Building Engineering 2024, 2(1), 1301.
https://doi.org/10.59400/be.v2i1.1301

Article

Architecting sustainability performances and enablers for grid-interactive efficient buildings

Riadh Habash*, **Md Mahmud Hasan**

School of Electrical Engineering and Computer Science, University of Ottawa, Ottawa, ON K1N 6N5, Canada
*** Corresponding author:** Riadh Habash, rhabash@uottawa.ca

CITATION

Habash R, Hasan MM. Architecting sustainability performances and enablers for grid-interactive efficient buildings. Building Engineering. 2024; 2(1): 1301. https://doi.org/10.59400/be.v2i1.1301

ARTICLE INFO

Received: 17 April 2024
Accepted: 16 May 2024
Available online: 31 May 2024

Abstract: Today, grid-interactive, efficient buildings are gaining popularity due to their potential sustainability performances through their ability to learn, adapt, and evolve at different scales to improve the quality of life of their users while optimizing resource usage and service availability. This is realized through various practices such as management and control measures enabled by smart grid technologies, interoperability, and human-cyber-physical security. However, despite their great potential, the research of those technologies still faces various challenges. These include a lack of communication and control infrastructure to address interpretability, security, cost barriers, and difficulties balancing occupant needs with grid benefits. Initially, system modelling and simulation are promising approaches to address those challenges ahead of time. It involves consideration of complex systems made up of components from various research domains. This paper addresses the above practices, highlighting the value of integrating technology and intelligence in the planning and operation of buildings, both new and old. It provides a way to educate architects and engineers about this emerging field and demonstrates how these practices can help in creating efficient, resilient, and secure buildings that contribute to occupant comfort and decarbonization.

Keywords: grid-interactive efficient building; digital twins; building information modeling; human-in-the-loop; human-cyber-physical security

1. Introduction

Buildings account for 40% of the primary energy consumption, 75% of the electricity consumption, and 35% of the greenhouse gas (GHG) emissions in the US [1], and probably a similar range worldwide. Accordingly, buildings have a major role in reducing GHG emissions and quantifying building resources such as energy efficiency and demand flexibility, which are vital to defining an optimal decarbonization route. This is enabled today by a set of new concepts coming up around smart grid technologies, such as microgrids, demand response (DR), load scheduling strategies, peer-to-peer electricity trading, energy storage services, energy hubs, energy prosumers, distributed energy resources (DER), etc. that make the functionality of the building more complex. In this new context, the energy is intermittent, distributed, mobile, and can be stored [2].

Grid-interactive efficient buildings (GEB) are networked systems consisting of hardware and software accompanied by natural, human, and machine intelligence. Several major sustainability performances underpin these buildings as a part of the urbanization system, including occupant comfort, energy efficiency and sufficiency, low carbon, controlled adaptivity, and demand flexibility. This is realized through management and control measures enabled by smart grid technologies, interoperability, and cyber-physical security [3]. Interoperability is even more significant in the context of GEBs, which rely heavily on communication within a building and between buildings and the grid. By embracing intelligent GEBs, it is possible to speed up the journey towards a sustainability performance agenda in three ways. Firstly, alleviating bottlenecks in the energy distribution network makes the smart grid stronger and more resilient. This allows for quicker rollout of renewable energy and electric vehicles. Secondly, by enabling energy savings of around 30%–40% in the buildings themselves. Thirdly, by being part of virtual power plants, which contribute directly to DERs. **Figure 1** shows an amalgamation of the five major sustainability performances and the two technological enablers.

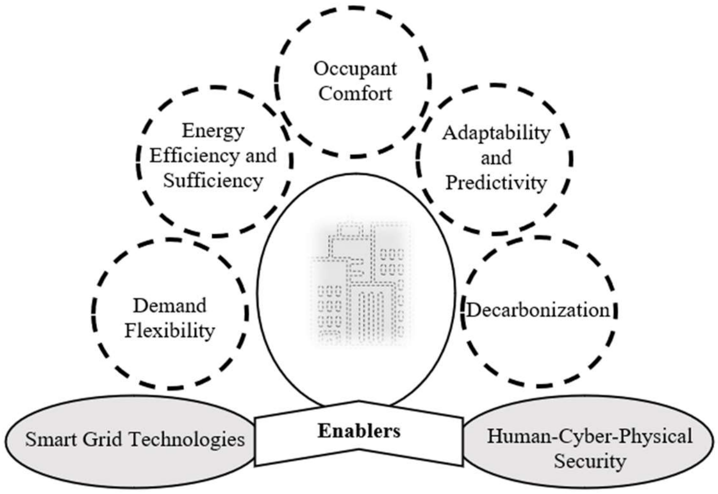

Figure 1. Sustainability performances and enablers for grid-interactive efficient buildings.

Appropriate energy-efficient design approaches, including insulation, thermal mass, orientation, tightness, shading, and space conditioning, decrease the volume of energy consumption. These are needed to manage heat loss or gain through the building envelope and to control the concentrations of airborne contaminants within the building. Controlling outdoor ventilation in buildings is important as it impacts indoor air quality (IAQ) and energy. Once building loads are reduced, the next is using energy-efficient equipment and on-site DER generation. The gain is especially true when energy efficiency and integration of DERs are selected early in the design process [4]. Using energy modeling and simulation can help eradicate human error by recognizing the least expensive factors for GEBs.

The less energy the building needs to operate, the less renewable energy it will need to produce on-site. This may be achieved by implementing efficient heating, ventilation, air conditioning (HVAC), lighting, and smart plug loads other than maintaining effective passive design approaches when possible. Energy from on-site DERs may be distributed through transmission means other than the electricity grid, such as charging electric vehicles [5].

This paper addresses several practices in designing and deploying GEBs, both new and old. It is organized as follows: Section 2 describes the proposed framework of the GEB within a microgrid and smart grid. Section 3 reviews the various system modeling and simulation techniques implemented in designing GEBs. Section 4 describes the concepts of energy efficiency and sufficiency analysis. Section 5 presents human-cyber-physical security as a major enabler of GEBs. Section 6 deals with conclusions and future directions.

2. Grid-interactive efficient buildings

The definition of GEB by the U.S. Department of Energy (DOE) Building Technologies Office involves using smart technologies that actively employ DERs to optimize energy usage for grid service and occupant needs while reducing costs consistently [5]. In addition, the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) further elaborates that GEBs engage proactively with the energy grid by utilizing renewable energy sources, energy storage systems, and smart technologies to optimize energy consumption and generation. This enables GEBs to respond to grid signals in real-time, lowering overall demand and GHG emissions [6]. GEB is a cutting-edge building designed to interact in both directions, meaning it can take in and give out energy. It is built or retrofitted in a way that seamlessly combines energy efficiency with DR and load flexibility (LF). By implementing DR and LF, the GEB can effectively reduce the overall electrical power consumption during peak demand periods. This ensures that the utility power grid operates stably and cost-effectively. This approach benefits the grid and consumers by lowering peak demand charges, resulting in economic advantages. **Figure 2** illustrates the architecture of a proposed GEB that contributes to the overall grid-level energy efficiency. Such a building can decrease the amount of electricity demanded and reduce utility costs without compromising the safety and health of its occupants.

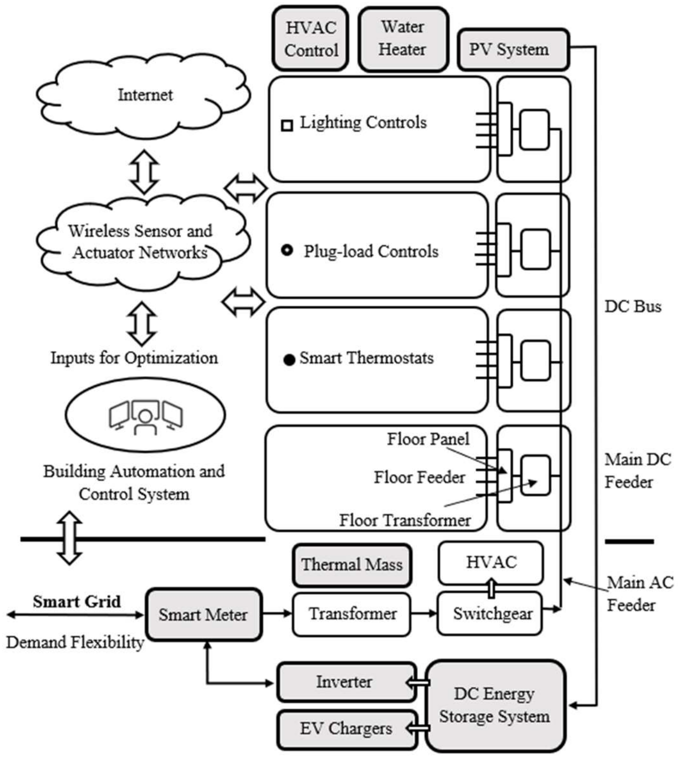

Figure 2. A proposed architecture for a grid-interactive efficient building.

DR is the modification of consumers' demand for energy consumption. It provides major services, including energy management and storage. Electric utilities use these services to compel their users to reduce or shift energy consumption from high-cost hours to low-cost hours of the day [7]. LF, also referred to as demand flexibility, is a valuable feature offered by DERs that allows for the manipulation of electricity through reduction, shedding, shifting, or generation. This technology not only reduces energy consumption but also provides the grid with flexible building loads. As the grid becomes increasingly complex, demand flexibility is crucial in maintaining reliability, improving energy affordability, and integrating various generation sources. Advanced controls can manage electrical loads in buildings, allowing them to operate at specific times and varying output levels. For example, space conditioning is a particularly significant and distinct load use due to its size, dependence on weather, and contribution to peak demand and grid congestion. It also affects occupant comfort, productivity, and health and interacts with the building envelope [3].

Smart metering is a prerequisite and starting point for effectively implementing smart grids and GEBs. For electricity providers to deliver intelligent services to customers, bidirectional metering interfaces should be used to obtain customers' energy demand information. Data collected from smart meters, building management systems, and weather stations can be used by artificial intelligence (AI) techniques and machine learning algorithms to infer the complex relationships between energy consumption and other variables such as temperature, solar radiation, time of day, and occupancy [8]. This intelligent interaction with the grid allows for better management of both energy generation and consumption in response to grid conditions.

Wireless sensor and actuator networks (WSAN) as part of the Internet of Things (IoT) represent a rapidly expanding area of research. They can convert analog signals into digitally encoded signals for direct communication over a network for onward transmission to other intelligent devices for control and measurement purposes. They can process, analyze, and transmit this data to locations across a network for use in various applications [4]. The function of sensor intelligence can vary between "think for itself" or be part of a "think as a group" methodology in which sensors and a central data analyzer perform together. The WSAN is a part of the field level of the building automation and control system (BACS). The majority of larger (100,000 sq. ft. or above) modern buildings today have BACSs that are capable of continuously monitoring the status of the building's energy consumption through the WSAN connected to the HVAC, lighting, plug loads, ventilation, and other auxiliaries in the building like the elevator [9]. With the growing installation of photovoltaics (PV), building energy management platforms, and DR-enabled smart devices, traditional energy operation is evolving from a unidirectional utility-to-consumer model into a more distributed bi-directional power flow paradigm. Each node of the network may have several sensing units, which can measure physical variables, such as temperature, humidity, and vibration, to record and react to an event or a phenomenon.

A significant architectural resolution for a GEB is the level at which various flexibility modes are combined within a building, both for an individual grid service and across services. Devices can directly interact with the grid, market, or any other external entity. On the other hand, a building can coordinate with its resident devices and interact with the utility smart grid or external entities [3]. Additionally, co-located buildings can collaborate and provide services at different levels.

3. System modeling and simulation

Building energy estimation can proceed through information gathering, modeling, simulation, corrections, and monitoring, as shown in **Figure 3**. Studying the impact of buildings' energy consumption can be divided into three stages [10]. First, information must be gathered or assumed, and a model will be created by referencing either the planning process or a simulated building. Second, the energy attributed to the building during its construction or calibration must be re-evaluated, using actual energy data if available. Third, the actual energy consumption of the building post-construction must be evaluated.

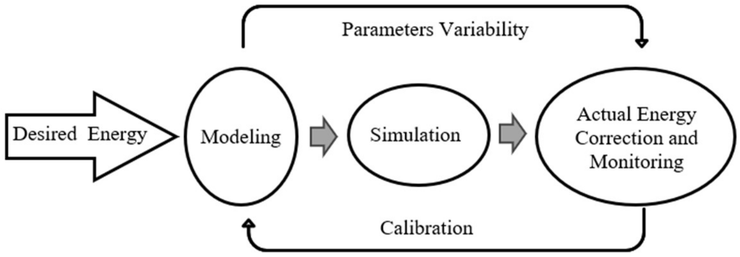

Figure 3. The process of energy estimation in a building.

3.1. Energy forecasting

The building energy model emulates the physical attributes of buildings under a given environmental condition [11] and simulates how buildings are operated to achieve indoor set points. The implementation of BACS can be explored by using models and simulations of buildings and the corresponding grid interfaces, which facilitate their potential participation in future market structures through energy forecasting. To maximize energy efficiency, accurate and consistent energy forecasts are crucial. These forecasts rely on different factors such as historical trends, weather patterns, tariff structures, and occupancy schedules. The building's thermal mass is the most promising grid service from an aggregate capacity perspective, which can help to shed and shift HVAC load. By optimizing the HVAC and lighting systems, energy forecasts can be of great help in achieving this goal.

There are three broad categories for predicting energy consumption: engineering (white-box models), AI-based (black-box models), and hybrid (grey-box models), as shown in **Figure 4**. White-box models use thermodynamic equations to estimate energy consumption, while black-box models use historical data and statistical models to predict future energy use. Grey-box models use a combination of both physical and statistical methods. In recent years, black-box models have gained popularity due to their ease of use and ability to provide optimal solutions [12].

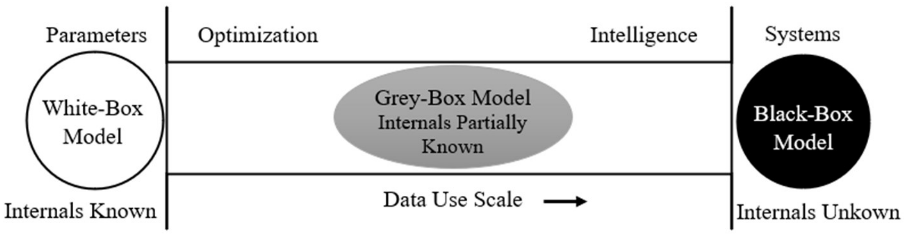

Figure 4. General categories of building energy forecasting models.

EnergyPlus™ is a popular white-box model for developing detailed physical-based building energy models [13]. Since some advanced control strategies are difficult to implement directly in EnergyPlus™, co-simulation provides a solution to conduct a two-way input/output data exchange between EnergyPlus™ and other tools for controls [14,15]. The time-series control variables are calculated by the EnergyPlus™ engine and passed to the external tools at each timestep. Then, the external tools calculate the control signal and return this to the EnergyPlus™ engine. This signal is used for the next timestep calculation. EnergyPlus™ has been commonly used in system modelling for supporting various GEBs [16,17].

Resistive-capacitive networks are one of the popular gray-box models that are considered simplified physical-based building energy models [18–20]. They may be used to model the thermal dynamics in digital twins of GEBs, which have become an emerging method for building energy modeling and simulation. In this regard, Mai and Chung [21] proposed a modelling framework for economic model predictive control that used an RC network model of a building that strongly relates to the power consumption of the HVAC system.

Data-driven models are one of the candidates for the research to support GEBs when historical data or measured data are provided using the neural network model [22]. Chellaswamy et al. [23] developed a new framework for residential building energy management systems with PV. A convolutional neural network was used to estimate the relationship between the PV array power and meteorological datasets.

3.2. Human-in-the-loop (HiL)

A comfortable indoor environment should be one of the primary services buildings provide. Nowadays, all thermal comfort standards include recommendations concerning indoor thermal conditions for both the design and operation of buildings. At its core, HiL focuses on enabling built environments that can learn, adapt, and evolve at different scales to improve the quality of life of its users while optimizing resource usage and service availability. Since these aspects are at the core of HiL, it is thus imperative to extend existing modelling tools and practices with this new emphasis [24]. A paradigm shift from 'set-point-based' control to 'perception-based' HiL control of buildings is necessary to increase comfort, reduce energy consumption, and support the transition to clean energy. However, considering these aspects in the building design phase would also be beneficial.

Indoor human comfort has been categorized into thermal, visual, and acoustic environments in addition to the IAQ. Although thermal and visual comfort are interrelated, these have been evaluated separately. Currently, the most frequently cited thermal comfort standards, namely ASHRAE 55:2020 [25], ISO 7730:2005 [26], and EN 16798-1:2019 [27], which was formerly EN 15251:2007 [28], propose requirements based on the Fanger model [29] (beyond also including other approaches), which solves the heat balance equations between the human body and its surroundings, represented as a uniform environment. Fanger defined the "predicted mean vote" (PMV) as an index that predicts the mean thermal sensation vote on a standard scale for a large group of persons exposed to a given combination of metabolic activity level, clothing insulation, and thermal environmental variables.

Based on the theory of thermal comfort, Segovia et al. [30] presented an outline of a temperature controller. It uses fuzzy logic to optimize comfort and reduce energy consumption. The controller allows multiple inputs from more than one user to set a temperature setpoint. The control logic was developed in MATLAB using the Simulink tool in the simulations. Energy use was optimized, resulting in a reduction of energy consumption between 22% and 31%.

3.3. Building Information Modeling (BIM) and digital twins

In the complex critical construction industry, buildings cannot be designed, built, and maintained without creating virtual models. This is comprised of big data, which refers to the vast quantities of information that have been stored in the past and continue to be obtained continuously. Primary sources of big data in buildings include people who are continuously generating and sharing information, information technology (IT)—enabled construction devices that gather and store data, and holistic systems such as BIM [4].

Incorporating digital technologies presents an excellent opportunity to reduce energy demand while enhancing comfort. This transformation is in line with the continuous progress in communication and information technologies as well as the advancement of interconnected and intelligent grids. Moreover, improving the energy efficiency in buildings can result in cost savings for owners and occupants and potentially better indoor comfort levels [31]. Digital twinning techniques were first used in aerospace and manufacturing, but now they are used in various applications throughout a building's life cycle (**Figure 5**). A digital twin refers to a digital or mathematical model of a physical asset that incorporates sensor readings and a data exchange mechanism between the digital model and the physical asset [32]. With the help of a building WSAN, the BIM models can be extended into digital twins, which reflect in a more precise way the behaviour and properties of the modeled building during any phase of its life cycle [33].

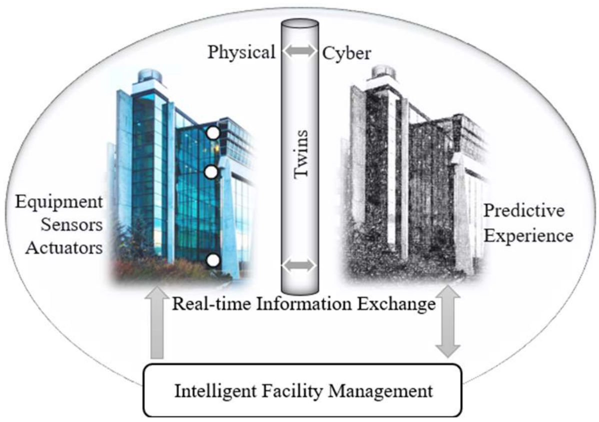

Figure 5. Digital twins for a grid-interactive efficient building.

4. Energy efficiency and sufficiency

There are two common ways to use self-generated solar energy in GEBs: on-grid and off-grid. In the off-grid option, a building has solar panels but isn't connected to the grid. In this case, the building must use all the energy panels produce through direct consumption or storage. On the other hand, in the on-grid option, a building has solar panels that can either use or export the produced energy to the grid. This is a common option, especially in urban areas [34].

Most studies on urban PV's impact on the grid only considered rooftop PV systems, mostly because of their maturity, easy integration, and low cost. However, the strong decrease in prices of PV systems, which is likely to continue in the coming years [35], facilitates the integration of PV on vertical façades as economically viable. This opens engaging perspectives in urban environments where the available area on façades is sometimes much larger than on roofs [36].

PV systems can be distinguished based on their operational and functional requirements, their possible configurations, and the nature of equipment connection to other power sources and electrical loads [37]. To achieve the desired voltage, a series-parallel combination of PV panels is used according to the maximum voltage and current of the inverter.

For optimized PV generation, it is essential to quantify the capabilities of the GEB. PV electricity estimation helps the GEB operator determine the PV electricity that can be generated over different periods of the day. This can be estimated using solar irradiance data with PV module parameters, inverter parameters, site location, array configuration, and other weather forecast information [9] as shown in **Figure 6**. The performance of PV systems typically decreases when operating conditions deviate from the nominal operating cell temperature due to environmental factors, such as wind distribution, dust density, temperature, and humidity changes, resulting in thermal losses and open-circuit voltage drops.

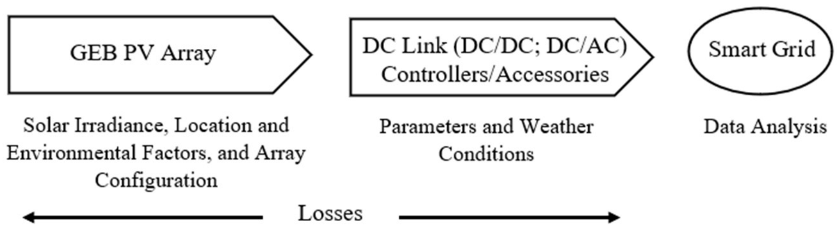

Figure 6. Components of a GEB PV electricity generation system.

Optimizing the performance of PV energy is a crucial task that requires careful planning and analysis. Optimal PV configuration is highly dependent on the local context. Differences in latitude and longitude significantly impact the integration of the façade. Computational resources are valuable assets, providing engineers and researchers with tools to model, simulate, dimension, and design PV systems.

Various tools are developed to help with the design, performance assessment, and economics of PV systems. A detailed study is necessary for the general architecture of the GEB PV system, maximum power point tracking algorithm, inverter synchronization, and grid connection [38,39]. One such tool is PVSYST, which can analyze the entire PV system, including stand-alone, grid-connected, pumping, and DC-grid PV systems. EnergyPlus™ can simulate PV production and estimate the incident solar radiation on each building surface. MATLAB/Simulink is also utilized for analyzing the performance of the PV system based on its current-voltage-power characteristics, inverter voltage, gird voltage and current, power factor, and total harmonic distortion under different environmental conditions.

5. Human-cyber-physical security (HCPS)

The HCPS is a seamless integration of human and computational entities with the physical world and its processes [40]. This is realized as an efficient embedded application that engages physical infrastructure with cyber computation to accomplish functional security desires. In this paper, security incorporates cyber and physical real-world consequences, including safety, real-time surveillance involving structural, energy efficiency, and other human-centric values such as health and comfort. The above integration is happening within the building through WSAN to environmental data and technical services while engaging stakeholders in the process [4]. In the above scenario, human roles as a designer, operator, or occupant have changed as knowledge has evolved. The role has transformed into a smart and skilled one that leverages human skills supported by information and technology to ensure the long-term sustainability of operations and promote the occupant's well-being in various situations [41].

The rise of the WSAN and other sweeping technology initiatives is creating a huge wave of technology adoption at every system architecture level. WSAN devices, in particular, are a potential weak point for security because they do not generally have the processing power to manage increasingly complex security protocols and encryption schemes [42]. They are more vulnerable to attack than computers or mobile phones, not only because of the surge in the use of WSAN devices but also on account of the complexity, diversity, and inherent mobility of such device application scenarios [43]. At the same time, WSAN has developed rapidly but has not yet matured. Therefore, there is a need to adopt a standardized approach to IT and architecture that leverages the WSAN and enables a future path to data analytics and edge intelligence by offering secure mass deployment of WSAN technologies that also allow for continuous monitoring and control of user access [44].

In general, there are three main issues for GEBs seeking to create a secure experience for their occupants: security planning and governance; security practices that can be enhanced by embracing some safety principles; and focus on the security lessons being learned in the convergence of IT (servers, laptops, and workstations) and operational technology (OT) (HVAC, lighting, elevators, fire alarms, etc.). The security goals of a GEB, including confidentiality (privacy and authorization of access to data or information), integrity (trustworthiness of the data or information storage), availability (availability of the systems and associated functions when required), safety, and resiliency (predict, absorb, and recover from disturbances), should be grounded on both the objectives of IT as well as those of OT. This holistic approach reflects any attack on a GEB and probably on a community that can pose impacts and risks to human safety.

The HCPS concept is becoming significant in the security agenda of the GEBs. **Figure 7** displays a proposed HCPS architecture for a GEB. In-building physical components and WSAN devices are located in the field layer. These assets require monitoring tasks such as surveillance (to detect physical intrusion), environmental (such as temperature, humidity, smoke, and fire), structural (vibration and deformation), energy efficiency, and other human-centric values. Some WSAN devices would be deployed to monitor the environment and structural integrity of the building. Other devices monitor the deployment area so that "physical intrusions" are detected. It means that the monitors also need to be monitored [45]. The WSAN gateway acts as an interface between the in-building and the outer network entities. The AI-based intrusion detection and prevention system (IDPS) monitors both ingress and egress traffic to detect cyberattacks and to protect the building from cyberattacks. At the supervisory level and other levels, there is a human-machine collaboration through knowledge and operation to implement security policies, perform maintenance, upgrade the system, and facilitate intervention. It also provides a reconfigurable interface between the cyber and physical parts of the building. The AI-based detection and analytics module gathers sensed data from the IoT sensing module and performs data preprocessing. It uses AI tools for physical event detection and prediction. The controller makes decisions based on the results obtained from the data analysis. It may generate control signals for actuators to activate the alarm system. It can also communicate with external entities (if policy allows) through the building gateway. Such entities include public safety and emergency management authorities. The alarm system is responsible for conveying alert messages to in-building occupants. The components in this architecture are assumed to be protected by standard cryptographic mechanisms [46]. GEBs or smart grid operators may also subscribe to cloud services for cyber security, energy management, data storage, and analytics [47].

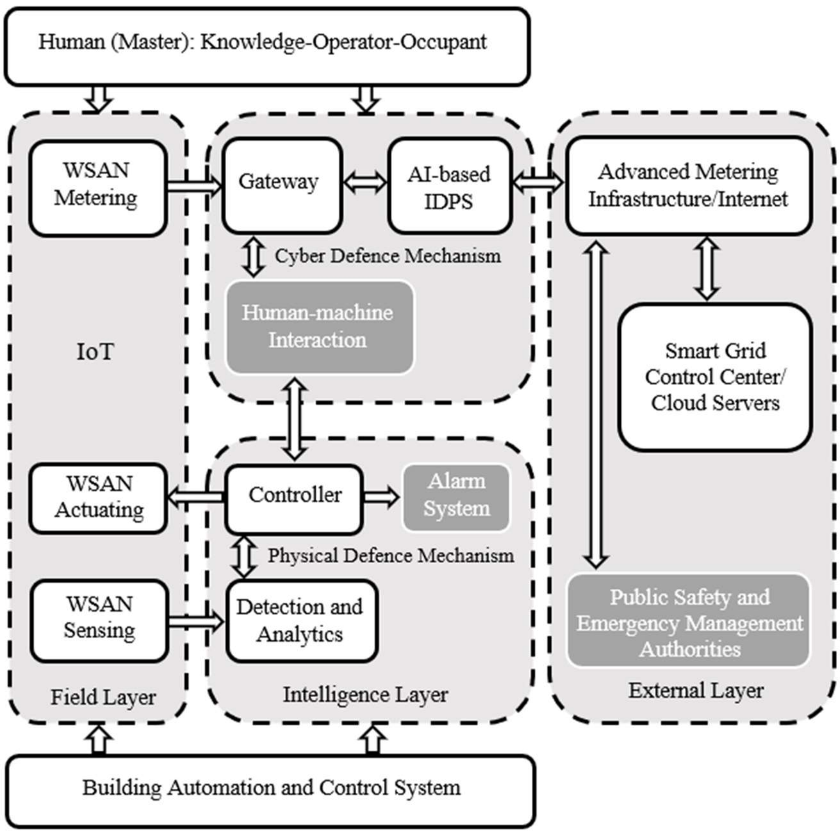

Figure 7. A proposed HCPS architecture for a GEB.

6. Conclusions: Looking ahead

Electrification provides a significant way to reduce carbon emissions and increase energy efficiency in buildings. Implementing the smart utility grid regulations and tariffs in GEBs benefits utilities, customers, and the environment. However, certain infrastructure challenges exist and must be addressed, particularly on the distribution grid. This matter requires a significant amount of funds to mitigate [48]. Additionally, new, simpler approaches to managing the proliferation of large numbers of GEBs need to be explored.

GEBs are gaining popularity due to their potential sustainability performances through their capability to learn, adapt, and evolve at different scales to improve the quality of life of their users while optimizing resource usage and service availability. Without new architecture and control techniques that move the distribution system to an open-access network, the industry will not progress toward full decarbonization quickly enough. This is achieved by implementing management and control measures enabled by smart grid technologies, interoperability, and HCPS. However, the research of these technological solutions still faces the challenge of maturity and availability of some technologies that would optimize GEB implementation. Other challenges include a lack of communication and control infrastructure, interpretability, security, cost barriers, and difficulties balancing occupant needs with grid benefits.

Finally, advancing the state of the art in GEBs can be achieved through energy efficiency, DERs, and demand flexibility. The resulting GEB developments should pave the way for cleaner, more efficient, secure, and healthy buildings. By merging grid-interactive approaches into building design and operation, it will be possible to establish a sustainable and robust future for the built environment, ensuring a smooth transition to zero-carbon buildings.

Author contributions: Writing the main text, RH; reviewing the text and adding Section 5 on HCPS, MMH. All authors have read and agreed to the published version of the manuscript.

Conflict of interest: The authors declare no conflict of interest.

References

1. NIST. Commissioning building systems for improved energy performance. Available online: https://www.nist.gov/programs-projects/commissioning-building-systems-improved-energy-performance (accessed on 16 January 2024).
2. Aguilar J, Garces-Jimenez A, R-Moreno MD, et al. A systematic literature review on the use of artificial intelligence in energy self-management in smart buildings. Renewable and Sustainable Energy Reviews. 2021; 151: 111530. doi: 10.1016/j.rser.2021.111530
3. Neukomm M, Nubbe V, Fares R. Grid-interactive efficient buildings. Available online: https://www1.eere.energy.gov/buildings/pdfs/75470.pdf (accessed on 22 January 2024).
4. Habash R. Sustainability and Health of Intelligent Buildings, 1st ed. Woodhead Publishing; 2022.
5. Peterson K, Torcellini P, Grant R, et al. A common definition for zero energy buildings. Available online: https://www.energy.gov/sites/prod/files/2015/09/f26/bto_common_definition_zero_energy_buildings_093015.pdf (accessed on 4 January 2024).

6. ASHRAE. ASHRAE releases guide on the role of grid interactivity in decarbonization. Available online: https://www.ashrae.org/about/news/2023/ashrae-releases-guide-on-the-role-of-grid-interactivity-in-decarbonization (accessed on 13 January 2024).
7. Hussain I, Ullah M, Ullah I, et al. Optimizing energy consumption in the home energy management system via a bio-inspired dragonfly algorithm and the genetic algorithm. Electronics. 2020; 9(3): 406. doi: 10.3390/electronics9030406
8. Kolokotsa D. The role of smart grids in the building sector. Energy and Buildings. 2016; 116: 703-708. doi: 10.1016/j.enbuild.2015.12.033
9. Rahman S, Haque A, Jing Z. Modeling and performance evaluation of grid-interactive efficient buildings (GEB) in a microgrid environment. IEEE Open Access Journal of Power and Energy. 2021; 8: 423-432. doi: 10.1109/oajpe.2021.3098660
10. Chang S, Yang PPJ, Yamagata Y, Tobey MB. Modeling and design of smart buildings. In: Yamagata Y, Yang PPJ (editors). Urban Systems Design: Creating Sustainable Smart Cities in the Internet of Things Era. Elsevier; 2020. pp. 59-86. doi: 10.1016/b978-0-12-816055-8.00003-8
11. Chang S, Castro-Lacouture D, Matsui K, et al. Planning and monitoring of building energy demands under uncertainties by using IoT data. In: Proceedings of the ASCE International Conference on Computing in Civil Engineering 2019; 17-19 June 2019; Atlanta, Georgia, USA. doi: 10.1061/9780784482445.027
12. Wang Z, Srinivasan RS. A review of artificial intelligence based building energy use prediction: Contrasting the capabilities of single and ensemble prediction models. Renewable and Sustainable Energy Reviews. 2017; 75: 796-808. doi: 10.1016/j.rser.2016.10.079
13. Crawley DB, Lawrie LK, Winkelmann FC, et al. EnergyPlus: Creating a new-generation building energy simulation program. Energy Building. 2001; 33(4): 319-331.
14. Qureshi FA, Lymperopoulos I, Khatir AA, et al. Economic advantages of office buildings providing ancillary services with intraday participation. IEEE Transactions on Smart Grid. 2018; 9(4): 3443-3452. doi: 10.1109/tsg.2016.2632239
15. Huang S, Wu D. Validation on aggregate flexibility from residential air conditioning systems for building-to-grid integration. Energy and Buildings. 2019; 200: 58-67. doi: 10.1016/j.enbuild.2019.07.043
16. Liu M, Heiselberg P. Energy flexibility of a nearly zero-energy building with weather predictive control on a convective building energy system and evaluated with different metrics. Applied Energy. 2019; 233-234: 764-775. doi: 10.1016/j.apenergy.2018.10.070
17. Li X, Malkawi A. Multi-objective optimization for thermal mass model predictive control in small and medium size commercial buildings under summer weather conditions. Energy. 2016; 112: 1194-1206. doi: 10.1016/j.energy.2016.07.021
18. Taha AF, Gatsis N, Dong B, et al. Buildings-to-grid integration framework. IEEE Transactions on Smart Grid. 2019; 10(2): 1237-1249. doi: 10.1109/tsg.2017.2761861
19. Joe J, Karava P. A model predictive control strategy to optimize the performance of radiant floor heating and cooling systems in office buildings. Applied Energy. 2019; 245: 65-77. doi: 10.1016/j.apenergy.2019.03.209
20. Jiang T, Ju P, Wang C, et al. Coordinated control of air-conditioning loads for systemfrequency regulation. IEEE Transactions on Smart Grid. 2021; 12(1): 548-560. doi: 10.1109/tsg.2020.3022010
21. Mai W, Chung CY. Economic MPC of aggregating commercial buildings for providing flexible power reserve. IEEE Transactions on Power Systems. 2015; 30(5): 2685-2694. doi: 10.1109/tpwrs.2014.2365615
22. Baranski M, Meyer L, Fütterer J, et al. Comparative study of neighbor communication approaches for distributed model predictive control in building energy systems. Energy. 2019; 182: 840-851. doi: 10.1016/j.energy.2019.06.037
23. Chellaswamy C, Ganesh Babu R, Vanathi A. A framework for building energy management system with residence mounted photovoltaic. Building Simulation. 2021; 14(4): 1031-1046. doi: 10.1007/s12273-020-0735-x
24. Becerik-Gerber B, Lucas G, Aryal A, et al. The field of human building interaction for convergent research and innovation for intelligent built environments. Scientific Reports. 2022; 12(1). doi: 10.1038/s41598-022-25047-y
25. ANSI/ASHRAE. Thermal Environmental Conditions for Human Occupancy. American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE 55:2020); 2020.
26. ISO. Analytical Determination And Interpretation of Thermal Comfort Using Calculation of the PMV and PPD Indices and Local Thermal Comfort Criteria—Ergonomics of the Thermal Environment (ISO 7730:2005). International Organization for Standardization; 2005.
27. CEN. Energy performance of buildings—Ventilation for buildings—Part 1: Indoor environmental input parameters for

design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics—Module Ml-6, European Committee for Standardization (EN 16798–1:2019). Available online: https://www.sis.se/en/produkter/construction-materials-and-building/installations-in-buildings/general/ss-en-16798-12019/ (accessed on 29 November 2023).
28. CEN. Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics (EN 15251:2007). Available online: https://standards.iteh.ai/catalog/standards/cen/92485123-bf64-40e3-9387-9724a642eae8/en-15251-2007 (accessed on 7 November 2023).
29. Fanger PO. Thermal Comfort: Analysis and Applications in Environmental Engineering. Danish Technical Press; 1970.
30. Segovia E, van Schaik P, Vukovic V. Indoor thermal comfort controller integrating human interaction in the control-loop as a live component. In: Nixon JD, Al-Habaibeh A, Vukovic V, et al. (editors). Energy and Sustainable Futures: Proceedings of the 3rd ICESF. Springer Nature Switzerland; 2023. pp. 107-115. doi: 10.1007/978-3-031-30960-1
31. Volk R, Stengel J, Schultmann F. Building Information Modeling (BIM) for existing buildings—Literature review and future needs. Automation in Construction. 2014; 38: 109-127. doi: 10.1016/j.autcon.2013.10.023
32. Bortolini R, Rodrigues R, Alavi H, et al. Digital twins' applications for building energy efficiency: A Review. Energies. 2022; 15(19): 7002. doi: 10.3390/en15197002
33. Hou H, Lai JHK, Wu H, et al. Digital twin application in heritage facilities management: Systematic literature review and future development directions. Engineering, Construction and Architectural Management. 2023. doi: 10.1108/ecam-06-2022-0596
34. Thebault M, Gaillard L. Optimization of the integration of photovoltaic systems on buildings for self-consumption – Case study in France. City and Environment Interactions. 2021; 10: 100057. doi: 10.1016/j.cacint.2021.100057
35. Fath K, Stengel J, Sprenger W, et al. A method for predicting the economic potential of (building-integrated) photovoltaics in urban areas based on hourly radiance simulations. Solar Energy. 2015; 116: 357-370. doi: 10.1016/j.solener.2015.03.023
36. Redweik P, Catita C, Brito M. Solar energy potential on roofs and facades in an urban landscape. Solar Energy. 2013; 97: 332-341. doi: 10.1016/j.solener.2013.08.036
37. Allouhi A, Saadani R, Kousksou T, et al. Grid-connected PV systems installed on institutional buildings: Technology comparison, energy analysis and economic performance. Energy and Buildings. 2016; 130: 188-201. doi: 10.1016/j.enbuild.2016.08.054
38. Sahri Y, Tamalouzt S, Belaid SL, et al. Performance improvement of Hybrid System based DFIG-Wind/PV/Batteries connected to DC and AC grid by applying Intelligent Control. Energy Reports. 2023; 9: 2027-2043. doi: 10.1016/j.egyr.2023.01.021
39. Khosravi N, Baghbanzadeh R, Oubelaid A, et al. A novel control approach to improve the stability of hybrid AC/DC microgrids. Applied Energy. 2023; 344: 121261. doi: 10.1016/j.apenergy.2023.121261
40. Zhou J, Zhou Y, Wang B, et al. Human–cyber–physical systems (HCPSs) in the context of new-generation intelligent manufacturing. Engineering. 2019; 5(4): 624-636. doi: 10.1016/j.eng.2019.07.015
41. Wang B, Zheng P, Yin Y, et al. Toward human-centric smart manufacturing: A human-cyber-physical systems (HCPS) perspective. Journal of Manufacturing Systems. 2022; 63: 471-490. doi: 10.1016/j.jmsy.2022.05.005
42. Schoechle T. Re-inventing wires: the future of landlines and networks, 2018. Available online: https://electromagnetichealth.org/wp-content/uploads/2018/02/ReInventing-Wires-1-25-18.pdf (accessed on 8 January 2024).
43. Wu H, Han H, Wang X, et al. Research on artificial intelligence enhancing Internet of Things security: A survey. IEEE Access. 2020; 8: 153826-153848. doi: 10.1109/access.2020.3018170
44. O'Brien L. Cybersecurity for smart buildings, 2019. Available online: https://www.arcweb.com/blog/cybersecurity-smart-buildings (accessed on 9 January 2024).
45. Hasan MM, Mouftah HT. Cyber-physical vulnerabilities of wireless sensor networks in smart cities. In: Song H, Fink GA, Jeschke S (editors). Security and Privacy in Cyber-Physical Systems: Foundations, Principles and Applications. John Wiley & Sons; 2017. pp. 263-280. doi: 10.1002/9781119226079.ch13
46. Hasan MM, Mouftah HT. Cloud-centric collaborative security service placement for advanced metering infrastructures. IEEE Transactions on Smart Grid. 2019; 10(2): 1339-1348. doi: 10.1109/tsg.2017.2763954

47. Hasan MM, Mouftah HT. Encryption as a service for smart grid advanced metering infrastructure. In: Proceedings of the 2015 IEEE Symposium on Computers and Communication (ISCC); 6-9 July 2015; Larnaca, Cyprus. pp. 216-221. doi: 10.1109/iscc.2015.7405519
48. Aikin KE. The future of grid-interactive efficient buildings and local transactive energy markets. In: Sioshansi F (editor). The Future of Decentralized Electricity Distribution Networks. Elsevier; 2023. pp. 437-463. doi: 10.1016/b978-0-443-15591-8.00022-x