited [37].

Modern electronic devices use change in electrical capacitance or resistance to measure humidity differences. Capacitive type sensors consist of a substrate (typically glass, ceramic, or silicon) on which a thin film of polymer or metal oxide is deposited between two conductive electrodes. The incremental change in the dielectric constant of the sensor is nearly directly proportional to the relative humidity of the surrounding environment. Resistive sensors usually consist of noble metal electrodes either deposited on a substrate by photoresist techniques or wire-wound electrodes on a plastic or glass cylinder. Resistive humidity sensors measure the change in electrical impedance of a hygroscopic medium such as a conductive polymer, salt or treated substrate [59]. The materials used in humidity sensors that exploit variations of electrical parameters can be classified into electrolytes, organic polymers and ceramics [64]. Commercially developed humidity sensors are mainly made of polymer films and porous ceramic [65]. Thick film technology, in particular, offers advantages of cost efficiency, robustness and flexibility in device design [66]. Thermal conductivity sensors (also known as absolute humidity sensors) are mostly used to measure absolute humidity even at high temperatures or in polluted environments by means of a system that employs two thermistors in a bridge connection [59].

3.7. Indoor air quality (IAQ)

According to Fanger [67], there are three basic requirements for human occupancy: temperature and relative humidity acceptability, maintenance of normal concentrations of pollutants gasses (mainly carbon dioxide (CO_2) and volatile organic compounds (VOCs) and secondly carbon monoxide (CO) and others) and distribution of adequately ventilated air. Internal air quality (IAQ) control aims to fulfil all these three requirements. As discussed above in this paper, temperature and humidity sensor technologies and measurement techniques have been widely developed and deployed in the industrial and civil sectors in recent decades. In contrast, carbon dioxide (CO_2), carbon monoxide (CO) and air pollutants control, though thoroughly studied in terms of concentration acceptability and related air-change rates for the building sector [68], has shown a massive technological development only in recent years.

According to the measurement principle, CO_2 sensors can be mainly classified into two categories: the first type uses chemical methods, which can ensure high accuracy, but lack of stability and durability due to heterogeneous gases poisoning effects; the second uses a non-dispersive infrared (NDIR) method based on the physical principle of gas-absorption at a particular wavelength. NDIR-based sensors have higher energy consumption but still are the most widely applied for the real-time monitoring, due to their higher durability, reliability and accuracy [69]. CO_2 sensor information can be directly used in building automation to increase the natural or mechanical airflow, but many studies have also suggested to use visual *traffic-light*-type sensors to inform the occupants of the increasing CO_2 concentration in a room [70]. CO_2 concentration can also be used to estimate occupancy within a building and this information can be used to implement a more efficient control of the HVAC system [71].

CO and VOCs detection in building, instead, is mainly achieved by using the physical principle of gas-adsorption on semiconductors. Simple metal oxides such as SnO_2, WO_3 and TiO_2 are well known for their high sensitivity to changes in the air composition [72]. Their operation relies on the establishment of adsorption equilibrium between the molecules of the measured gas and the grains of semiconductor, resulting in a change of electrical conductivity of the sensor's material [73]. Metal oxide sensors show high and stable sensitivity, but they also require an electric heater to keep the sensing element to approx. 300 °C, resulting in high electric consumptions. This aspect and the very short life of these devices have led to the recent development of new gas sensors based on electrochemical methods. Their operative principle does not different from a fuel cell, which in this case is designed to produce a current output proportional to the concentration of the particular pollutant in the air. Due to their very low power consumptions, quick response time, high sensitivity and longer life, electrochemical gas sensors have been increasingly used for CO detection [74]. The same method can also be used for VOCs monitoring, but provides inaccurate results when sensing mixtures of chemicals; its exploitation is therefore generally limited to the industrial sector for the monitoring of individual pollutants.

Table 3 reports examples CO_2, CO and VOCs concentration measurement devices currently available in the market. Technical data is taken from the datasheets of different manufacturers while costs have been deduced from information found on the Internet.

3.8. Occupancy and daylight sensors

Lighting energy consumption can be significantly reduced by switching off or dimming lamps based on factors like occupancy and availability of daylight [75]. Technologies that perform this type of lighting control differ in their input parameters, their control method, control algorithm, cost of installation, complexity of commissioning, etc. [76]. In below sections, the focus of the discussion will be on different occupancy and lighting sensors that can be used in building for controlling lighting systems.

3.8.1. Occupancy sensors

Occupancy sensors employ motion sensing techniques to detect the presence of occupants in a given range of space; the lights are turned on when the sensor detects any occupant while are turned off when there is no occupant within a pre-fixed delay period [76]. Although many studies have demonstrated the importance of occupancy information for whole building climate control [77], occupancy sensors in buildings are currently mainly used for lighting control purposes.

Among the available sensing systems passive infrared (PIR) detection systems and ultrasonic sensors are the most common. PIR sensors rely on detecting a change in the temperature pattern in the observed space using a pyroelectric detector [78]. The sensitivity of these type of sensors depends on the distance of the subject from the sensor, and this can lead to *False-off* errors when movements of occupants very far from the sensor are not accurately detected [79]. Ultrasonic sensors work based on the principle of Doppler effect; emitting ultrasonic waves and comparing them to reflected signals. Ultrasonic waves are reflected by room surfaces, and, therefore, these sensors do not require a fixed field of vision like the PIR sensors. As a consequence, ultrasonic sensors have been proven to be more reliable in detecting presence over long distances [80], though movements coming from activities in the room other that occupants can lead to *False-on* errors [76]. Some other types of sensors that are also gaining popularity include sensors based on radio frequency identification (RFID) and imaging techniques such as camera and body recognition to detect occupancy [76]. RFID sensors are mostly used in offices for personnel identification [76].

3.8.2. Daylight sensors

Daylight-linked lighting control can be used either to switch lights ON or OFF when daylight level inside the occupied space is above or below a threshold value or in combination with dimmable electronic ballasts to adjust the artificial lighting level according to the daylight contribution [81]. Daylight-linked lighting control can be divided into *Switching systems* and *Dimming systems*, according to the way the lighting system is controlled [76]. A daylight responsive system is composed of a sensitive element, such as a photosensor, a lighting controller and an electronic dimming ballast [82].

Table 4 lists different types of occupancy and lighting sensors. Data comes directly from datasheets of the various manufacturers while cost is collected from information found on the web. It can be clearly seen that price mainly depends on the type of the system – Standalone system with direct load control are cheaper. Price also depends on the accuracy of different sensors and type of communication medium used. Sensors which offer wireless functionality are more expensive as compared to wired connected sensors. In the case of occupancy sensors, Ultrasonic sensors are more expensive as compared to PIR sensors. For lighting sensors, photosensors are more expensive than photodiodes.

4. Selection of sensing solutions

In this section, different factors that influence the selection of sensing and metering solutions will be discussed. The key factors are listed below:

- Accuracy
- Ease of deployment
- Communication protocol
- Granularity
- Cost
- Availability

Table 4
Summary of daylight and occupancy sensors.

Parameter	Type of sensor	Accuracy/range	Response time	Communication	Approx. price (US$)	Dimmer compatibility
Occupancy	PIR	3–5 m radius or 5–12 m front and 3–8 m lateral	10 s–15 min	Wireless Wired Standalone[a]	25–80	N/A
	Ultrasonic	185 m^2	30 s–30 min	Wireless Wired Standalone[a]	150–300	N/A
Light	Photo-diode	±8–10% of illum.	N/A	Wireless Wired Standalone[a]	50–150	Yes
	Photo-sensor	±8–10% of illum.	N/A	Wireless Wired Standalone[a]	100–250	Yes
Daylight	Photo-diode	±8–10% of illum.	N/A	Wireless Wired Standalone[a]	50–120	Yes
	Photo-sensor	±8–10% of illum.	N/A	Wireless Wired Standalone[a]	100–250	Yes

[a] Standalone sensors are directly connected to an actuator to switch on/off or dim artificial lighting.

4.1. Accuracy

In Europe, there are different bodies to govern meter accuracy and one of these is the Measuring Instrument Directive (MID) (2004/22/EC) [83]. MID is a European Directive to harmonize the requirements of different measurement instrument types (including electricity and gas meters). In the UK, only MID approved electricity and gas meters can be used for both supplier–consumer billing and tenant billing [84]. By reviewing available sub-meters, it is found that although none of them are MID approved however they do comply with other standards. MID approved meters also comply with those standards as well. Some example of the meters' accuracy standards for kWh are EN 62052-11 [85], EN 62053-21 [86], EN 62053-23 [87], BS 8431 [88], IEC 1036 [89], IEC 687 [90], ANSI C12.20 [91]. One of the common feature of most of these standards is to categorise meters into Classes representing their percentage accuracy e.g., Class 0.5 = ±0.5% accuracy, Class 1.0 = ±1% accuracy and Class 2.0 = ±2% accuracy. In Table 5, most widely available fiscal and non-fiscal meters are categorised according to their classes and whether they are MID approved or not. It is clear shown that some of Class 0.5 and Class 1.0 meters are MID approved. Class 1.0 meters are most suitable for sub-metering purposes, and Class 2.0 meters' accuracy is considered as the minimum standards for sub-metering.

For electricity meters, it is also necessary to consider the accuracy of current transformers (CTs), as there are most commonly used current sensors in high current solid state electricity meters [92]. CTs are used in fiscal metering when a high operating current (typically above 100 A) is applied directly to a meter [93]. CTs are also widely used in retrofit electricity sub-metering installations as they allow sub-meters to be fitted safely with minimal interruption of power provision. Their use in fiscal meters is evident of their acceptability as an accurate measurement instrument.

4.2. Ease of deployment

Deployment of metering and sensing solution can offer different installation and networking challenges that must need to be tackled. Wireless sensors reduce the installation cost and also provide greater flexibility. A study conducted by [94] showed that wireless sensors have more advantages rather than just replacing wires. Milenkovic and Amft [95] have demonstrated that it is feasible to use existing BEMS sensors and controls to improve energy efficiency and reduce installation requirements. Their study also demonstrated the effectiveness of self-powered sensors (incorporating a battery and small solar panel) with wireless communications ability. On the other hand, the deployment of energy meters offers less flexibility as these needs to be connected to the energy distribution system. In general practice, sub-metering of electrical services is carried out by using either a panel or rail meters installed in electricity distribution board using CTs to minimise cost, have safety and ease of deployment. Installation of mechanical energy meter for gas, oil and heat metering also offer less flexibility as these need to be installed on the relevant pipe that serves devices, area or building. General practice is to install these mechanical meters based on finding a suitable location, minimising disruption to supply and compliance with safety regulations. These restrictions are to some degree offset by the fact that typically far fewer devices are served by the utilities monitored by mechanical meters so limiting the number of sub-meters is required. Different factors that should be considered while deploying sensors and meters in building are listed below:

- New sensors and meters need to be interoperable with the existing installation in the building including BEMS, IT network, communication protocol and transport layers.
- The wireless capability of any new sensors should be examined to make sure that they will satisfy the coverage limitation.
- Meters location should be easily accessed for the installers.
- Making sure that there is minimal disruption in the supply.
- Safety legislations and regulations regarding metering installation should be complied.

4.3. Communication protocol

A wide range of communication and network technologies are discussed in Section 5 to transfer sensor and metering data. Table 5 listed fiscal and non-fiscal meters along with the available communication protocol those meters offer. Fiscal meters offer the widest range of network and communication protocol options but are not ideal for multiple sub-metering installations. ModBus and Ethernet are commonly available for sub-meters and offer the most attractive option due to ease of integration with existing communication networks and the potential to collect other energy data. In summary, commercially available meters do offer a wide choice

Table 5
Accuracy classes of some common fiscal and non-fiscal electricity meters.[a]

Manufacturer	MID approved	Class 0.5	Class 1.0	Class 2.0	Connectivity					
		±0.5%	±1.0%	±2.0%	Ethernet	WiFi	ModBus	M-Bus	GPRS GSM	PLC
Fiscal meters										
Elster A1120/40	•				•		•	•	•	
Elster A1170	•		•		•		•	•		
Elster AS230	•		•		•	•	•	•	•	
EDMI MK10A	•		•			•	•	•	•	•
Landis &Gyr ZMD405	•	•			•	•	•	•	•	
Landis &Gyr E650	•	•			•	•	•	•	•	
Non-fiscal meters										
ND Meters Cube/Rail 350 IP			•		•		•	•		
Schneider Electric PM750		•								
Schneider Electric PM850		•			•		•			
Selec MFM 384			•		•		•			
Carlo Gavazzi EM21-72R				•	•		•			
Carlo Gavazzi EM24	•		•		•		•	•		
Carlo Gavazzi WM4-96			•		•		•		•	
Hager EC310				•						
Hager EC320				•						

[a] This table is based on most widely available fiscal and non-fiscal meters in the UK.

of communications and network compatibility that gives flexibility for integration with most existing systems.

4.4. Granularity

Granularity or resolution of measurement determines the possible level of analysis that can be performed on the metered or sensed data. It can be considered as a function of equipment's resolution, data collection interval and the number of equipment connected to a data collection device or system. Resolution of equipment has an apparent impact on granularity as it determines the minimum level of data that can be collected. Pulsed outputs on many of the electricity meters can be scalable and configured by the user. However, a pulsed output is only generated when a threshold value is exceeded, for example if a device is scaled at 1 pulse per kWh there will be no information available on consumption between 0 and 999 Wh. Typical data collection intervals in non-domestic buildings for fiscal metering and data logging in BEMS are 30 min and 15 min; and are considered as sufficient for building level collection and lighting, HVAC motors, and pumps due to infrequent changes in power modes. For devices with more frequent changes in power states or with very low levels of energy use (e.g., computers, screens, and printers) more frequent sample rates may be required. A study by Lanzisera et al. [96] concluded that date sampling at 1 min provided sufficient accuracy to determine power states for electrical loads in an office building. However, this study was performed for a limited period (6–16 months) and concluded that two months was sufficient to generate representative data for the particular study. Data resolution as frequent as 1 min is useful for some specific purposes but it may not be required for monitoring over extended periods. Also, data resolution at this level is very rarely available in existing commercial meter and sensor systems.

Granularity is also affected by the network structure adopted for the data collection system and specifically the number of sensor devices connected to a data collection device or system due to the time required to communicate with each sensor and retrieval of data from the sensing point. This time can be approx. up to 30 s per sensor. Therefore, in a data collection network with a large numbers of sensors the time delay between retrieving data from the first and last sensor can be few minutes. This issue can be addressed by a combination of increasing the number of installed data collection devices and also by installing sensors with built-in storage so that data collectors can recover historical data as opposed to live data. This solution has a drawback of increased cost and, therefore, there should be a trade-off between granularity requirements and installation costs.

4.5. Cost

Equipment cost is identified as a primary driver in deciding on investing in metering and sensing equipment; operating cost is more important to those stakeholders who are choosing to integrate the system, on the other hand, initial cost reduction is more beneficial to those who do not want to integrate the system [23]. Cost perceived as a financial risk factor by building owners or design teams. The data to enable a clearer understanding of the balance between the cost of control systems and the savings those systems might achieve is often lacking. As a result, the number of sensors and meters installed in existing buildings is usually limited to the minimum to provide adequate control of HVAC systems and ensure compliance with any relevant legislations.

4.6. Availability

The availability of a particular manufacturer's meters and/or sensor will vary geographically and from a practical point of view it is necessary to have reasonable lead in times for delivery and provision of technical support and spare parts. Product availability makes one of the most critical factors in deciding which devices to deploy, and it is a factor that can only be assessed at the time of deployment. As a result, similar monitoring and sensing requirements are met by a range of devices in different countries depending on the geographical availability of products.

5. Communication and network technologies

Communication and network technologies are mainly divided into two categories, i.e., wired and wireless technologies. These technologies can be used for data transmission between utility meters and utility providers, building energy management system and indoor environmental monitoring sensors, building users and smart appliances, etc. Both of these technologies (wired and wireless) have their advantages and disadvantages e.g., wireless technologies are low-cost solutions as compared to the wired technologies, and have low installation and operating costs. On the other hand, wired technologies are a more secure way of data transfer as compared to the wireless technology. The choice of the technology depends on the requirements of the problem.

Communication network will play a significant role in the success of smart grids, and smart buildings and cities. According to Depuru et al. [97], the selection of the communication network and design of the communication devices are critical and must satisfy complex requirements. As we are moving towards smart buildings and cities, the amount of data transfer will be enormous and different challenges needs to be tackled to handle sensitive and confidential data. There are different communication networks' guidelines and standards to make sure that the data transmissions between various components are secured. Sood et al. [98] mentioned that the communication links will be using different kinds of communication technologies i.e. hard-wired links to fibre optics, wireless, satellites and microwave links; due to the fact that smart grids will be covering a vast geographical territory. In the below section, we will discuss some of the widely used communication and networks technologies for metering and sensory purposes in the buildings.

5.1. ZigBee

ZigBee was built on the IEE 802.15.4 standard and operates in the 2.4 GHz and 900 MHz bands [99], this standard defines the physical layer and medium access control sub-layer specifications for a low rate and cost personal area networks. ZigBee supports the star, tree and mesh networking topologies. ZigBee provides a low cost, reliable data transfer, short range, low power consumption home area wireless network solution. ZigBee is mostly used for security system, building automation and remote meter readings. ZigBee has application limitations due to its low power and rate, and also short-distance nature. Therefore, it is not recommended to be used for the applications with strong real-time and large amount of data [100].

This low cost and power consumption are also selling points for ZigBee. It is also an automatic dynamic network and with high security [101]. ZigBee meets the requirements of a seven-layer protocol layer and also has an additional module for security purposes. A ZigBee network can be extended to a maximum of 255 nodes; this makes it a highly expandable network [102]. ZigBee network is based on Master/Slave and facilitates two-way communication. The media storage control (MAC) layer operates on talk-when-ready collision prevention mechanism [103], which means the data is transferred when it is required, and the receiver also confirms when the data packet is being received. This feature increases the ability of the ZigBee network to make sure the transmission data packet. Although Zigbee HAN devices have a very low energy consumption (<1 mW), ZigBee network may not be suitable for rural areas due to having a 100 m line of sight range [104].

Different studies developed and experimentally validated ZigBee-based smart meters. Luan et al. [105] used ZigBee communication technology to transmit not only the detailed power consumption data but also outage event data to rear-end processing system. Experimental results showed a high potential for using ZigBee-based solution to build the area-based advanced metering infrastructure (AMI). Han and Lim [106] proposed and implemented a smart home control system using ZigBee and IEEE 802.15.4. The authors also developed a new routing protocol, DMPR (Disjoint Multi Path based Routing), to enhance the performance of ZigBee sensor network [107]. Luan et al. [108] designed a ZigBee-based smart power meter with outage recording function to develop an automatic reliability system for AMI. It was concluded that the proposed system has great potential to be integrated into the AMI to improve the accuracy of reliability calculation. Cao et al. [109] presented a remote wireless AMR reading system based on wireless sensor networks and embedded technology. ZigBee was used to transmit data from the sensor nodes to the data collector, and Ethernet was used to transmit data from the data collector to the server. It was found that the average receive rate of the sensor node using ZigBee was 92.81%, therefore, it was concluded that it is possible to implement the proposed system for remote AMR applications. Kang et al. [110] implemented a smart loading monitoring and control system with ZigBee wireless network. The integration of ZigBee smart loading control module and digital meter was able to monitor and control the electricity consumption of household appliances and also manage standby power. ZigBee technologies have also been used for monitoring photovoltaic and wind energy systems [111]. The authors also used ZigBee for building and home energy management. The experimental results demonstrated the proficiency of ZigBee devices applied in smart metering systems and distributed renewable generation.

5.2. Power line carriers

Power line carriers (PLCs) uses existing electricity grid, cellular network, mesh network, licensed and unlicensed radio, wireless modem, power line communication, RS-232/485, WiMAX, Ethernet and Wi-Fi to upload data using IEC DNP [97]. PLCs are more suitable for remote locations, where cellular or GPRS coverage is not available or where the number of consumers are relatively low [14]. The data transmission near electricity transmission can be problematic in PLC as there is data distortion and in most cases it is ideal to avoid transformer points. PLCs also have low bandwidth (up to 20 Kbps) but the advantages of PLCs are that they have low running cost and can be installed using current infrastructure, there also have low initial cost. For utility providers, PLCs are better options due to having full control over the network and their low cost [112]. According to Depuru et al. [97], power line carrier is an efficient technology for automation of data in smart meter applications. PLCs can be used to transmit data to and from the building along low and high voltage power line [113]. As PLCs have lower bandwidth, therefore, they are mostly suitable for lower bandwidth applications e.g., changing traffic light signals, switching on and off street lights, etc. Kim et al. [114] used PLC to transmit control data, however, its integration with other systems (e.g. window mounted security insurance system) was difficult to perform. Choi et al. [115] also used PLC as a communication protocol for their smart metering system. It was acknowledged by the authors that wireless mode of communication without repeaters could be challenging in buildings that are constructed from ferroconcrete as most of the signals will be blocked.

5.3. ModBus

ModBus was introduced by Modicon Corporation and used it as a point-to-point connections with EIA-232C interfaces of Programmable logic controllers). It is one of the widely used communication protocol due to its simplicity and reliability. It includes RTU (Remote Terminal Unit), TCP (Transmission Control Protocol) and ASCII mode of transmission and supports RS-232, RS-422, RS-485 and Ethernet based equipment [116]. ModBus is based on Master/Slave method for data communication; an information request is sent by the Master and Slave produces the response to the requested information. ModBus, because of its simplicity and open source availability, is more popular for local communication in buildings and also has become standard for industrial SCADA systems [117]. ModBus is a client-server protocol that was initially designed to communicate low-speed serial in process control network, and security issues were not addressed [118]. One of the primary concerns of ModBus is that it does not support authentication nor encryption [119], which means it is less secure and more vulnerable to cyber attacks. ModBus has been used in different research works; Bhatt and Verma [120] developed ModBus based intelligent Building Automation System (BAS). The authors wired sensors and ModBus compliant I/O modules to form an RS-438 network at field level. A ModBus compliant submeter was also used by [121] to monitor real current consumed by up to 21 devices.

5.4. GPRS and GSM

GPRS and GSM stand for general packet radio service and global system for mobile. GSM is well known as one of the world's most deployed technology and is present even in the remote parts of the world. Reliability of short message service (SMS) during network congestion times can be a challenging issue for GSM/GPRS technologies [122]. GSM based smart meters are already being used and available in the market. Tan et al. [123] and Ashna and George [124] proposed a GSM based meter for energy billing; SIM (subscriber identity module) are embedded in the utility meters, and the data is sent over to the utility provider through SMS or GPRS. However, as discussed previously missing SMS can be a serious issue for GSM/GPRS based technologies. Two other issues from supplier perspective could be the hacking by the consumer to alter their energy consumption data, and someone can also cut the power remotely (this can be cutting the power of an entire cities or cities).

There are other applications of GSM/GPRS apart from automatic energy metering. Technologies based on these communication protocols are also used for indoor environment and load control purposes. Al-Ali et al. [125] developed a GSM based home appliances monitoring and control system. Alheraish [126] also proposed a similar system, which shows the popularity of GSM/GPRS based system due to their extensive coverage. However, before deploying a GSM/GPRS based solution, the strength (quality) and availability (quantity) needs to be checked/determined [127].

5.5. M-Bus

M-Bus stands for Meter-Bus and is a European standard (EN 13757-2 physical and link layers [128], EN 13757-3 application layer [129]) and is used for transmitting gas, heat, oil, etc. meter readings to utility providers. M-Bus was specifically designed for meter reading and is less popular than ModBus protocol. By using M-Bus, a large number of devices can be connected with each other, and there can also be the possibility of network expansion. Metering bus also have wireless applications, and recent research has been focussed on Wireless M-Bus e.g., [130,131]. Open Metering System group has proposed the use of Wireless M-Bus for metering scenarios and recommended to be used in smart meters [130].

M-Bus is been used by researchers in different R&D projects; REMPLI project [132] included the support for the M-Bus protocol in the automatic metering domain. Hosek et al. [133] also used M-Bus in their study to investigate the feasibility of cost-efficient measurement architecture based on already deployed home and network access technologies. M-Bus was also used in Intelligent Metering project [134] to transmit energy and water consumption data to monitor occupants' behaviour. Spinsante et al. [135] analysed the adoption of the Wireless Metering-Bus (WM-Bus) in future smart water grids. It was found that the WM-Bus protocol at 169 MHz ensured adequate transmission capabilities.

5.6. Ethernet

Ethernet is a low-cost communication method and is widely used for communication between PLCs and supervisory control and data acquisitions (SCADA). Ethernet is available on three media: i.e. optical fibre, shielded twisted pairs and coaxial cables. Among these three mediums, optical fibre is more secure and popular because of the absence of electromagnetic interference and electrical current [136]. Ethernet uses carrier sense multiple access collision detection (CSMA-CD) methods for sending data [137]. According to Bertoluzzo et al. [138], Ethernet is not suitable for real-time application because the a priori estimation of the data packet's maximum transmission time is impossible. Different solutions can be used for real-time applications of Ethernet and are known as real-time Ethernet (RTE) e.g., Powerlink [139], EtherCAT [140], PROFINET IO [141], etc. Ethernet requires cabling and is often less favourable option. Ethernet is a robust and common solution with no running cost, but it can be interfered easily and also require the involvement of IT team.

5.7. WiFi

In recent years, wireless sensing technology has gained more popularity because wireless sensors are easy to install and cheaper in price. However, its use for the metering technology is still at very early stage because of security issues. Mushtaq [142] has discussed in detail the security vulnerabilities concern of wireless networks. WiFi can use existing wireless local area network (WLAN) and there is no addition need of a dedicated network. This communication technology is more expensive as compared to other technologies because of its high power consumption and model price. Wireless technology is mostly used for building automation, remote control, meter reading, security systems, etc.

A WiFi based home automation system was designed and implemented by ElShafee and Hamed [143]. The proposed system can be scalable and one server was able to manage many hardware interface modules (as long as they existed on WiFi network coverage). The proposed system has the benefits of low cost, secure, remotely controllable, auto-configurable and ubiquitously accessible system. Martani et al. [144] proposed a method to measure occupants' activity by using WiFi connections as a proxy for human occupancy. Although this study was not particularly focussed on WiFi communication protocol, however, WiFi was used to study the correlation between energy consumption and occupancy. Balaji et al. [145] performed an occupancy based HVAC actuation by using the existing WiFi infrastructure in commercial buildings. It was found that the system accurately determined the occupancy in office spaces and resulted in energy savings of 17.8%.

5.8. BACnet

BACnet stands for building automation and control network and was initiated by ASHRAE (American Society of Heating, Refrigeration and Air-conditioning Engineers) and is now an American National Standard (ANSI/ASHRAE 135-1995) and ISO Standard (ISO 16484-5) standard protocol [146]. The advantage of using BACnet is its ability to be integrated with different types of equipment without having any need for additional hardware. BACnet has the capabilities from field layer (bottom layer) and BAS layer (top layer) for building control application and is considered as the full-fledged international standard [146]. A wireless version of BACnet using short range wireless networks (e.g., ZigBee) has also been developed [14]. The use of using ZigBee as a communication protocol for BACnet was announced in addendum 135-2008q to take advantage of reduced installation cost, flexible extension and mobile device connectivity of ZigBee [147]. BACnet's popularity can be judged by the fact that ASHRAE SSPC 135 has established the Smart Grid Working Group to enable buildings as full participants in the Grid [148]. In that regard, the Smart Grid Working Group has released some BACnet objects that can be used for demand reduction in buildings [149]. The BACnet Web Services issued by ASHRAE can allow external application to have interaction with building energy management or automation system for advanced control and/or optimisation of HVACoperation.

An effort has been done to couple building energy management and control system (EMCS) with different simulation programmes [150]. Haves and Xu [150] has developed a software called building controls virtual bed (BCVTB) to couple EnergyPlus[1] with control systems. A BACnet interface [151] is also been developed allowing the simulation programme to communicate with BACnet-compatible building control system. This interface was also used by Pang et al. [152] to compare actual and expected building energy performance in real time. Hong et al. [149] experimentally evaluated BACnet-ZigBee smart grid gateway for demand response (DR) applications in buildings. The gateway was used to map application of ZigBee to that of BACnet and vice versa. Another study by Li and Hong [153] also introduced a gateway architecture for mapping the DR applications of BACnet to those of EnOcean,[2] and vice versa. A study by Krioukov et al. [154] demonstrated a personalised lighting control system by using BACnet protocol to control different zones and several switches.

6. Future directions and challenges

6.1. Interoperability

Interoperability, in its broadest sense, can be defined as the ability of products and services to work together and to exchange information during all lifecycle stages without the loss of semantics [155]. Standardised representation of information is at the heart of interoperable solutions. In the case of metering and sensing devices, it refers to the standardized exchange of data so that the components of building energy monitoring and metering system can communicate with each other irrespective of different manufacturers and physical medium. Advanced sensing and monitoring solutions are available in the market from different manufacturers; with a different range, communication protocol and capabilities; therefore, interoperability needs to be maintained between these technologies for their consistent communication.

This challenge can be tackled by developing frameworks that should include standards and protocols to achieve interoperability between metering, sensing devices and also with the control system. An example of such framework for Smart grids is known as NIST framework [156]. NIST framework includes protocols and standards for information management for interoperability of smart grid systems and devices [157]. Such kind of frameworks needs to be developed on building level as well. Also, there is a need to introduce, develop and deploy vendor-independent metering and sensing solutions to increase flexibility.

6.2. Security

The security of the advanced metering infrastructure (AMI) will be one of the biggest challenge for and high priority of consumers, suppliers and policy makers. AMI will be able to transfer all kind of data e.g., socio-economic status, work habits, which and when appliance are used, food consumption patterns, etc., which can be assessed both legitimately and illegitimately) [43]. Attackers can alter the transmission and can also get access to the information. This issue needs to be discussed not only for deliberate attacks but also for unintentional user errors and equipment failures [157]. The privacy of customers' energy and environmental data should be respected as the customers do not want to share their energy related information to unauthorised people or marketing firms [158].

Wireless communication protocols are more vulnerable because of air (open medium) being used for data transmission. Different standards bodies are working towards making securing data transfer links. Wireless protocols will be secured by using technologies such as 802.11i [159] and 802.16e [160]. On the other hand, wired links will be made more secured by using virtual private networks (VPN), firewall and also by using secure shell (SSH), security socket layer (SSL) [157].

6.3. Cost

Cost is one of the deciding factors for selecting sensing and/or metering solution in buildings. Wired communication solutions are costly due to their initially cost, on the other hand, mobile phone technology based solution such as GSM and GPRS are expensive as well due to their high power consumption. Wireless solutions are cheaper because of the absence of the wires, but there are other drawbacks. Despite implementing different policies and legislations, there are not many incentives from government's side for building owners to pay towards their smart solutions. There are other incentive schemes e.g., Warm front, The Green Deal, etc., but unfortunately, there are not many incentive schemes for metering and sensing technologies. In the UK, householders can get an optional payment of £230 per year for purchasing a metering and monitoring solution on the installation of heat pumps through renewable heat incentive (RHI) [161]. The smart grid is a key step towards sustainable energy future [137], Stanislav et al. [162] defined smart grids as the power system will be *smart* by using meter, controls, sensors and analytical tools to control and monitor the energy flow from plant to plug. Therefore, there should be more incentives rather than just policies to reduce energy consumption and to move towards sustainable future. Also, cost related to a dedicated communication network for the transmission of data will be a very expensive solution and according to MacDonald [163] 'piggybacking' on existing communication infrastructure may be less expensive.

6.4. MEMS sensor technologies

Sensors and processing devices are getting smaller and cheaper, microelectromechanical (MEMS) sensor technology is one the advancements in this regard. In future, more advancements are expected in MEMS technology to develop sensors that are more capable and versatile. One of the many applications of MEMS in buildings is using MEMS based 'Smart Dust motes' wireless platforms by [164]. The authors used the platform for controlling daylighting systems in commercial buildings and concluded that the proposed solution enabled less expensive and disruptive retrofitting of commercial buildings. MEMS sensors show immense potential towards energy saving and smart sensing solutions.

6.5. Lack of ICT infrastructure

The European Commission has plans to replace 80% of electricity meters with smart meters by 20%. It is projected that the installation of smart meters will lead to a reduction of 9% in emissions in the EU. The cost of installing a smart energy meter will provide a savings of £160 for gas and £309 for electricity per metering point. However, the installation of smart meters and moving towards smart grids and smart cities will also require the deployment of advanced measurement and control devices along with different sensors [165]. Strbac [165] mentioned that the key ingredients for smart grids and cities do exist, however, target trials are required to gain more experience and most importantly a commitment to

[1] EnergyPlus. http://energyplus.gov.

[2] EnOcean. https://www.enocean.com/en/technology/.

implementation would be a key factor towards smart grids and smart cities. We can also learn from the trials/implementation that were carried out in other countries. One of the examples of such implementations, the example of implementation of smart meters in the Australian state of Victoria needs to be studied before moving forward. A report by Auditor-General [166] criticised the deployment of smart meters due to the risk of accelerated installation schedule in advance of national and international standards.

7. Conclusions

In this article, we presented a comprehensive review discussing metering and sensing technologies for buildings. The study suggests that there has been active research and technological advancements in building energy metering and environmental monitoring. There are a broad range of technologies available and used by the researchers and industry people to overcome different challenges. In home automation and HVAC system monitoring, wireless area networks show promising trends towards deploying a low-cost metering and monitoring solution. Wireless networks are easy to retrofit the exciting system as compared to the wired system, and they are also more preferred because of their lower installation costs. However, choosing a proper metering and monitoring solution is a challenging task as it depends on different factors such as granularity, accuracy, cost, availability, ease of deployment and communication protocol. This paper also overviews different drivers for energy metering and environmental monitoring. The paper also reviewed some of the policies and regulations that are in place in the various countries and it is evident that only a few countries address the need to install metering and sensing technologies in buildings.

Communication and network technologies should be cost benefit and be able to provide good transmittable range along with secured data transmission and better power quantity and bandwidth. One of the biggest challenges of AMI is the protection of metering data against unauthorized access. The privacy and quality of the transferred data are important to both clients and service providers. To detect forged or hacked smart meters an end to end secured communication protocols can be used and also encryption of data needs to be ensured for protecting against leakage of information. Also, future research should focus on developing multi-protocol devices, or further standardisation is required to address the issue of interoperability, which is one of the biggest challenges for AMI. This article also highlighted some other challenges and future directions that need to be addressed. It can be concluded that the area of building energy metering and indoor environmental technologies has witnessed many technological advancements in recent years, and it will be continued because of the developments in information and communication technologies.

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