Predictive Digital Twin Technologies for Achieving Net Zero Carbon Emissions: A Critical Review and Future Research Agenda

Citation: Elghaish, F., Matarneh, S., Hosseini, M. R., Tezel, A., Mahamadu, A. M., & Taghikhah, F. (2024). Predictive digital twin technologies for achieving net zero carbon emissions: a critical review and future research agenda. Smart and Sustainable Built Environment. doi:10.1108/SASBE-03-2024-0096

Abstract

Purpose

Predictive digital twin technology, which amalgamates digital twins (DT), the Internet of Things (IoT), and artificial intelligence (AI) for data collection, simulation, and predictive purposes, has demonstrated its effectiveness across a wide array of industries. Nonetheless, there is a conspicuous lack of comprehensive research in the built environment domain. This study endeavours to fill this void by exploring and analysing the capabilities of individual technologies to better understand and develop successful integration use cases.

Design/methodology/approach

This study uses a mixed literature review approach, which involves using bibliometric techniques as well as thematic and critical assessments of 137 relevant academic papers. Three separate lists were created using the Scopus database, covering AI and IoT, as well as DT, since AI and IoT are crucial in creating predictive DT. Clear criteria were applied to create the three lists, including limiting the results to only Q1 journals and English publications from 2019 to 2023, in order to include the most recent and highest quality publications. The collected data for the three technologies was analyzed using the bibliometric package in R Studio.

Findings

Findings reveal asymmetric attention to various components of the predictive digital twin's system. There is a relatively greater body of research on IoT and DT, representing 43% and 47%, respectively. In contrast, direct research on the use of AI for net-zero solutions constitutes only 10%. Similarly, the findings underscore the necessity of integrating these three technologies to develop predictive digital twin solutions for carbon emission prediction.

Practical implications

The results indicate that there is a clear need for more case studies investigating the use of large-scale IoT networks to collect carbon data from buildings and construction sites. Furthermore, the development of advanced and precise AI models is imperative for predicting the production of renewable energy sources and the demand for housing.

Originality/value

This paper makes a significant contribution to the field by providing a strong theoretical foundation. It also serves as a catalyst for future research within this domain. For practitioners and policymakers, this paper offers a reliable point of reference.

Keywords

Digital twins, AI for net zero, Machine learning, Decarbonisation pathways, Emission analytics, Digital ecosystem, Sustainable built environment.

1. Introduction

In July 2023, a significant climatic event unfolded, marked by the highest recorded global average daytime temperature, with sea surface temperatures surging to unprecedented levels. These alarming indicators collectively underscore the profound imbalance within Earth's climate system, demanding immediate action from major industries worldwide. Such action is imperative to mitigate the potentially catastrophic consequences that may ensue if these climate anomalies persist unchecked (Bulkeley and Newell, 2023).

The objective is unmistakable: the world needs a significant curtailment in global greenhouse gas (GHG) emissions, targeting a nearly 50% reduction by 2030 and aiming for the ultimate benchmark of net-zero emissions (Kodoth, 2023, Levin et al., 2023, Chen et al., 2024). Achieving net zero - a state where the sum of carbon emissions and its removal from the atmosphere balance out - is more than an environmental imperative (Levin et al., 2023); it is a cornerstone for sustainable development. But the transition towards net zero requires more than just intent; it demands the translation of this global carbon constraint concept into a practical and actionable framework for decision-makers. This involves tailoring decarbonization pathways for specific entities and streamlining efforts not just at global or national levels but also diving deep into sub-national regions, corporate strategies, and other organizations (Fankhauser et al., 2022, Bello, 2021). As part of their strategy for this transition, tech giants like Microsoft and consultancies like PwC emphasises the critical role of innovation and the use of cutting-edge technologies to shape and steer the net-zero transition (Insights, 2023, Herweijer, 2020, Ghansah, 2024).

In the landscape of Industry 4.0 innovations such as cloud computing, the Internet of Things (IoT), artificial intelligence (AI) and machine learning (ML)/deep learning (DL), and digital twins (DT) stand out (Goulding and Rahimian, 2012, Getuli et al., 2021). These have emerged as pivotal enablers, enhancing the efficiency of energy-intensive systems and playing a catalytic role in accelerating the net-zero transition (Ahmed et al., 2023a, Newman et al., 2021, Jia et al., 2023). They enable better data collection, increased transparency, collaboration, and precise control, ultimately guiding more informed decision-making processes (Wood, 2021, Darko et al., 2020, Zhang et al., 2024, Ghansah and Lu, 2024).

Among these innovations, the integration of IoT, DT, and AI marks a revolutionary stride, developing the concept of predictive DT. Going beyond the traditional DT that mirrors physical systems in a digital space, predictive DT blends data-driven learning and predictive modelling with the existing systems (Kapteyn et al., 2021, Sohal et al., 2023). This approach leverages physics-based modelling, data-driven ML techniques, and uncertainty quantification, providing a holistic decision support tool for offering predictive insights (Kapteyn and Willcox, Haghshenas et al., 2023).

The integration of predictive DT with environmental strategies heralds a transformative shift, providing unprecedented precision in monitoring and proactive management of environmental variables. Such advancements are vital when juxtaposed against the global goals of net-zero carbon emissions. These technologies empower industries to simulate various carbon emission scenarios, anticipate potential setbacks, and develop strategies that resonate with sustainable developmental goals (SDGs). They not only allow for real-time monitoring, analysis, and prediction of environmental parameters but also open the avenue for predicting future scenarios, thereby equipping industries to better prepare and strategize for a sustainable future.

Few studies have explored the integration of all technological components that form predictive DT (Tahmasebinia et al., 2023). While its potential as a cornerstone for carbon mitigation strategies is unequivocal, the literature within the built environment context remains scant and fragmented. A comprehensive and systematic analysis encompassing the collective advancements in this field and the identification of prominent research gaps have been notably absent. The present study endeavours to fill this void by employing a multifaceted approach, which integrates bibliometric techniques alongside thematic and critical review methodologies.

The rest of this paper is structured as follows: Section 3 contains a description of the research methods and techniques. Section 4 focuses on the critical analysis of research related to the three main components of a predictive DT, followed by section 5, which presents a research agenda. Section 6 concludes the paper.

2. Background

The goal of achieving "net-zero emissions by 2050" is a global target aimed at curbing global warming to within 1.5°C above pre-industrial levels, with the overarching objective of substantially mitigating the risks and consequences associated with climate change (Ohene et al., 2022). Net-zero emission assets utilise emission-free energy sources and fulfil energy demands through on-site renewable energy generation. Their benefits encompass a reduced environmental footprint, lower operational and maintenance costs, enhanced system reliability, and improved energy security (Ohene et al., 2022, Wang and Wang, 2024, Chen et al., 2024).

As the world transits to net-zero emissions, the construction industry has a major role to play (Function, 2022), being responsible for approximately 25% of global emissions (Assunção, 2022). The emergence of technological advancement in the construction context can expedite the transition of the industry in various ways. The 3D parametric model can significantly facilitate the optimisation of a building’s performance during its lifecycle; BIM in integration with computational fluid dynamics and energy performance simulation can facilitate energy conservation assessments (Utkucu and Sözer, 2020). Other examples are the use of ML/DL algorithms to compute energy consumption (Desislavov et al., 2023, Olu-Ajayi et al., 2022), the use of IoT based energy efficiency solutions to control emissions (Liang et al., 2023b, Ra et al., 2023), using blockchain technology-based digital twin to predict asset management (Tavakoli et al., 2024, Hellenborn et al., 2024, Götz et al., 2022) and using DT to automate the monitoring and controlling of emissions (Arsiwala et al., 2023, Tahmasebinia et al., 2023).

In essence, the attainment of net-zero objectives within the construction industry hinges upon the advancement of digital technologies, enhancements of their functionality and the resolution of their limitations (Council, 2019, Malagnino et al., 2021). These technologies are indeed paramount to the success of major net zero initiatives of the construction industry such as circular economy and energy efficiency (Jia et al., 2023, Newman et al., 2021, Arsiwala et al., 2023, Elghaish et al., 2023).

Both industry sources and academic literature concur on the definition of a DT as a living digital representation of a physical system. This representation is consistently refreshed with data to properly replicate the actual structure, condition, and behaviour of the physical system, ultimately with the objective of impacting business outcomes (Rasheed et al., 2022). DT are typically categorised into four levels: descriptive, informative, predictive, and living DT. Predictive DT is specifically designed for forecasting unmeasured variables and future states, primarily relying on historical data (Rasheed et al., 2022). In this arrangement, IoT serves as a tool for data collection, including measurements — such as CO2 equivalent and energy consumption. DT technologies are employed to reflect, simulate, and visualize the data retrieved from IoT sensors. Meanwhile, AI/ML is used to predict future scenarios based on the collected data from IoT. Consequently, the future practical applications of DT for achieving net-zero goals are promising (Arsiwala et al., 2023).

As illustrated in Table 1, a few papers published on the integration of AI, IoT, BIM, and DT to provide preliminary solutions for achieving net-zero in the built environment. Arsiwala et al. (2023) developed a predictive monitoring system that estimates CO2-eq and TVOC emissions from existing buildings utilising DT, IoT, BIM and AI. Eneyew et al. (2022) investigated the feasibility of integrating BIM, IoT and DT to support the smart building digital twin capabilities. To aid timely adaptive adjustment of the digital twin and realistic lighting, Tan et al. (2022) linked between the lighting system, the surveillance system and a digital twin lighting (DTL) system based on dynamic BIM while utilised YOLOv4 to detect pedestrians to reduce energy consumption by 97%. Schweigkofler et al. (2022) combined the DT, IoT and BIM technologies to create a shared data environment for crossed management energy aspects. Finally, Wang et al. (2022) used big data approaches, emphasizing data fusion algorithm on the wireless sensing link in energy efficient building digital twins to enhance DTs' feasibility.

As shown in the literature above, there are few studies that focused on the integration of different technologies with the DT to provide comprehensive bespoke solutions. Therefore, there is a significant need for further exploration and analysis of the capabilities of individual technologies to better understand and develop successful integration use cases.

Table 1. Noteworthy studies on predictive DT for net zero solutions

No.	Author and Year	Technologies	The focus of the study
1	Arsiwala et al. (2023)	DT+ AI+ BIM+ IoT+ Big data	For predictive monitoring of CO_2 equivalent from existing buildings

2	Eneyew et al. (2022)	DT + IoT + BIM	to enable semantic interoperability among smart-building DT applications
3	Tan et al. (2022)	DT + BIM + Computer vision	to improve the energy efficiency of indoor lighting
4	Schweigkofler et al. (2022)	DT + IoT + BIM	to represent and visualize sensor data in BIM, in a user-friendly way to support complex decisions for more responsive building management and improved energy efficiency.
5	Wang et al. (2022)	AI + BIM + DT	for assessment of environmental satisfaction in energy-efficient building

3. Research methodology

AlRyalat et al. (2019) conducted a comparative study on using PubMed, Scopus, and Web of Science for bibliometric analysis. The results showed that Scopus provides access to a wide range of sources and offers search analysis tools that can produce representative figures. Moreover, Mishra et al. (2021) stated that Scopus is preferred for bibliometric analysis studies due to its extensive abstract and citation database, especially in terms of journal coverage compared with other databases such as PubMed and Web of Science. Therefore, Scopus is selected to collect and refine data for this mixed-methods systematic review. A mixed-methods systematic review (couched within inductive reasoning and an intelligent interpretive design) was espoused as being the most effective epistemology for conducting a review study (McGowan and Sampson, 2005). Utilising a mixed-methods systematic review allows for a more objective presentation of the phenomena to be articulated. Moreover, a mixed-methods systematic review improves the depth and breadth of the literature studied (Rajendran et al., 2011, Heyvaert et al., 2016). Figure 1 shows the process of collecting, filtering, and analysing data. Three separate lists were developed using the Scopus database. These covered AI and IoT, along with DT, as AI and IoT are the cornerstones of forming predictive DT (Hosseini et al., 2021). The same criteria were applied to develop the three lists, including limiting results to only Q1 Journals, English publications, and timeframe from 2019 to 2023 to cover the most recent publications of the highest quality. For transparency and quality assurance, the authors have reviewed the relevance of papers to three technologies: AI, Digital Twins, and IoT. This was conducted through manual scanning of titles and abstracts, resulting in the grouping of 137 papers into three categories, as shown in Figure 2.

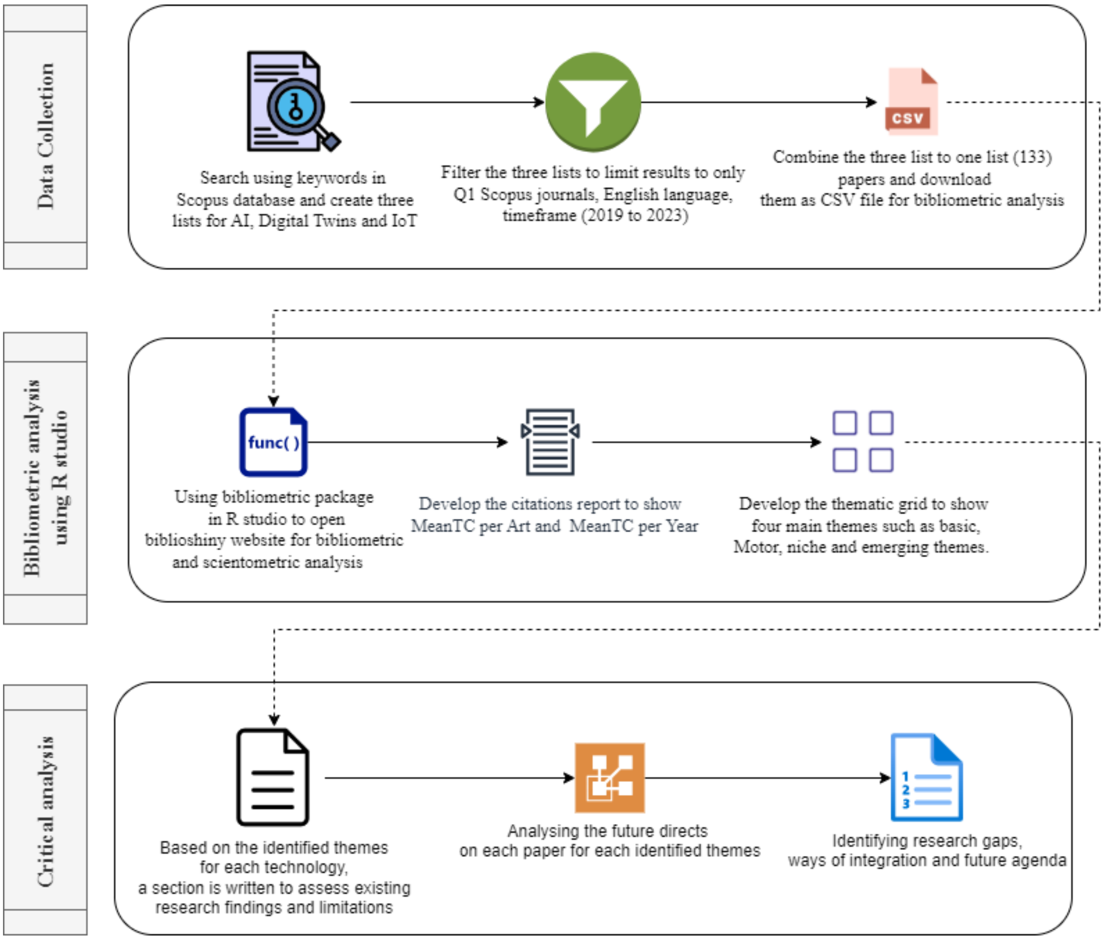

Figure1. Research methods and logic

Figure 2 shows the number of papers identified for each technology, indicating a much lower level of activity for research in the AI-related domains. The bibliometrix package in R studio was used to analyse the collected data for the three technologies.

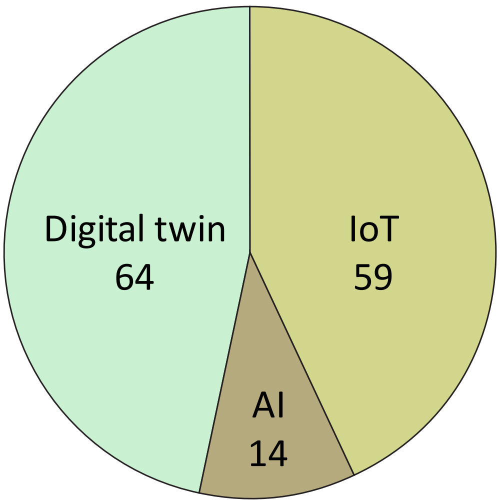

Figure 2. Research publications for the three themes.

The bibliometric package in R Studio enables researchers to examine thematic quadrants, the evolution of themes over time, and patterns of publications within each theme. It also can assess the scientific production of authors and countries throughout the review study's timeframe (Martin Gomez and Bartolome Muñoz de Luna, 2023).

4. Critical evaluation against the net-zero agenda

4.1. IoT for net-zero emissions solutions

The Internet of Things (IoT) is a key technology of Industry 4.0 that has led to the fusion of the physical and virtual aspects of objects. It allows for enhanced data collection from smart devices (or things) involving the internet, with further integration of advanced data analytics such as AI, ML and DL for robust management of information (Ozturk, 2021, Sawhney et al., 2020).

Figure 3 illustrates the identified themes from a pool of 59 papers. Notably, 27% of these publications concentrate on energy and user comfort monitoring and control. Following closely is the category of smart energy management systems, accounting for 25% of the papers. Meanwhile, the scientific production pertaining to the use of IoT for direct research on net-zero energy homes comprises 7%, and carbon prediction research represents 9% of the total publications. This gives insights regarding producing more research on IoT for carbon emission prediction and net zero energy homes, which can significantly contribute towards achieving the net zero target for the built environment sector.

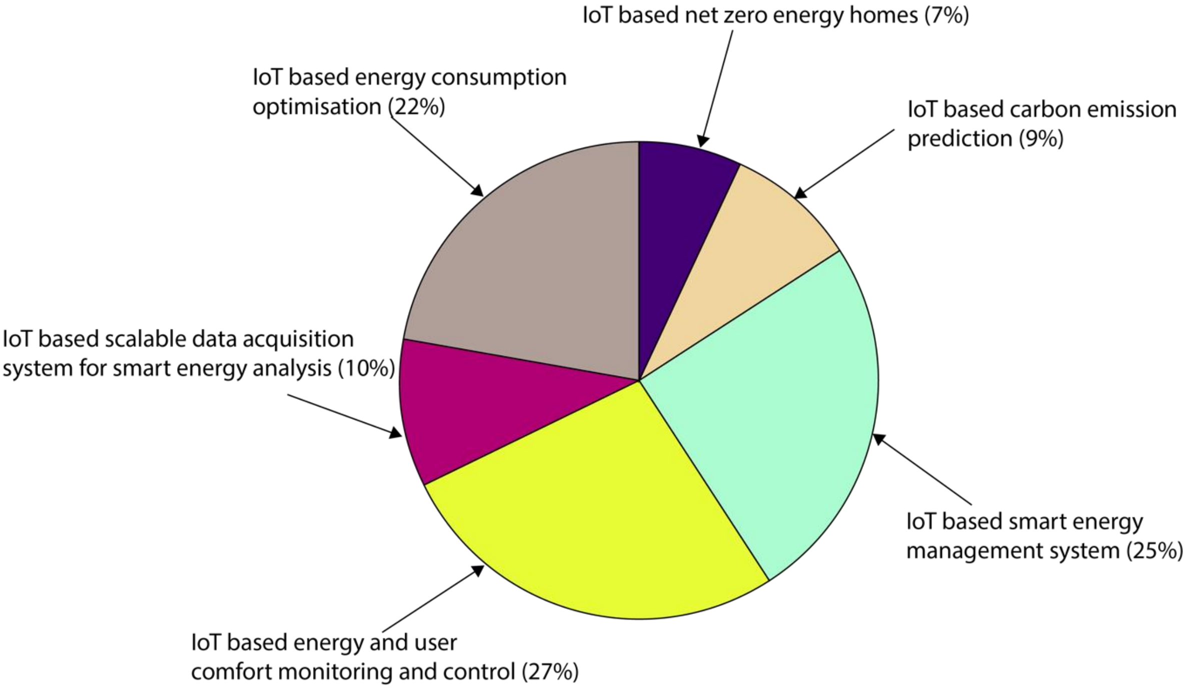

Figure 3. IoT themes for net zero carbon emission research

A study by Kourgiozou et al. (2021) recognise IoT as an enabling technology for achieving the targets of net zero buildings; smart energy systems and smart grid form an important aspect, focused on improving efficiency and rationalising energy consumption (Hu et al., 2022). IoT provides the required structure and protocols for data sensing, communicating, and processing, which supports the transformation from a conventional energy grid to a modernised smart grid system (Abir et al., 2021). In addition, IoT helps to control power uses more effectively and reduces energy waste by supporting the real-time monitoring of energy consumption on the end-user side in smart homes (Hossein Motlagh et al., 2020, Aggarwal et al., 2021). Adopting IoT devices and networks is effective in developing a cost-effective, platform-neutral, scalable, and portable building data acquisition system for smart building innovations (Gao et al., 2021).

Another study presented the effectiveness of integrating IoT-based sensing systems into smart buildings (Kumar et al., 2022). The authors created a building energy model to determine the operational energy of the building and used a custom-built CO2 sensor to collect the real-time occupancy data to be incorporated into the building energy model. The study results showed that the sensor integration in the solar house is environmentally effective.

Bashir et al. (2020) presented in their study the practical use of IoT in smart building environments by developing a framework for IoT-enabled smart buildings to integrate big data management and analytics metamodel. To optimise the indoor thermal comfort and the energy consumption, Carli et al. (2020) developed an IoT based system for the model predictive control of HVAC systems in smart buildings. The study results indicated significant energy savings. The same concept was adopted by Kharbouch et al. (2022); the authors presented the combination of recent IoT and big data platforms with ML algorithms for predictive control of smart building ventilation. The study results revealed that the developed approach provided acceptable performance in regulating the indoor CO2 concentration and allowed significant energy reduction by approximately 16% compared to on/off. Focusing on the heating, ventilation, and air conditioning (HVAC) systems, Liang et al. (2023a) developed an IoT-based intelligent energy management system for a real net-zero emissions photovoltaic (PV) battery building. The developed system tends to efficiently manage the HVAC systems to trade-off between the battery's remaining energy and thermal comfort level based on the demand compliance concept. In this study, the authors conducted several case studies to provide the implementation details of the IoT platform to present the real-world applications of the energy management system. IoT devices and a cloud-based server were used to collect, store, and process the data collected from a newly constructed net zero energy house with a PV system, efficient appliances, and an efficient hybrid HVAC. The collected data is used to monitor energy generation and consumption. Results showed that a cloud-based intelligent control system, which automatically selects the best fuel source to use, can benefit the homeowner (19% energy cost savings is possible) and contribute to decarbonization (29% reduction) (Yu et al., 2019). While Xia et al. (2021) developed an online energy management system framework based on IoT to incorporate the intermittency of renewable energy sources and dynamic electricity tariffs to develop online scheduling strategies.

Although there is interest in integrating IoT into the clean energy sector, direct adoption of IoT technologies is not possible owing to diverse barriers such as labour/workforce skill insufficiency, an ineffective framework for performance, a technology divide, insufficient legislation and control, and lack of time for training and skill practice (Reddy et al., 2023).

4.2. Digital twin for net-zero emissions solutions

In the context of Architecture, Engineering, Construction, and Facility Management (AEC-FM) industry, the three major components of a DT include Wireless Sensor Network (WSN), data analytics, and 3D model (extracted from BIM) of the physical asset (building, bridge, etc.); these facilitate real-time data visualisation, data-driven decision making and improved building efficiency (Khajavi et al., 2019).

Deng et al. (2021) conceptualised a framework of an advanced DT in the built environment for the seamless synchronisation of real-time scenarios with the virtual world. This system is aimed at monitoring construction processes, environmental assessments, and facility management. According to Villa et al. (2021), a SQL database can be used to store data from IoT sensors on a cloud platform with open-source tools for integration with the BIM model. The authors proposed a preventive maintenance proof of concept for HVAC plants that allows the detection of faults for better, faster, and decisive solutions. Indicating a need for a single robust platform for predictive maintenance — using historical data for machine learning — and forecasting of the physical parameters of a building's components was accomplished through the development of a framework by Hosamo et al. (2022); their study recognised DT as a foundation for data processing and visualization, overcoming the challenges of BIM and IoT integration. Similarly, a qualitative analysis by Camposano et al. (2021), argued that DT can offer an integrated single platform of complex software ecosystem transitioned from BIM requirements, made feasible by the convergence of IoT, cloud computing and big data.

Thus, a DT in the built environment serves a specific purpose across a project's lifecycle. It is comprised of a 3D model-based representation and related data that simulate the realistic properties of the physical asset based on its defined use case (Shahzad et al., 2022). In addition, the DT technology has proven its capability in supporting the sustainable environment agenda and net zero emissions. This has been through facilitating the monitoring and optimisation of energy efficiency and thermal comfort and by supporting net-zero energy buildings (Arsiwala et al., 2023).

Figure 4 shows that the majority of publications focus on using DT to optimise energy consumption, with around 45% of publications directly addressing this topic. This is followed by 35% of publications concentrating on monitoring thermal comfort. Meanwhile, only 20% of publications are centred on DT for net-zero energy buildings.

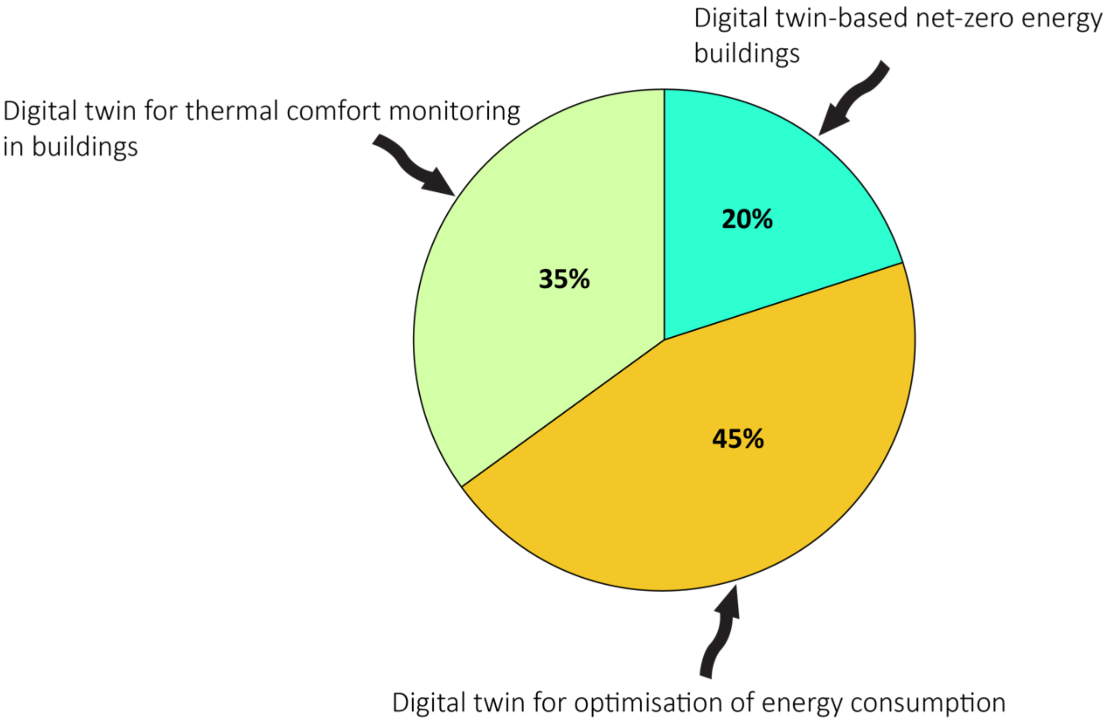

Figure 4. Categories of publications on DT for net zero solutions

4.2.1. Digital twin for optimising energy consumption

The immense potential of DT has sparked interest in applying them to enhance energy efficiency and promote sustainability. For lighting energy-saving strategies in educational buildings, Seo and Yun (2022) developed a DT-based assessment framework that combined the existing building's hardware system, the building's operational — education purposes — schedule database, and a probabilistic model of occupant behaviour. Results showed that turning lighting systems off through sensors after the end of the last class produced energy savings of more than 60% and the overdesigned LED lighting in most classrooms can be adjusted to an appropriate level to save 46% of the consumed energy. Combining BIM and computer vision technologies, Tan et al. (2022) proposed a DT lighting system to provide intelligent decision-making on lighting control. The DT assets of the intelligent lighting system along with the large amount of the generated lighting data, can pave the way for realising a whole life cycle operation and maintenance of green intelligent buildings.

Shifting from a static sustainability assessment to a DT-based and IoT-enabled dynamic approach, Tagliabue et al. (2021) presented an approach that allowed for a real-time evaluation and control of a wide range of sustainability criteria with a user-centred point of view. The system started with a data collection system to ease data mining for predictive maintenance, indoor air quality preservation, space organisation, people flow optimisation, with the focus being energy efficiency. A sustainability assessment was added to revise the building score in real time through a continuously updated connection between the sensor data and sustainable DT. Another study conducted by Agostinelli et al. (2021b) focused on optimising and automating energy management of a residential district using a 3D data model integrated with IoT, artificial intelligence and machine learning.

The review reveals a considerable number of studies, which were selected carefully with different methods to present different approaches of published recently, particularly in 2023. Table 2 illustrates examples of these recent studies, which were selected carefully using different methods to present different approaches to using DT for optimising energy consumption.

Table 2. Noteworthy studies on the evaluation of DT for the optimisation of energy consumption

Authors	Aim	Primary methods	Results
Al-Mufti et al. (2023)	To develop a DT for building energy consumption	Using an artificial neural network (ANN)-based	The predicted energy consumption from the DT compares well with the

		forecasting model, Open Studio software and energy consumption data	experimental data from the smart sensors.
Mohseni et al. (2023)	To establish a cost-effective energy management system in a single-zone HVAC system.	A new, reliable, DT proximal policy optimisation–based, model-independent, non-singular terminal sliding-mode control.	The performance of the proposed DT-based controller is better than the compared control methodologies in terms of unknown uncertainties compensation, fast-tracking, and smooth response.
Nie et al. (2023)	To reduce peak-to-average ratios (PARs) and energy usage costs in the smart home.	Local photovoltaics, suitable power storage systems and the improved leader particle swarm optimisation method	The proposed system can efficiently optimise energy usage costs and PARs.
Zhang and Sun (2023)	To optimise resource allocation in smart grids	DT virtual machines and fog servers.	The DT environment could benefit the system in terms of improved scalability, visibility, and collaboration
Alshenaifi et al. (2023)	To investigate the potential of integrating a passive downdraught evaporative cooling tower into a multi-space building	Thermal modelling tool, and passive downdraught evaporative cooling (PDEC) DT.	The integration of the PDEC tower resulted in a reduction of approximately 22% in cooling energy consumption

Gao and Huang (2023)	To optimise energy economics and renewable energy-based microgrids considering load uncertainties	The moth flame optimisation algorithm and distributed energy management strategy in a DT area	Both grid-connected and islanded modes of the algorithm perform well and are resilient to failures of communication
Almutairi et al. (2023)	To adjust the energy consumption patterns of households according to the price signals	The bald eagle search optimisation algorithm and DT	Using DT-supported users to optimise the scheduling of their rooftop solar home appliances to maximise efficiency and minimise costs
Zohdi (2023)	To track and optimise the flow of incoming solar power through a complex solar-thermal storage system	A genetic-based machine learning DT framework	The proposed framework optimises the configuration layout to balance meeting customer demands and operational efficiency
Shen and Yuan (2023)	To manage a microgrid based on the energy generated by renewable sources	The DT concept, double stochastic optimisation levels and shark optimisation algorithm	Using DT of renewable energy sources, electricity market operators can take corrective action to optimize their operations and reduce their environmental impact
Chalal et al. (2023)	To improve energy management in real time of hybrid energy system.	IoT and DT based on energetic macroscopic representation	The developed system is efficient for an autonomous photovoltaic system.
Liu et al. (2023)	To develop effective energy management	Reinforcement learning and fuzzy	The simulation in the DT environment demonstrates that the proposed device

	for household demand response	reasoning in DT simulation	planning method smooths the energy consumption and reduces the energy cost

4.2.2. Digital Twin for thermal comfort monitoring in buildings

Building design can create comfortable environments for all occupants and still reduce energy consumption. Gnecco et al. (2023) used a DT to decode human-building interaction for environmental comfort and energy saving, with four different sources of information being integrated and interoperated: the geometrical BIM model; environmental sensors data; wearable sensor signals and subjective answers from occupants. The authors concluded that DT offers a full understanding of a facility operation. Bringing spatial representations into the DT paradigm, Abdelrahman et al. (2022) attached spatially and temporally dynamic data to BIM to explore the relation of occupants' location in a building to their indoor environment satisfaction perception. The authors developed the Build2Vec model by integrating the location data and occupants' feedback with indoor environmental data to formulate the thermal preference prediction model. Results showed that Build2Vec outperforms the baseline model noticeably. Deng et al. (2022) built on their earlier study of utilising a DT and proposed a framework for human-centric monitoring and control of smart buildings. The authors reported that the proposed framework provides real-time information for both an overview of the indoor environment and the occupants' states, which can be valuable references for building managers. Clausen et al. (2021) presented the application of a DT and a generic control algorithm to control heating and ventilation in buildings. The authors demonstrated the practical application of the developed approach and found that it was possible to transition from rule-based control to model predictive control without immediate adverse effects on comfort or energy consumption. It is increasingly recognized in the construction industry that digital technology enables the monitoring of building users or entire portfolio performance to ensure user comfort. Several recent studies have focused on using digital technology to improve building users' comfort. Some examples are listed in Table 3.

Table 3. Noteworthy studies on DT for thermal comfort monitoring in buildings

Authors	Aim	Methods	Results
Hosamo et al. (2023)	To automatically detect HVAC fault sources and predict for comfort performance evaluation of existing non-residential buildings	Using Bayesian Networks (BNs), satisfaction survey, BIM, and real-time sensor data	Aiding the facility management sector by offering insight into the aspects that influence occupant comfort, speeding up the process of identifying equipment malfunctions, and pointing toward possible solutions
Gnecco et al. (2023)	To develop a method for DT from a test room for human comfort and energy behaviour analysis.	An as-monitored BIM model was integrated with monitoring information from the facility, physiological signals, and survey answers from occupants through Graph Neural Networks	The recognition of patterns, connections, and the influence of diverse stimuli in the human perception of the surrounding environment

Khampuong et al. (2023)	To provide sustainable comfort monitoring for smart campuses	Wireless sensors and DT	Highlighting the significance of workspace monitoring, as performance can be directly affected by the environment
Banfi et al. (2022)	To improve building comfort and efficiency	BIM, specific grades of generation, API and DT	The developed system interacts with DT to learn characteristics and environmental parameters to increase the degree of control and improve users' comfort
Nurumova et al. (2021)	To explore the potentials and challenges of a DT for the occupant-centric operation of facilities	BIM, wireless sensors, and predicted mean vote (PMV) and the predicted percentage of dissatisfied (PPD) method	Accessing historical facility performance data, identifying areas for optimization to minimize energy waste, and estimating the comfort of occupants in real-time
Zaballos et al. (2020)	To explore a DT in the fields of environmental monitoring and emotion detection to provide insights into the level of comfort	BIM, Dynamo and IoT-based wireless sensor networks	Highlighting the significance of monitoring workspaces because productivity has been proven to be directly influenced by environmental parameters
Xie et al. (2020)	To automatically detect environmental anomalies and faults that affect building	Fault tree analysis (FTA), augmented reality and DT	The results showed that the visualised inspection system helps formalise the link between temperature issues and the corresponding failed assets

	occupants' thermal comfort.	

4.2.3. Digital twin–based net-zero energy buildings

Few studies were found on using DT to address net-zero energy buildings (NZEB). A study conducted by Kaewunruen et al. (2019) highlighted the technical and financial viability of using DT in NZEB. The study revealed that a suitable NZEB solution for an existing building can achieve a 23-year return period in the UK. Another study conducted by Zhao et al. (2021) focused on evaluating the feasibility of existing building retrofitting schemes based on the concept of nearly zero-energy buildings (nZEBs). Authors used 3D laser scanning to efficiently develop the building energy model (BEM) of existing buildings and DT model. The authors argued that an nZEBs solution suitable for the building can reduce building energy costs by 14.1%; increase solar photovoltaic power generation by 24.13%; and reduce carbon dioxide emissions by 4306.0 kg CO2eq/a. To quantify the smart readiness indicator (SRI) for NZEB (university buildings), Martínez et al. (2021) used two conceptual spaces (physical and digital) within two dimensions (users and infrastructures) over an IoT three-level model with a focus on CO2 and energy consumption monitoring. The study results revealed the effectiveness of using DT and IoT to achieve sustainable development goals. In an attempt to meet NZEB requirements, Agostinelli et al. (2021a) developed a DT-based method to achieve an intelligent optimisation and automation system for energy management in buildings. Using three-dimensional data models integrated with IoT, artificial intelligence, and machine learning, the developed approach enabled the evaluation of the effectiveness of the integrative system for renewable energy production from the solar energy necessary to raise the threshold of self-produced energy. Similarly, Deena et al. (2022) used DT to develop an intelligent optimisation and automation system to manage energy to meet NZEB requirements in buildings. Using an open international standard approach and the ontology-based representation method, Shen et al. (2022) developed a conceptual framework to integrate BIM and DT to support decision-making for the whole life cycle net-zero carbon buildings. For future optimal NZEB HVAC design, commissioning and operation, Ochs et al. (2023) presented a model for a DT as a benchmark to compare actual against predicted performance.

The existing literature addressing the NZEB requirements has predominantly focused on new buildings while many buildings are already built. There is a need to address the application of NZEB on existing buildings. Integrating technologies such as DT, BIM, IoT, and artificial intelligence can balance out energy demand with the energy from renewable technologies (NZEB options) for existing buildings. However, the availability of solutions to meet each performance requirement is limited, and an accurate evaluation is required. Besides, existing studies have focused on heating and cooling energy management, whereas the focus should be on the overall building systems.

4.3. Artificial intelligence (AI)- based net-zero emissions

The proliferation of IoT sensors and devices has led to the generation of large amount of unstructured data, which cannot be handled by conventional data-processing tools and software.

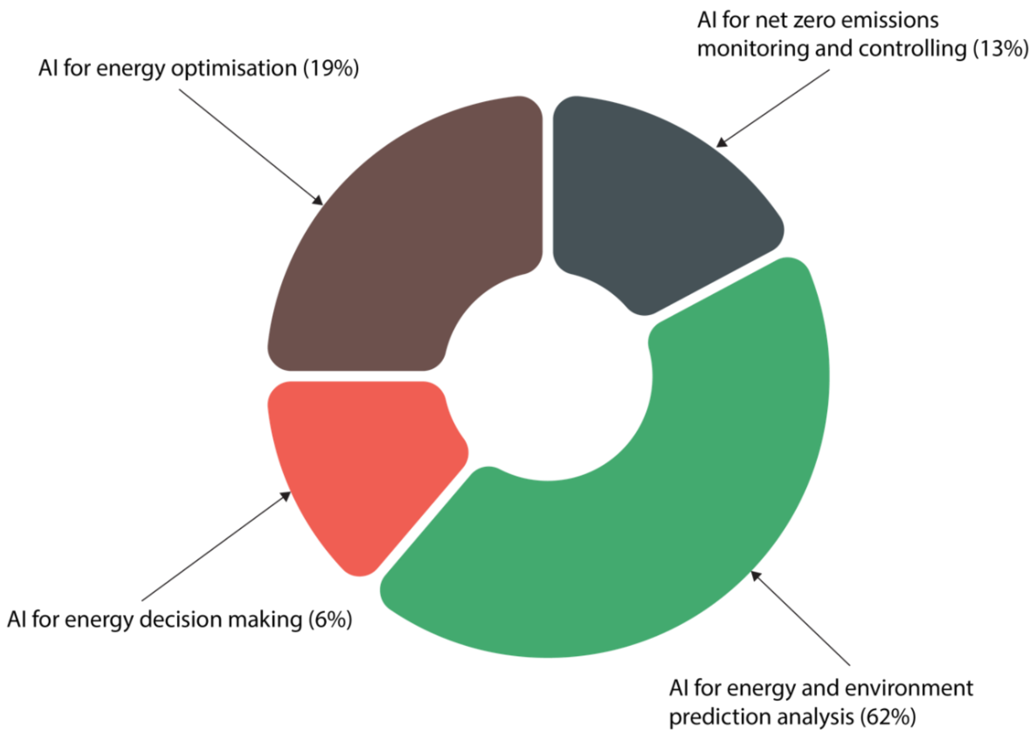

Figure 5. Categories of publications on AI for net zero solutions

As seen in Figure 5, approximately 62% of the publications on AI are focused on energy prediction analysis, while the remaining publications are distributed across various applications such as energy optimisation and energy decision-making systems. It is worth noting that only 13% directly addressed practical applications of carbon emission monitoring and control, highlighting a need for further research in this area.

Artificial intelligence techniques such as machine learning (ML) algorithms, provide valuable insights by analysing big data, enabling informed decision making (Gandomi and Haider, 2015). ML utilises structured data with human experts to extract and determine feature sets for the input data, enabling the algorithm to learn and provide its results, for instance, in terms of prediction analysis. ML algorithms have the ability to learn from the behaviour of the observed, emphasising its prediction accuracy rather than model accuracy (Leo, 2001). Feroz et al. (2021) identified several potentials of integrating big data and AI in the built environment, relating to monitoring and controlling air pollution, optimisation of water resources and efficient energy management of assets while predicting their impact on climate change .

Several studies were conducted recently based on data-driven approaches to predict energy consumption and demand to enable energy consumption savings. A study by Mehmood et al. (2019) emphasised its potentials achieving operational efficiency of assets in residential housing with use of machine learning algorithm, forecasting and minimising energy consumption to mitigate their climate impacts.

Ward et al. (2023) used computer vision techniques to quantify building features to estimate energy consumption from mobile sensing data. The developed framework proved its effectiveness with gold standard datasets. Noteworthy studies on the use of AI to predict and estimate energy consumption are tabulated in Table 4.

Table 4. Key publications on the use of AI for net-zero emissions purposes

Authors	**Aim**	**Methods**	**Results**
Abumohsen et al. (2023)	To forecast electrical loads using different algorithms	Long Short-Term Memory (LSTM), Gated Recurrent Unit (GRU), and A Recurrent Neural Network (RNN) Algorithms	GRU model achieved the best performance in terms of accuracy with the lowest error
Qiao et al. (2023)	To predict building energy consumption based on limited types of features	Empirical mode decomposition (EMD) and Boruta feature selection (BFS)	A significant improvement in prediction performance

Sarmas et al. (2023)	To predict the energy savings of energy efficiency renovation actions	Machine-learning algorithms namely RF, XGBoost, and LightGBM and ensembling model	The model can generate accurate forecasts
Huang and Kaewunruen (2023)	To estimate the energy consumption of a public building	Transformer and support vector regression (SVR)	The SVR presents superior performance and is more sensitive to the input
Sheng et al. (2022)	To predict energy consumption for residential buildings	Deep convolutional neural network and Google Street View images	Predicted an annual energy consumption with a mean absolute difference of 0.01kWh/m2 per annum on average
Wen et al. (2022)	To improve solar forecasting accuracy	Spatial and temporal attention-based neural network (STANN) in conjunction with the federated learning (FL) technique	The proposed approach outperforms other benchmarks with higher forecasting accuracy
Dash et al. (2021)	To predict long term household electricity demand load	A neural network gradient boosting regression tree (RNN-GBRT) forecasting technique and a novel	The proposed approach is efficient in forecasting the load demand

		energy theft detection method	
Lei et al. (2021)	To predict building energy consumption to reduce redundant influencing factors	Rough set theory and deep learning algorithms	The integrated rough set and deep neural network was the most accurate

Many researchers have worked on Reinforced Learning (RL)-based energy management systems (EMS) (Si et al., 2021, Mathew et al., 2020, Liu et al., 2020, Lee and Choi, 2020, Ahrarinouri et al., 2021, Diyan et al., 2020, Esrafilian-Najafabadi and Haghighat, 2022, Fu et al., 2023). To create comfortable and healthy indoor environments with minimal energy requirements, Duhirwe et al. (2023) employed a virtual sensor and a double Q-learning control agent hat interacting with a deep reinforcement learning (DRL)-based control to efficiently control indoor CO2 while using the minimum amount of energy possible. They achieved a 58% energy reduction. A smart home energy management was formulated as a cost minimisation problem using a safe reinforcement learning (SRL) approach with the Primal-Dual Optimisation (PDO) policy search-based algorithm (Ding et al., 2022). The developed model could make optimal decisions targeting energy cost reduction. For optimal control of HVAC, Fu et al. (2022) proposed a multi-agent deep reinforcement learning method for building cooling water system control (MA-CWSC) to optimise the load distribution, cooling tower fan frequency, and cooling water pump frequency of different types of chillers. Similarly, Yu et al. (2021) used the Markov game based on multi-agent deep reinforcement learning with attention mechanism to reduce the HVAC system energy costs in a commercial building.

Other studies have used different AI approaches to optimize energy consumption to achieve sustainability. Han et al. (2023) developed a model-free deep reinforcement learning (DRL)-based heat pump operation strategy. The model used the Rainbow deep Q network algorithm to reduce electricity costs with artificial neural networks to train the regression of future load demands and coefficient of performance. The proposed model reduced the year-round demand charge by 23.1% and the energy charge by 21.7%, resulting in a 22.2% reduction in the electricity cost. Yu et al. (2023) used deep transfer learning to capture energy-essential building variables through reasoning building façade images to optimise energy consumption and reduce greenhouse gas emissions. To optimise the operation of sports facilities and reduce the energy consumption of the HVAC system, Elnour et al. (2022) developed a neural network (NN)-based model predictive control (MPC) management and optimisation system. The study results revealed that up to 46% energy reduction was achieved while jointly optimising the thermal comfort and indoor air quality.

Few studies have focused directly on net zero emissions. Mills et al. (2022) developed a cloud-edge architecture that integrated AI and data analytics for microgrid energy optimisation and net zero carbon emissions. Ahmed et al. (2023b) used AI in the monitoring of a net zero energy building to understand energy savings and methods to reduce consumption. To optimise energy consumption to achieve net zero and sustainability, Srivastava et al. (2023) developed a multi-stage ML-explainable AI (XAI) model that related the drivers of energy consumption to reduce harmful emissions and to enable transition to green energy net zero emissions alternatives. The significance of the study is the use of XAI to monitor carbon consumption to provide a holistic perception of environmental harm and facilitate proactive conservation measures. Moraliyage et al. (2022) used AI algorithms to improve the accuracy, efficiency, and consistency of measurement and verification (M&V) protocols of energy-efficient infrastructure for net zero carbon emissions. The proposed approach used small volumes of energy consumption data to develop efficient predictions for energy savings estimation leading up to a net zero carbon emissions strategy.

4.4. Bibliometric analysis of publications

Figure 6 shows the scientific output in predictive decision tree (DT) technologies over the last five years. It is noteworthy that China has the highest number of publications, exceeding 60 papers. Furthermore, the graph illustrates a consistent upward trend in the number of publications in this field over the past five years.

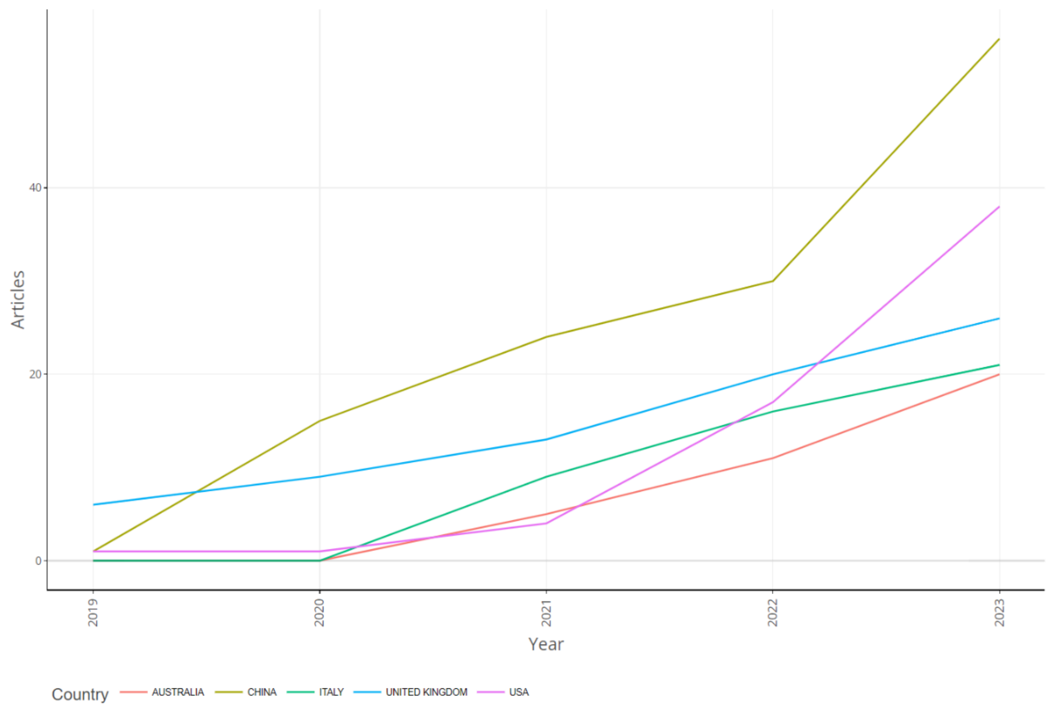

Figure 6. Country production over time for predictive DT technologies (data was analysed using R studio-bibliometric package)

Figure 7 visually illustrates the distribution of keywords into four distinct themes. The first theme, labelled as the 'basic themes', covers research areas such as BIM and DT for sustainability, green buildings, and smart cities. The second theme, named as the 'motor themes', represents topics characterized by strong centrality and high density, including climate change and BIM. In contrast, the 'niche theme' lacks strong connectivity but demonstrates how predictive digital technologies interact with other areas, such as decision-making systems, energy, and heat management. Lastly, the 'merging themes' emphasize the integration of various Industry 4.0 technologies, with primary focus on achieving integrated solutions for net-zero emissions.

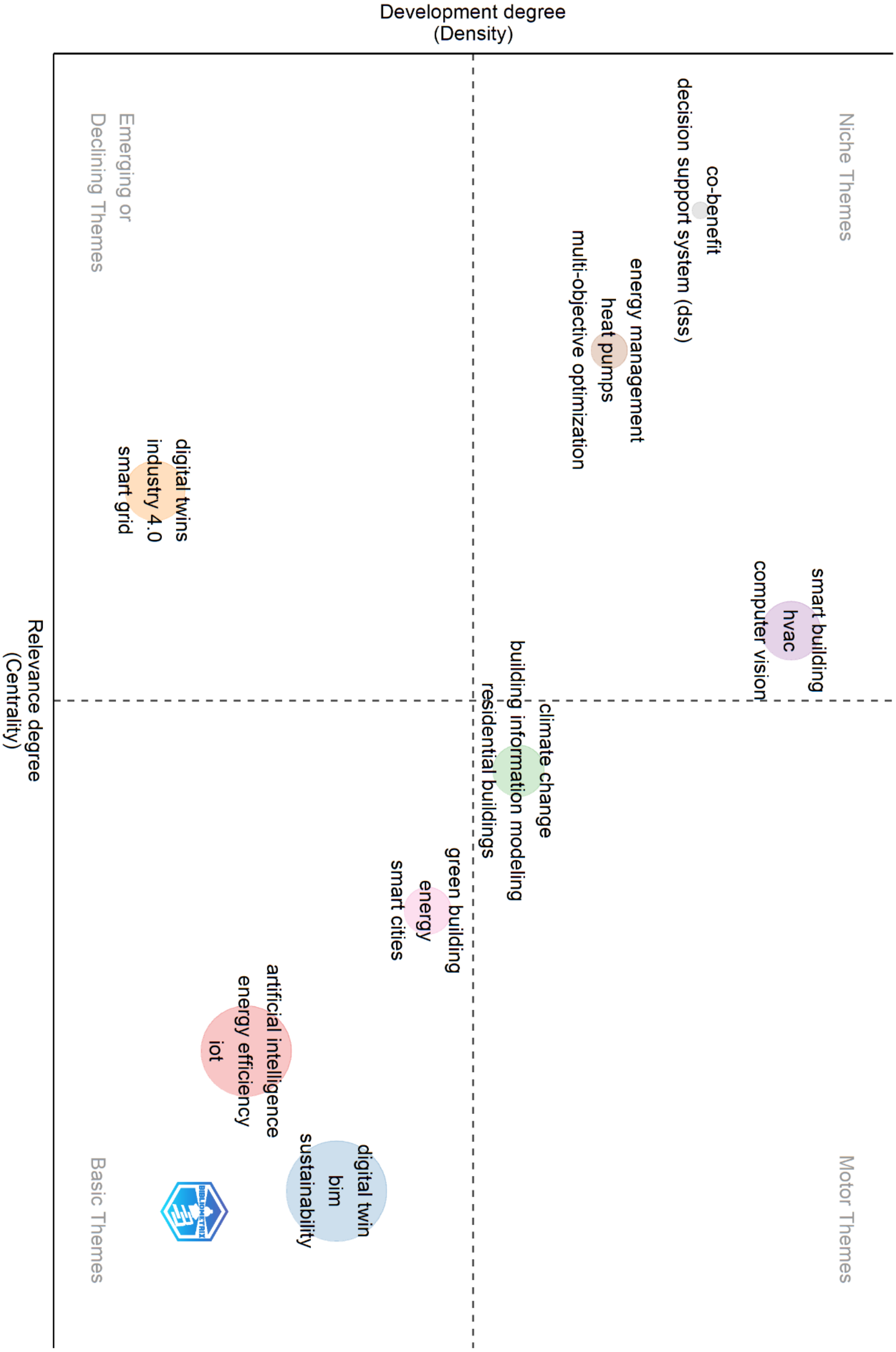

Figure 7. Thematic analysis of predictive DT publications (R studio-bibliometric package).

5. Critical analysis and research agenda

5.1. IoT for net zero applications

Affordable digital technology solutions like IoT pave the way to achieve net-zero targets. IoT-enabled technology solutions have a variety of applications that can optimise renewable energy distribution models. The integration of IoT technology with ML and AI can allow renewable energy solutions like solar panels and wind turbines to perform efficiently and cost-effectively. However, operating billions of these connected devices raises an alarm to ensure that they are a net zero technology themselves. It is essential that the gains of using IoT are not cancelled out by the energy consumed. There is a need to conduct different studies that address low-carbon and efficient communication networks while identifying an optimum number of sensor nodes necessary for reliable analysis outcomes.

In addition, to make use of the enormous amount of structured and unstructured data gathered from various IoT devices, there is a need to do in-depth research in the field of construction data management. An efficient data management infrastructure is required to identify semantic links between various data attributes in addition to maintaining the integrity, availability, quality, and privacy of data. Moreover, the consistency and quality of data collected from IoT devices need to be tested and verified in real-world scenarios especially when heterogeneous devices are used in the same building with different vendor settings which could affect the data quality and accordingly the building control performance (Ekström et al., 2021).

Finally, more studies are needed to examine IoT devices in real-world scenarios when there are attenuation and interference losses. Therefore, future studies should thoroughly test their recommended solutions and systems in a more complicated, dynamic, and real-world setting to assess the credibility, precision, and performance of their suggested solutions.

Figure 8 summarizes the future research agenda of IoT for net zero applications in four main areas: low-carbon efficient communication networks, data management, data quality, and examination of various IoT devices in real-world scenarios.

Figure 8. Future research agenda of IoT for net zero applications.

5.2. Digital Twins for net zero applications

The review reveals that the research on DT for energy consumption management (monitoring, visualisation, optimisation, and control) at the building and room level has been extensive. The thermal comfort of users has also been studied at different levels, with the optimisation of HVAC being crucial for energy efficiency. However, the focus of most existing studies is on new construction. New construction only replaces or adds a few per cent per year at most to the world's existing building stock. Improving the performance of our existing building stock is incredibly important to achieving the sustainable development goals (SDGs). Accordingly, more studies are needed to explore practical solutions to manage the energy consumption of existing buildings.

Reducing operational carbon in the construction sector requires attention to buildings in use. Only one study was found in this review with a focus on using DT and AI to develop a predictive monitoring system that estimates equivalent carbon dioxide (CO2-eq) emissions from existing buildings (Arsiwala et al., 2023). The system can predict future emissions based on received time-series data from installed devices. The results are then analysed using a machine learning algorithm and finally presented on a dashboard to identify patterns. With buildings and construction making up 37% of energy-related CO_2 emissions globally, more solutions that integrate existing technologies, such as DT, are required to shift to low-emissions and climate-resilient developments.

Contributing to a sustainable future involves effective maintenance strategies to reduce energy consumption and carbon emissions. Several researchers have advocated introducing DT to improve the performance of building operations and maintenance (Hosamo et al., 2022, van Dinter et al., 2022, Falekas and Karlis, 2021). However, only one study attempting to identify energy consumption-related factors during the operation phase to achieve sustainable operation and maintenance for building infrastructures was found (Jiao et al., 2023). The proposed model in this study combined the DT operation and maintenance model to strengthen the sustainable link. This enables the model to continuously mine and update the influencing factors of operation and maintenance to realise the building's sustainability. To support the low-emission and climate-resilient agenda, more studies should focus on finding practical solutions for sustainable operations and maintenance in the construction sector.

Figure 9 summarizes the future research agenda of DT for net zero applications in three main areas: the practical application of DT in existing buildings, the development of predictive monitoring systems to estimate emissions, and the application of the DT concept for sustainable operation and maintenance.

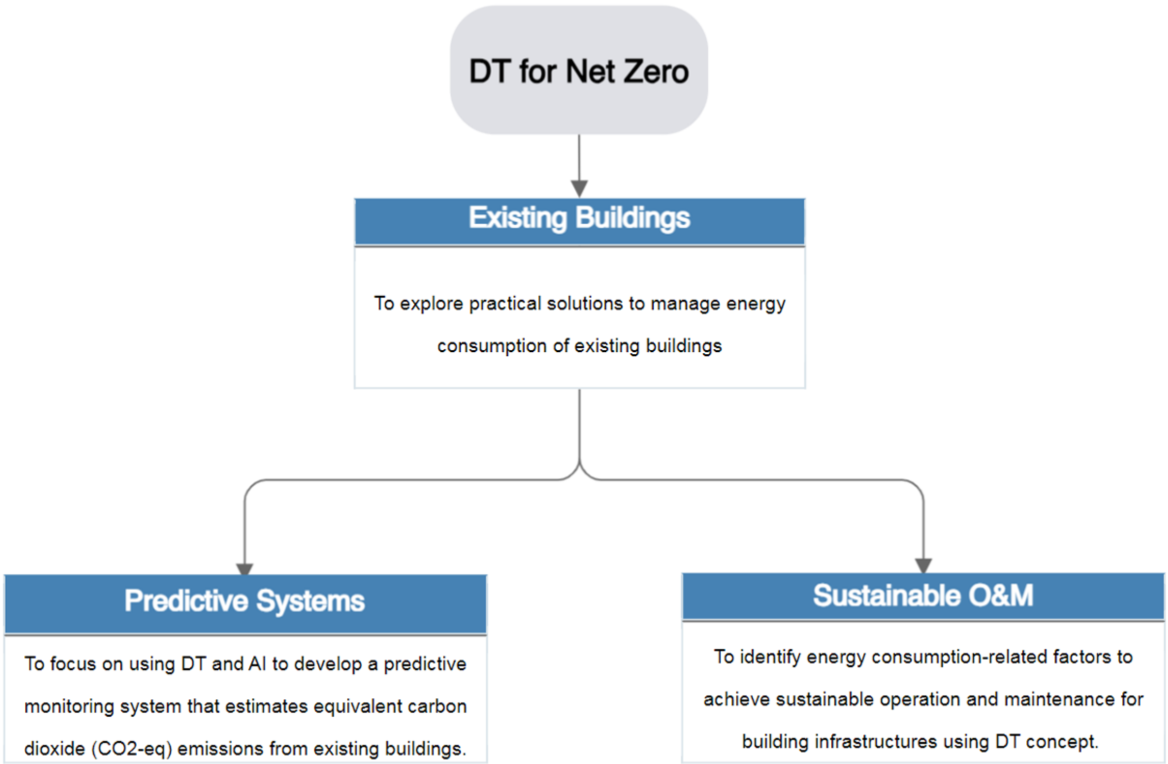

Figure 9. Future research agenda of DT for net zero applications.

5.3. AI for net zero applications

More studies are required to develop digitally supported adaptive capability that considers significant environmental change-related uncertainties. For instance, many AI and ML models can enable prediction, optimisation, and control activities, but they frequently have substantial uncertainties that make it difficult to characterise them as random variables. Additionally, there are unanswered problems surrounding the effective application of AI due to the absence of streamlined methods for combining the knowledge received from data with the expertise of professional users to make decisions.

The review revealed that most of the studies have focused on AI algorithms in energy consumption optimisation and prediction to achieve net zero or low-energy buildings. Thus, there is a need for future studies that focus on the capabilities of AI and other technologies together in developing solutions that consider energy demand forecasting, energy consumption optimisation, and planning over the lifecycle of the facility taking environmental uncertainty such as climate into consideration.

Finally, most of the existing studies focus on net zero energy buildings or low energy buildings, and very few about positive energy buildings were found (Shen et al., 2021, Mousavi et al., 2023). Thus, there is a need for more studies to explore the use of AI techniques in positive energy buildings to reduce emissions impact and energy consumption.

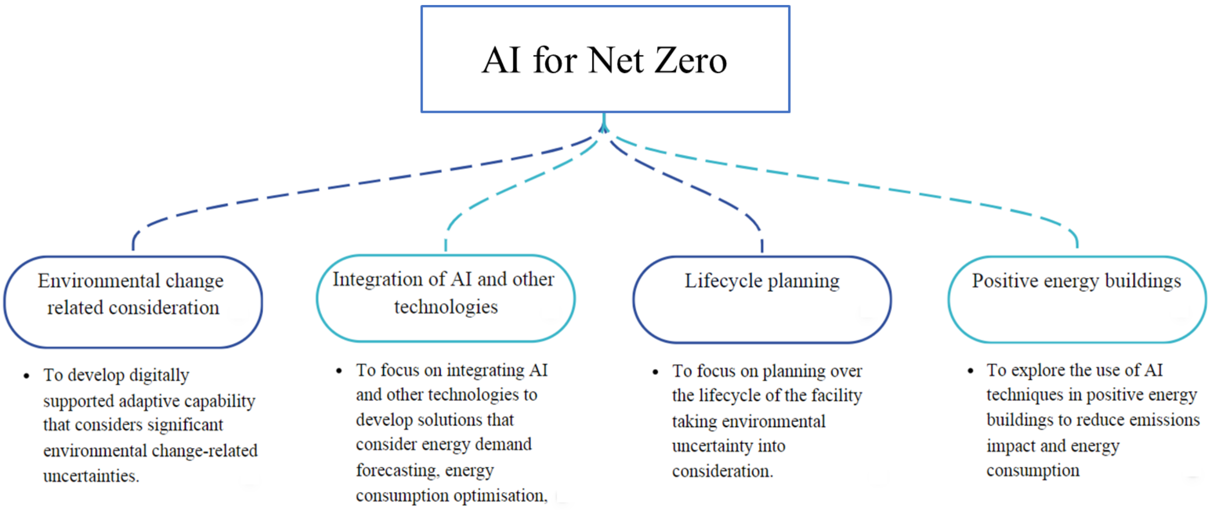

Figure 10. Future research agenda of AI for net zero applications.

Figure 10 summarizes the future research agenda of AI for net zero applications in four main areas namely: the consideration of the environmental change related uncertainties, the integration of AI and other technologies, the planning over the lifecycle of the facility and the positive energy buildings.

6. Conclusion

This paper presents a critical overview of the existing use of predictive DT technologies, including IoT, AI, and DT for achieving the net zero target in the built environment sector. It also explores the existing areas of integration towards integrated DT solutions. Novel insights and fresh discoveries have surfaced, marking a departure from previous review studies within the same domain.

Findings reveal that most of the research has focused on IoT (n=59) and standalone DT solutions (n=64 papers), with only a few papers (n=16 papers) focusing on using AI for net-zero solutions. Moreover, only a few papers on integrating the three technologies were found.

Current AI solutions aimed at achieving net-zero energy consumption focus on developing reliable models for predicting electrical loads and data-driven solutions to forecast energy consumption and demand, ultimately enabling energy savings. Additionally, computer vision techniques have been employed to quantify building features for estimating energy consumption based on mobile sensing data. Furthermore, ML models have been developed to enhance the accuracy of solar energy forecasting. However, findings bring to light a need for further exploration in two key areas: synchronous prediction of energy using streaming data with machine learning models and the development of more AI models to support positive energy buildings powered by renewable sources.

There is a significant emphasis on IoT solutions to advance net-zero objectives within the built environment sector. For instance, the review of 59 papers revealed a focus on deploying IoT sensors to estimate and monitor energy consumption during the transition from a conventional energy grid to a modernised smart grid (SG) system. Additionally, there is limited research on using IoT sensors to quantify equivalent carbon emissions and monitor air quality in smart buildings, particularly with TVOC sensors. Furthermore, automated building facility control strategies have been explored to reduce energy consumption, such as monitoring the trade-off between remaining battery energy and thermal comfort levels based on the demand compliance concept for HVAC systems. However, the evaluation of the existing research highlights a significant gap in the literature regarding the use of IoT for net-zero solutions. This includes the utilisation of building case studies involving multiple IoT sensors for energy data collection and the development of AI-based data management systems capable of handling both structured and unstructured data from IoT sensors to provide better insights for decision-makers.

While digital twin (DT) solutions for achieving net-zero objectives have gained attention in recent years, the publication volume has not surpassed that of other technology domains such as IoT. Three key areas of application emerge: DT for optimizing energy consumption, monitoring and enhancing thermal comfort, and creating net-zero-energy buildings (NZEB). However, most solutions are currently conceptual, and there is a pressing need for more practical and mature solutions. Addressing research gaps and integrating IoT, DT, and AI for achieving net-zero goals in the built environment is still in its early stages, requiring more practical research efforts and real-life case studies to demonstrate effectiveness. Looking forward, the authors recommend conducting comprehensive studies that evaluate the existing research on other technologies such as blockchain, big data, and immersive technologies in the context of achieving net-zero strategies for the built environment sector.

Several limitations of the research deserve mention, with a prominent concern being the utilisation of an interpretivist methodological approach, which may be susceptible to individual researcher bias. To mitigate this risk, the study relied on validated data gleaned from the existing literature. Nonetheless, further investigation is warranted to evaluate users' perspectives regarding the adoption of these technological innovations. Additionally, comprehensive reporting on the barriers and facilitators associated with such adoption is necessary.

Author statement

Faris Elghaish: Methodology, Data curation, Visualization, Writing - original draft, Sandra Matarneh: Writing, Data analysis - original draft. Reza Hosseini: Writing, Editing- original draft. Algan Tezel: Review, Editing - final draft. Abdul-Majeed Mahamadu: Review, Editing - final draft. Firouzeh Rosa Taghikhah: Review - final draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. It is also confirmed that all authors agreed with the current version and revisions and there is no conflict of interest among all authors or with third parties with respect to this paper.

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