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INVESTIGATING ENERGY SAVINGS WHEN USING IOT DEVICES IN BUILDINGS: A CASE STUDY IN THE UK

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Abstract

Smart buildings are described to be efficient in their daily operation by integrating IoT technologies into the building systems (e.g., lighting and HVAC). However, concerns have been raised about how and if they perform this task. This study investigates the balance of emission levels from smart buildings with embedded IoT sensors against energy reduction using Integrated Environmental Solution Virtual Environment software. Findings show that the annual energy consumption from smart buildings was reduced by over 38% with smart HVAC and smart lights. The embodied emission level from the smart building increased by 7% at over 2 $kgCO_2/m^2/yr$, a drawback that should be considered during the production of IoT materials used in buildings. This study recommends that real-time monitoring, measurement and analyses are carried out to increase potential renewables penetration into the energy mix.

Keywords: energy saving; IoT; sensors; smart building; IES VE simulation.

Introduction

The energy crisis is happening, and it will only worsen given the current increases in energy demand if no drastic measures are put in place to improve the existing production and consumption practices. Among the different sectors of the economy, the building and construction sector alone accounts for 38% of global energy-related Carbon dioxide (CO_2) emissions (UNEP, 2020). In 2019, emissions from this sector stood at an all-time high of 10 gigatonnes of carbon dioxide ($GtCO_2$), attributed to direct and indirect emissions caused by increased demands in the operational phase of buildings and adverse weather changes, which resulted in an increase of 8.47% in final energy use between 2010 and 2019 (IEA, 2020). The construction industry in the UK alone contributed more than 13 million (m3) tons of CO_2 in 2019, of which buildings and building-related works contributed 17% (Tiseo, 2021). However, due to the COVID-19 pandemic, global emissions were reduced by 7% (UNEP, 2020), and will be continuously reduced by 6% each year if we are to halve the target of the present direct emission by 2030. Another source of concern is the direct emission from fuels used in domestic buildings for heating during the winter months, as this accounted for 10% of the UK's carbon footprint back in 2016 (UKGBC, 2021). Several studies have investigated and made recommendations on how the built environment can reduce its embodied and operational emissions rate. They also mentioned several adaptive measures aided by technology, from system automation to passive controls deployed over the last decade. One such adaptive and dynamic technology is the Internet of things (IoT), which has shown huge savings (Amaxilatis et al., 2017; Machorro-Cano et al., 2020; Alsalemi et al., 2022).

The use of IoT technology in buildings has proved effective, and energy savings are well documented. Different studies exist that measure and quantify the emissions levels from using these IoT components for building operations and maintenance and suggest how to reduce them. For example, Zhao et al. (2022) proposed an innovative IoT framework to promote low-energy building in densely populated urban areas, which was approved to achieve low energy costs. Tanasiev et al. (2021) explored detailed IoT solutions to control the HVAC system and monitor the environmental performance in a real building, which led to significant CO_2 emission reductions. However, little research has been done about the potential environmental ramification of IoT devices in buildings to justify if the energy savings can equate to the carbon emission levels.

Therefore, the complete picture of excluding the impact is missing. Because of this gap, the energy savings in terms of green impact have not been estimated closer to reality in smart buildings, prompting an urgent need for a more holistic approach guided by data. The impact of building emissions embedded with IoT systems should be clearly known to provide stakeholders with a better image for decision-making, particularly as it affects the environment. However, that is missing in the current body of knowledge. This study seeks to address this gap by investigating how the emission levels from embedded IoT devices operating in smart buildings do balance the energy reduction of the smart building. The investigations are performed using the Integrated Environmental Solution Virtual Environment (IES VE) simulation tool.

Literature review

IoT developments in general

IoT technologies have been widely considered to have the potential to connect objects to the internet, enabling objects to see, observe, detect, record, learn, make decisions, and take actions based on data with little or no human interference (Alsalemi et al., 2022). Therefore, they improve business workflows by minimizing errors, and reducing operational costs and waste, while increasing speed and system efficiency. However, these improvements naturally come with increased demand, growth, production, and network connections where IoT components numbers spike over the roof through the years. These increasing numbers are likely to raise great concerns and challenges from the economic, social, and environmental aspects (Quisbert-Trujillo et al., 2020). The smart items connected to the internet grew from 6.4 billion in 2016 to 25 billion in 2021, while some researchers predicted these numbers will run into billions ranging from 125 to about 160 billion by 2030 globally (Nižetić et al., 2020). Another issue is the environmental stress by way of e-waste as numbers soared. Le Brun & Raskin (2020) discussed the sourcing and the utilization of rare earth metals required for their production as vital, especially as it consumes six times the energy used in plastic or metal processing. Quisbert-Trujillo et al. (2020) sounded more alarmed about the energy consumed in manufacturing, the ecotoxicity at the end of life, and the required components to support accessories that make IoT systems work, e.g., battery replacement on some of these battery-powered devices, and the resources for compressing data to prevent traffic of communication of radiofrequency. Nižetić et al. (2020) questioned how the monitoring of the network would occur with no current standard framework guiding policy on-demand maintenance, security, and privacy. They also alluded to an increase in fossil fuel use in production and the low rate of recycling e-waste, currently at about 20% or less. Furthermore, the lead content of these e-wastes is dangerous to life. Finally, the urgent legislature on e-waste, the need for harmonization of the recycling process, and improvement in the percentage amount being recycled each year as annual generation stood at 44 billion metric tonnes. The wastes generated from the IoT deployment should be compensated by their benefits in terms of energy savings and carbon emissions.

IoT in Building Energy Savings

The global energy savings conundrum necessitates retrofit measures in buildings to reduce energy intensity. Papadopoulos et al. (2019) divide this into the technical and operational retrofit. Walls, roof insulation, and high-performance windows are some examples of technical retrofits, and may not be economically feasible to replace in the existing buildings due to the high upfront cost associated with them. Also, it involves the physical alteration in the design, something particularly challenging for the old and historic buildings as is in the UK. Another challenge is the operational or human-based retrofit, which refers to actions that occupants and building managers can take to improve energy performance by adjusting the HVAC system, reducing light and equipment usage, and opening windows for natural ventilation during the summer months. Dong & Andrews (2009) combined the distribution of IoT sensors and energy plus simulation tools to achieve 30% energy savings while maintaining indoor comfort levels for a room. For it to be efficient, it requires a large number of network sensors to accurately detect occupant activities, making it costly and unpractical, especially in large open offices fitted with more people at once. Papadopoulos et al. (2019) demonstrated it is possible to have as high as 60% in energy savings for a large office when the HVAC setpoint ranges between 17.50 °C for heating and 27°C for cooling during occupied hours without compromising occupant comfort.

Since there is a lack of empirical studies, whereas related evidence is needed for evaluating the benefits of IoT deployment in the HVAC and lighting system, the scope of this study will be concentrating on some of these human-based retrofits – HVAC and light systems embedded with IoT sensors.

Methodology

Simulation Design

Simulation tools are appropriate to calibrate and compare the performance of different building design options at the early design stage. This will minimize information losses, reduce cost, and increase speed, time, and analysis flexibility. It also provides important data for stakeholders, particularly regarding the early concept design stage of buildings.

Different building simulation studies have been conducted in the past using a host of applications – Design builder, Energy Plus, IES VE, E-Quest, and Green building Studio, to name a few. The question does sometimes arise as to which is best to use during design. Each comes with something unique to offer, and the decision on which simulator to use lies with the designer and depends on certain parameter(s) of interest and the nature of the analysis required.

The IES VE tool was used for this study because it offers a wide range of modeling applications within its virtual environment – SunCast and SunPath for Solar Analysis, Apache HVAC for thermal comfort, and Radiance and FlucsDL for lighting and Sensor settings, among others.

Life Cycle Analysis (LCA) was used to estimate the environmental impacts (the carbon emissions in terms of $kgCO_2$) throughout the building life cycle. IES VE version 2021 comes with the added feature of the One-Click life cycle assessment (LCA) tools within its VE Gia virtual environment, allowing users to run environmental impact and energy performance simultaneously, thereby saving time and reducing error. Therefore, IES VE with One-Click LCA add-in was used in this study to conduct the LCA process.

IES VE also uses other plugins to design and analyze building models. In this work, we created the building geometry using the ModelIT, which is the central 3D core application for geometry data input shared by all modules. The model also includes relevant weather files and specified zone thermal conditions. ApacheSys and ApacheHVAC were used to define and integrate the HVAC system to the model and apply setpoint temperatures and system flow rates. Daylight and artificial light analysis and sensor activation were performed with SunCast and RadianceIES, which would serve as the input during the following dynamic simulation run. Then the dynamic simulation engine, Apache interphase, was used to run all the energy analyses, and the results were presented on Vista for interpretation. Both models were directly transferred to the VE Gia with links to One-Click LCA for the environmental analysis (IESVE, 2021).

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This study modeled a 5-story commercial office building with an underground tunnel and a bridge that connects it to the adjacent section, housing the server rooms and more offices, situated at Newcastle, North-eastern part of England. It is located at longitude 1.690W and latitude 55.040N, and 81m above sea level. The design was created using the 2013-2016 amended version of the Building Regulations 2010 Part L1A document, focusing on the cold-humid climate of the location in mind. The building design details are presented in Figure 1, Figure 2 and Table 1.

The building comprises offices, meeting rooms, a restaurant, a café, and ICT system rooms. We will be simulating two basic models – a conventional and a smart building model; however, the smart building will be further broken down into smart HVAC change (i.e., HVAC with independent sensors control system) and smart light sensing (i.e., sensor-controlled artificial light bulbs). The annual percentile for the heating load was (99%), while the monthly cooling load percentile was (10%), giving an outdoor winter design heating temperature of (-2.70^{0}C) and maximum cooling load of (19.90^{0}C db. and 15.80^{0}C wb.) because the model was a thermally heavy classed model.

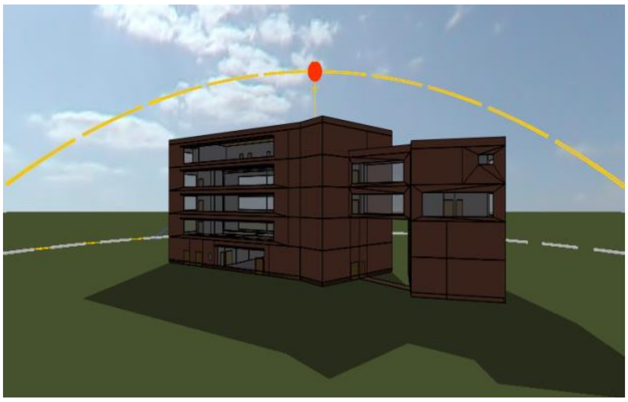

Figure 1: Back view of the investigated building model

Figure 2: Front view of the investigated building model

Table 1: General building parameters

Building parameter	Details
Building area	4303.14 m^2
External wall thermal transmittance	0.2599 W/m^{2}K
Window-wall-ratio	36%
External window thermal transmittance	1.6 W/m^{2}K
Infiltration rate	0.25 ac/h
Orientation	210 degrees
Building height	14.8 m
Service life	30 years
Roof thermal transmittance	0.18 W/m^{2}K

In line with the literature review above, we carried out two distinct changes and analyzed their effects with the 2020 (present data) and 2050 (future data) weather files obtained from the University of Northumbria database for Newcastle. Both weather files have been integrated into the IES VE tool for easy access and application during the simulation runs. The isolated changes were independently applied to the conventional model to determine the effect, from which comparison will be drawn for present and predicted future weather data. For this simulation, we have chosen the 16th – 20th July as the typical summer week and the 22nd – 26th January as the typical winter week for further analysis. Also, 1st January – 31st December is the annual duration. Table 2 shows the design parameters for the investigated systems, which are simulated in IES VE simulation software.

Table 2: Design parameters for the investigated systems in the smart building model

Design Parameters	Investigated
Boiler loads	Apache System – ApacheHVAC with Sensors
Chiller Loads	Apache System – ApacheHVAC with Sensors
Light Gains	Non-Dimming – Dimming with Sensors
Total System Energy	HVAC and Light systems.
CO_2 Emissions	Embodied and Operational Emissions.

Scenarios development

For the energy phase of this analysis, we have developed four scenarios: Conventional Building, Daylight Harvesting Model, Apache HVAC Model, and the Smart Building. The energy analysis covers the boiler, chillers, and light energy from the artificial bulb present in the model.

- The Conventional Building system controls are set to ON or OFF only all day, all year and following occupants' daily profiles. The heating and cooling supplied to the building are not by passive method but an active Apache System with timed switches. The systems are single or multi-split, fan coil, and single room cooling systems. The lighting gains for this case were non-existing as the artificial lights were set to be ON continuous throughout the working hours and go OFF at the end of the day following the weekly profile adopted without any dimming effect, keeping the light energy consumed the same all through the year. A similar approach applies to the HVAC systems and other forms of internal gains - people and equipment, as no difference occurred due to no change in the profile. As a result, the internal environment of the model was only affected by the building envelope and the applied weather data.
- Apart from the HVAC system in buildings, another area with huge potential for energy savings is the lighting system on the radiance application. We applied the open-loop system with the IoT light sensors placed at the roof level pointing downwards to control the dimming effect of the artificial light bulbs within set boundaries throughout the day depending on the occupancy movement and natural daylight illuminance level within the space per time. The results obtained were compared against the conventional building without these sensors activated to analyze their energy savings for present-day and predicted future weather files.
- Apache HVAC systems with independent sensors were integrated into the conventional building model, replacing the initial Apache system sensing and controlling dry resultant temperature and flow rates into spaces. The Apache HVAC model created consists of the same three different systems as the Apache system used for the Conventional building, with independent sensors replacing the timed switches. Sensors monitor and control set temperatures and relative humidity within the zones to which they have been assigned.
- A smart building is a model integrated with the Apache HVAC system and artificial light sensors working in sync to improve energy savings by sensing and controlling the internal environment within a space. These systems have been set up with their respective profiles and boundaries to keep the internal condition of a room within defined ranges and not compromise on occupant thermal comfort and vision.

After calculating the energy savings, both models were transferred to the One-click-LCA via the VE Gia tool. The LCA analysis was run for the building using 30 years (2020-2050) life horizon from cradle to grave. The benefit of using the One-click-LCA is that it recognizes the model materials, makes all the necessary adjustments and assumptions, and pulls the data from its global resources to calculate the carbon emission levels for each model with the result presented in a .csv file.

Findings

Total system energy result - Conventional Building

The total energy use intensity (EUI), i.e., the ratio of total energy to building floor area, increased by 3% from 131.2 KWh/m^2/yr to about 135.2 kWh/m^2/yr for the 2020 and 2050 weather data, respectively. For both weather files, July was the dominant month with figures surpassing 60 MWh, while February had the minimum consumption all year, as shown in Figure 3.

For most periods of the year, the total system's energy consumed for the future weather data (2050 data) was more, except for January, February, and December, for which the present weather data (2020) was dominant. Furthermore, the total system energy during the summer months (May – Sept.) was, on average, 26% more than the winter months (Nov. – Mar.) by 2020 and 30% more by 2050.

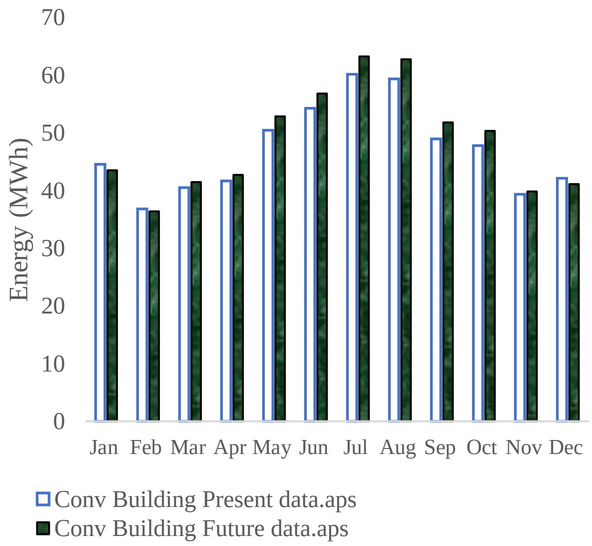

Figure 3: Monthly total systems energy consumption of Conventional Building (MWh) (For interpretation of the references to color in all colored figure captions, the reader is referred to the web version of this paper.)

Total system energy result - Daylight Harvesting Model

The impact of daylight harvesting on the total system energy compared to the conventional system is presented in Figure 4. In this case, the energy savings were minimal at about 3% per annum. Again, energy savings for the summer months exceeded that of winter, but the winter period provided some remarkable results with 78% and 73% in ratio to the summer figures even with the shortened daylight hours during this period. July showed the biggest savings of 3.3 MWh and 3.2 MWh when results were compared with the conventional model for both weather files.

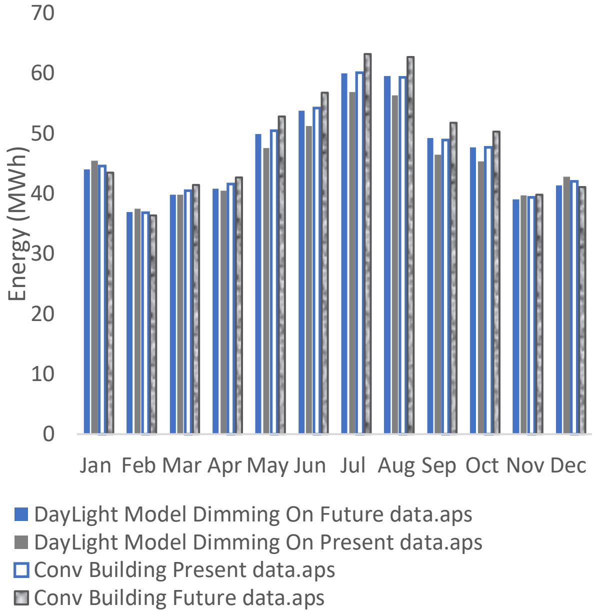

Figure 4: Monthly Total System Energy Daylight Harvesting Model vs. Conventional Model (MWh)

Total system energy result - ApacheHVAC Model

The total annual system energy of smart building, compared to the conventional building shown in Figure 5, decreased by over 55% in both weather files. Similar to our Conventional Building model, July was the month with maximum energy consumption at over 28 MWh and 30 MWh respectively for future and present data. The average annual system consumption was more than double between both models, with the conventional model standing at above 47% for both weather files. Finally, when considering the HVAC model alone, the mean system energy demand during summer was 1.68 MWh more than the present data, and 0.52 MWh less in the winter months. This indicates dominant future summers where temperatures are expected to rise due to anthropogenic activities.

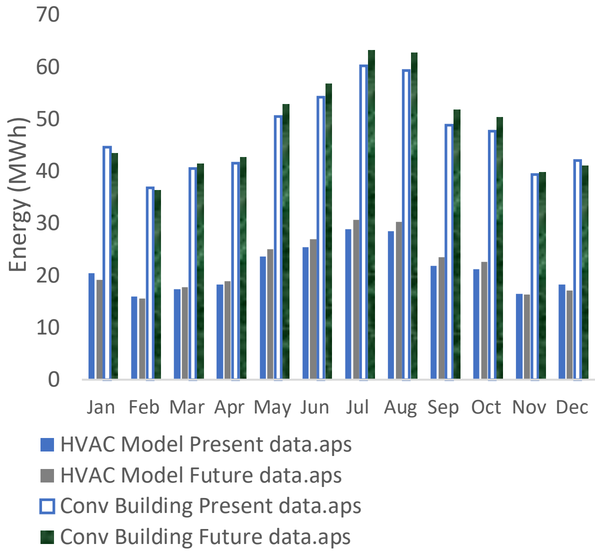

Figure 5: Monthly Total Energy Conventional Building vs. ApacheHVAC Model (MWh)

Total system energy result – Smart Building

Annual system energy saving improved by 56.8% and 57.2% for both weather files, respectively, amounting to over 300 MWh in savings in favor of the smart building, as shown in Figure 6. Monthly, the smart building's energy savings also improved by at least 58% compared to its corresponding pair in the conventional building. The maximum monthly energy consumed stood at 28.3 MWh and 26.5 MWh in July for both weather files. Of the yearly total, summer alone accounted for more than half of the smart building's energy for the future weather data, while it stood at 47.9% for the present weather data.

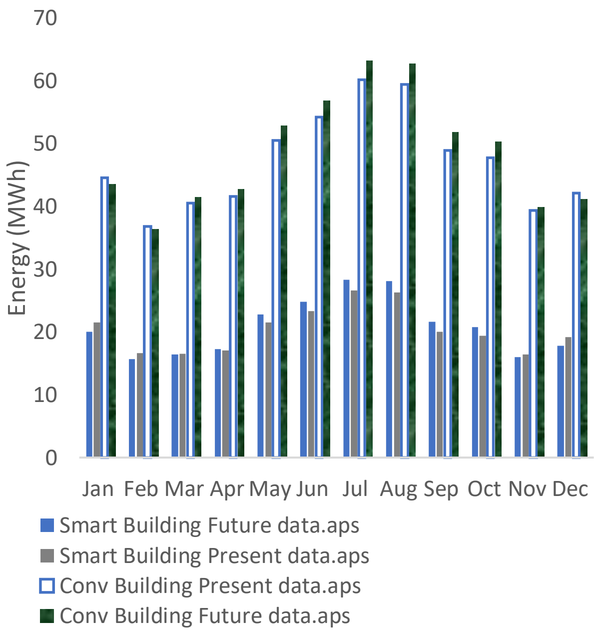

Figure 6: Monthly Total System Energy, Smart vs. Conventional Building (MWh)

Carbon emission – Smart vs. Conventional Building

The CO_2 emissions of the smart and conventional buildings were assessed with One-click-LCA from cradle to grave. The external impacts include benefits and loads beyond system boundaries. These are energy recovered by recycling materials and reusable products; hence their values were subtracted from the total CO_2 emissions. The total CO_2 emission for the smart building by the end of 30 years lifetime (1.83 t CO_2 e / m^2) is 37.1% lower than that of the conventional building (2.91 t CO_2 e / m^2), which is similar to the results provided by Su et al. (2020).

The embodied carbon emissions are 33.12 kg CO_2/m^2/yr for the smart building and 30.91 kg CO_2/m^2/yr for the conventional building. Based on CO_2 classification, the embodied carbon emissions of both models are presented in Table.3. Electricity consumption contributes to the highest portion of the total embodied emissions, which are 93.3% and 95.3% for the smart and conventional buildings, respectively. The internal walls and non-bearing structures contribute to the least emission (less than 0.1%) for both designs. The electricity consumed in this stage is sometimes referred to as the embodied energy, i.e., the electricity consumed in material extraction, manufacture, transportation, and all other processes in the supply chain during the construction and end of life phases of both buildings (Su et al., 2020).

Table 3 Embodied Carbon emission between smart and conventional buildings.

Category	CO_2e emissions - ton (Smart Building)	CO_2e emissions - ton (Conventional Building)
Electricity use	7377.8	11949.4
Floor slabs, ceilings, roofing decks, beams, and roof	187.7	187.7
External walls and facade	159.2	178.6
Fuel use	117.9	159.2
Windows and doors	58.6	58.6
Internal walls and non-bearing structures	8.1	8.1

The operational emissions for both designs were measured by the carbon emissions generated from the fuel consumption, including heating, cooling, lighting and appliances. As shown in Figure 7, the life cycle operational emission of the smart building is 28.15 $kgCO_2/m^2$/yr, which is over 65% less than the conventional buildings. The peak emission for the conventional building during the summer months reaches 41.9 $kgCO_2$/h, which is over two times higher than the emissions from the smart building.

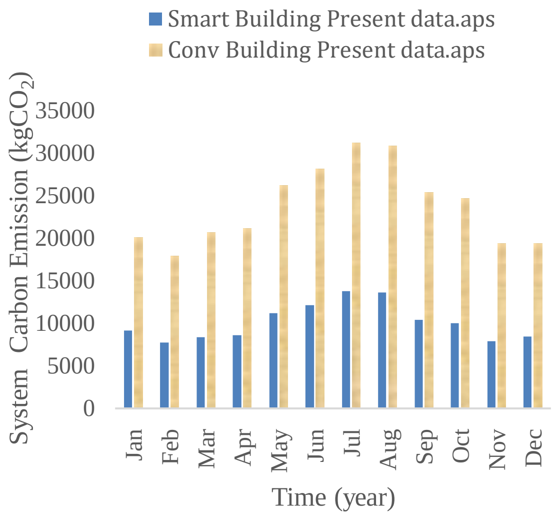

Figure 7. Annual Operational Emission – Smart vs. Conventional building.

Discussion

Energy savings and carbon emissions from buildings are two key aspects that recent research has focused on addressing issues of global warming associated with the built environment. The impact of IoT technologies, e.g., sensor-based systems, on energy savings is well documented and presented in the literature review section. We have demonstrated the potential of these systems in improving the energy savings in smart buildings by enhanced automation in the prediction, monitoring, and sensing of occupant behaviors and other factors, and activating systems controls to maintain thermal comfort of occupants within set limits. The EUI for the smart model was 135.4kwh/m^2, which is about 38% lower than a conventional building at 219.3kwh/m^2. This result follows the trend observed by Ali Al-janabia et al. (2019) for buildings of similar size. Annual heating system energy savings for the smart design stood at over 35% (8 MWh) and over 85% (300 MWh) for cooling system demands which agrees with the works of Papadopoulos et al. (2019), who carried out similar studies on building energy at different locations.

Energy savings from cooling demand more than doubled those from heating and can be attributed to several reasons. First, the effect of weather on temperature rise and shortened winter months in the future makes cooling demand a dominant parameter for the smart designs and should be factored into future design decisions. Climatic conditions also control cloud cover within the external environment. Secondly, both models were not created to use the passive cooling method (i.e., Natural ventilation) but the active method (Apache HVAC). Internal gains from people, equipment, and lights were very active, contributing to the increased demand for cooling in the summer months and resulting in the dry temperatures exceeding setpoints at peak hours of the day. However, a reverse effect occurred in the winter months as internal gains played a role in reducing the boiler energy consumption. Building orientation indirectly affects the cooling demands, as our designs were south-facing, with about 5% more glazing in the north than the south zones. The excessive heat gains from the solar position further add to the internal gains, which, in turn, can also contribute to the cooling energy demand of both models and even may result in overheating. The effect of local shading was not considered as this is not within the scope of this work, but we believe it will be of significant effect in swinging the energy demands depending on the location and height of the shading object. The same goes for building insulation. The results of dimming control by the sensors from both designs kept the minimum illuminance level within the spaces above 500lux.

IoT devices' environmental impact was also investigated to better understand certain issues raised earlier – particularly the carbon emission from smart buildings. The embodied emissions from the models showed a slight increase in the smart building (2.21 $kgCO_2/m^2/yr$), although the bulk materials were the same in both models; however, we believe this result is justifiable in reality. Given that IoT devices are incorporated into the building envelope, it increases the amount of embodied carbon emissions of the building. Considering the mining and extraction, transportation, and all the other processes on the supply chain plus e-waste generated at the end-of-life of these components are accounted for as discussed in the literature study. At 33.12 $kgCO_2/m^2/yr$, the embodied carbon emissions in the smart building are 7% more than that recorded for conventional buildings. At the same time, the operational carbon emission from the smart building is 57% less than the value of the conventional building. The ratio of embodied to operational carbon emission from both designs stood at 32:68 for conventional buildings and 46:54 for the smart building, which falls within the acceptable range for UK buildings. In the studied models, energy was the major determinant in both embodied and operational carbon emissions. The CO_2 emission level of the smart building was less compared to the conventional model, probably because of the sensor controls present to regulate the operations of the boiler, chillers, and consumption of the artificial lights while keeping the internal environment comfortable. To reduce the emissions of not just CO_2 but all greenhouse gases (GHG) within the built environment, the UK must continue to push for green energy generation and utilization. One of the goals of the 2021 United Nations climate change conference (COP26) that took place in Glasgow is to "Secure global net-zero by mid-century and keep global temperature rise of 1.5 degrees within reach" (COP26, 2021). This will only become a reality through sincerity of purpose and people-focused business models integrated into energy generation, transmission, and utilization. For example, sources of fuel used in generating these energies are a major concern, especially in the Newcastle area, where heating during winter is predominantly by gas boilers. Building professionals, homeowners, and tenants should embrace the support from the UK government that advocates replacing boilers with heat pumps and thermal photovoltaics in residential and commercial buildings for space heating and daily hot water supply to help reduce emission rates at home, offices, and even at the grid.

Conclusions and future work

Several technologies and digital devices have been deployed in both real and simulated environments to try and achieve the net-zero target of the UK government by 2050. Systems of interconnected digital devices, objects, machines, and people (e.g., users, facility managers) with the ability to transfer and share data over a network, broadly defined as the Internet of Things (IoT), are used in buildings to reduce energy consumption and improve the thermal comfort of an occupant by real-time monitoring and employing different management strategies. To better understand the environmental impact of these IoT technologies – particularly the use of sensors in buildings, we set out to investigate if the energy savings balances the carbon emissions on IES VE for a commercial office building in Newcastle, UK.

The EUI of the smart building was reduced by over 38% compared to the conventional building with the deployment of smart HVAC and light sensors used in controlling dry bulb temperatures and daylight within a space according to defined occupant profiles. The annual cooling demands were also reduced by over 300MWh representing 85% savings during the summer months as the independent sensors on the smart HVAC sensed and controlled both flow rates and dry bulb temperatures to keep occupants cool and comfy all summer within limits. A similar result was recorded during the winter months with 35% energy savings.

The artificial light sensors in the smart building showed great potential savings by controlling dimming proportion with increased or decrease external illuminance. At maximum, it reached 72% (1.3KW) energy-saving daily during the early spring and kept the level of internal illuminance above 500 lux, which is the minimum requirement for commercial offices.

The positive ripple effect of these IoT sensor actions is visible in the operational emissions for the smart building as boilers, chillers and light bulbs are being regulated, indirectly controlling the level of fuel and electricity consumed in the process in line with the occupant profile. Operational emissions from the smart building are 57.8% less than that of the conventional building at 66.24 $kgCO_2/m^2/yr$.

However, a negative result was recorded for the embodied carbon emission from the smart building at 33.12 $kgCO_2/m^2/yr$, representing 7% more than the embodied emission level for conventional buildings. It was attributed to the increased material, energy used in manufacturing, end-of-life e-waste and transportation from the addition of sensor components and other devices to help them work efficiently in the smart building.

Therefore, the result suggests the energy savings from embedded IoT sensors do, in fact, balance and outperform their emission levels, but caution must be in place. While embedded IoT sensors reduce energy utilization and improve performance and comfort inside smart buildings, their embodied emission contribution margin should be considered. If advances in technology increase the level of smartness of buildings, then the embodied emissions will become a concern for the future. Simulation results sometimes do not transcend to reality. Future research will include real-time monitoring, measurement, and analyses of the energy savings in smart buildings against the measured emission level from the building with IoT sensors. Also, it will include the shading control system and use of motion detection sensors, as these were part of the limitations of this study.

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