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From bricks to bytes: Verifiable data for decarbonizing the building sector

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Abstract
Amidst the pressing need to combat climate change and curb greenhouse gas (GHG) emissions, the building sector emerges as a pivotal sector, substantially impacting worldwide emissions. Despite efforts to improve energy efficiency and incorporate non-fossil energy sources, the sector still lags in achieving the necessary decarbonization goals. Existing Building Energy Management Systems primarily prioritize economic criteria, overlooking the vital aspect of emissions reduction. Energy Informatics and Information Systems hold the potential to bridge this gap by enabling precise and verifiable GHG emissions accounting, end-to-end real-time tracking, and automated verification within Energy Management Systems (EMS). This paper presents research on designing the advancement of EMSs in the form of a Building Energy Emission Management System (BEEMS) leveraging verifiable emission data for emission-based actions. The central research question revolves around designing BEEMS to facilitate emission-based actions based on verifiable data. Following a multi-step approach, the research methodology encompasses a comprehensive literature review and iterative evaluation of our design principles through a workshop and semi-structured interviews with experts from industry and research. The contributions include a conceptual architecture of a BEEMS and six design principles for future BEEMS development. Ultimately, this research strives to facilitate end-to-end verifiable GHG emissions management in the building sector to enable emission-based energy consumption decisions, contributing to the existing body of knowledge of the Energy Informatics field on BEEMS.

Keywords Building energy emission management system, Energy informatics, Decarbonization, Building sector, Verification, GHG accounting

Introduction

In an era where environmental sustainability has become a paramount concern, the quest for reducing greenhouse gas (GHG) emissions has escalated to a global imperative (Thomas et al. 2004; van Zalinge et al. 2017). Governments, organizations, and individuals worldwide are compelled to act, aiming to achieve climate neutrality by 2050 (IPCC 2021; UNFCC 2018). The IPCC underscores the urgency of reducing buildings' operational emissions by more than 95% (2021 levels) until 2050 to meet sectoral sustainability targets (UN 2022). Despite the clear goals, the persistent rise in operational energy demand for heating, cooling, and lighting, reflected in a 4% increase from 2020, coupled with a 5% spike in GHG emissions in 2021, signals the dimension of the challenge (IEA 2023; UN 2022). Addressing this issue necessitates a twofold approach: scrutinizing energy sources and emissions, as well as energy consumption behaviors of building occupants. On the one hand, this relates to reducing overall energy consumption while providing cost and efficiency benefits for occupants (UN 2022). On the other hand, it requires aligning energy consumption with the related GHG emissions to enable effective emission-based consumption decisions (Glenk 2023; Körner et al. 2023a). The essence of aligning energy consumption with GHG emissions to support informed decision-making fundamentally relies on using accurate, real-time emission data instead of relying on generalized average emission figures. Granular and reliable emission data and their alignment with the energy flow are essential to foster stakeholders' trust in the information. This aspect is essential for energy consumers to align their consumption activities with their emission footprint and for other stakeholders involved in buildings' energy flow to utilize the information provided for their individual use cases (e.g., energy distribution, sustainability reporting). Thus, using average emission values might be a first step in the right direction, however, neglects the importance of granular and verifiable emission data on the effectiveness of emission-based actions (Reichelstein 2023; Sullivan and Gouldson 2012).

In the endeavor to integrate energy consumption and emission reduction into the building sector, Building Energy Management Systems (BEMSs) have become an integral part of modern buildings. By leveraging information technology (IT), BEMSs manage the holistic energy flow, connecting energy providers, distributors, and occupants (Cavalheiro and Carreira 2016; Gholamzadehmir et al. 2020). However, the complexity of building energy management has escalated with the shift toward more diverse and decentralized energy sources (e.g., energy generation through solar systems or wind power stations), an increasingly complex energy consumption grid provoked by a growing number of energy users (e.g., electric vehicles), and the evolving role of consumers into 'prosumers' who not only consume energy but also contribute to the grid with locally generated power (Bjørndal et al. 2023; Fridgen et al. 2022; Hanny et al. 2022; Michaelis et al. 2024). Contemporary BEMS approaches already attempt to handle this growing set of complex management tasks while also incorporating GHG emissions into the decision-making process for household energy management. Fiorini and Aiello (2018) use the dynamic CO_2 equivalent intensity of one kWh of energy to provide recommendations for tenants for optimal energy utilization (Fiorini and Aiello 2018).

These initial endeavors underscore the critical importance of GHG emission data in the realm of energy management, signaling a clear demand for accurate, real-time GHG emission data across the entire energy spectrum, from production to consumption. The alignment of energy flows with GHG emissions emerges as a vital prerequisite for deploying effective management strategies. However, reliance on average emission figures tends to undermine the impact of initiatives to reduce emissions. It is essential to anchor energy management practices in reliable and technologically validated emission data to enable effective emission-driven actions that tangibly lower the emissions associated with energy use. Therein, BEMSs serve as a critical infrastructure for the effective execution of management and verification mechanisms across the full spectrum of a building's energy lifecycle and its associated service providers. An integrated BEMS has the potential to empower building operators, landlords, energy providers, and occupants to vigilantly monitor and regulate energy use, ensuring it aligns with verifiable data on the GHG emissions tied to their energy consumption. This empowerment may facilitate the adoption of efficient, emission-conscious energy consumption behaviors among all stakeholders, paving the way for more sustainable energy practices (Wang et al. 2023; Zampou et al. 2022).

Nevertheless, allocating verifiable real-time data on GHG emissions is a complex task that requires reliable tracing, verification, and quantification of GHG emissions along the entire energy flow– from production and distribution to the end-user (i.e., tenant) utilization (Cavalheiro and Carreira 2016; Melville and Whisnant 2014). Verifiable real-time GHG emission data is essential not only for occupants to be certain of the effectiveness of their emission-based actions but also for other stakeholders, such as legal authorities, which demand reliable reports of large building owners (e.g., investment funds) on their emissions (Babel et al. 2022; Körner et al. 2023b). The ongoing digitalization of the building sector has opened new possibilities for addressing this issue (Konhäuser 2021). Besides, some Information Systems (IS) scholars already consider advanced technological solutions (e.g., distributed ledger technologies) to facilitate precise and verifiable emissions accounting (Babel et al. 2022; Heeß et al. 2024). These approaches are essential to provide reliable information on the emissions tied to energy flows and steer energy consumption effectively without risking the information's validity. Despite these technological approaches, to the best of the authors' knowledge, no such concept has already been transferred to the sphere of BEMSs to trace the GHG emission efficiently, verifiably, and securely along a building's energy flow. In light of current research, we recognize the imperative for a more cohesive and design-oriented approach to establish overarching criteria for creating a system, which we designate as a Building Energy Emission Management System (BEEMS). Therein, we highlight the necessity for such BEEMS to provide verifiable GHG emission data to enable the stakeholders involved with the operational energy consumption of a building to not only reduce their consumption but to center it around the related GHG emissions to facilitate effective emission-reduction practices. Consequently, this study sets out to bridge the research gap by posing the following research question:

How to design a Building Energy Emission Management System to enable verifiable GHG emission-based actions?

Our research objective is to bridge the identified gap in the IS literature and to answer the question by developing design principles (DPs) for a BEEMS. Our problem-centered approach follows the Design Science Research (DSR) paradigm of Hevner et al. (2004) and addresses current BEMS constraints and deficiencies, focusing on GHG emission data and their verifiability. Accordingly, we conduct a comprehensive literature review and incorporate insights from Energy Informatics experts through a research workshop. The investigation identifies ten challenges in developing a BEEMS that serves the mentioned stakeholder groups, building on verifiable GHG emission data. Upon these challenges, we derive meta-requirements (MRs) and DPs for a BEEMS to enable effective GHG emissions reduction measures. Following the DSR approach, we iteratively refine the DPs through interviews with experts from practice and research. Therein, our study aims to stand out from current research by explicitly enriching the state of the research of BEEMS with highly relevant practical evidence from experts of different areas of building energy supply (i.e., energy providers, BEEMS service providers) and end-user level (i.e., landlords, real estate managers) to ensure a comprehensive assessment. Following this two-sided approach ensures the rigorous development of relevant design criteria for the consecutive development of a BEEMS.

This paper builds upon existing technological knowledge on Energy Emission Management Systems (EEMSs) (Al-Ghaili et al. 2021; Hannan et al. 2018; Zampou et al. 2014, Zampou et al. 2022), but to the best of our knowledge, it is the first to propose a concept for a BEEMS– thus focusing on the building sector– that facilitates verifiable emission-based actions. Hence, we intend to make the following primary contributions: (1) Developing DPs for a BEEMS will provide practical insights into the opportunities and challenges of implementing a central management system to align multiple stakeholder interests within the complex energy market. (2) Building on prior research in the field of Energy Informatics on BEEMSs and EEMSs for other sectors allows us to enrich BEMS research.

The remainder of this paper is organized as follows: The second section introduces Energy Informatics, Digital Decarbonization, and Energy and Emission Management in the buildings sector. The third section describes our methodological approach. Section four outlines the challenges and requirements for a BEEMS, the DPs, and the conceptual architecture. We discuss our findings with the status quo of current research in section five and conclude our research with an outlook for future work in section six.

Background and related work

To build a comprehensive understanding of the pertinent background for our work, we present related literature and research streams on Energy Informatics, followed by an overview of efforts on reducing carbon emissions using digital technologies, and ending with recent literature on the specific topic of our study, namely energy and emission management in the building sector.

Energy informatics as catalyst for climate change mitigation

The burgeoning field of Energy Informatics, alongside Green Information Systems (Green IS), has emerged as a cornerstone in the scholarly and business communities' efforts to combat climate change over the past decade (Loos et al. 2011; Pernici et al. 2012; vom Brocke et al. 2013). With its roots intertwined with the Green IS domain, Energy Informatics is dedicated to two primary objectives: enhancing energy efficiency and augmenting renewable energy supply (Goebel et al. 2014). The discipline's core revolves around leveraging fine-granular energy-related data to minimize energy consumption through innovative IS solutions and to pioneer practical strategies for transitioning to green energy sources (Kumar et al. 2023; Watson and Chen 2010). As noted by Babel et al. (2022), the range of applications within the field has expanded in recent years– including energy efficiency (Watson and Chen 2010), energy flexibility (Körner et al. 2024) and its optimization through artificial intelligence (Fridgen et al. 2022; Hanny et al. 2022; Holly et al. 2020), data centers to facilitate the energy transition (Fridgen et al. 2021; Klingert 2018), as well as energy data spaces to enhance collaboration and bolster the resilience of energy systems (Körner et al. 2022). According to Kumar et al. (2023),– across all Energy Informatics application areas– challenges arise in data collection, assignment, and contextualization, and thus multidisciplinary solutions are required. Babel et al. (2022) further call for end-to-end verifiability and traceability of data to overcome current barriers in Energy Informatics to facilitate decision-making for decarbonization and emission-based actions.

Digital decarbonization: enabler for verifiable emission-based actions

The pivotal role of IS in environmental management is increasingly recognized, especially in facilitating the urgent reduction of GHG emissions through the deployment of emerging technologies for precise tracking and verification of energy-related emissions (Mueller et al. 2023; Page and Rautenstrauch 2001; Seidel et al. 2017). The current landscape, however, is marred by scarcity of integrated solutions that leverage reliable and verified emission data to guide stakeholders in making informed, emission-based decisions (Babel et al. 2022; Krasikov and Legner 2023; Melville and Whisnant 2012). This gap highlights the critical need for frameworks and architectures capable of reliably tracking and tracing GHG emission-related data across value chains, addressing the challenges associated with capturing and processing such data for effective emission allocation (Körner et al. 2023b; Mueller et al. 2023). As the literature stresses, in complex value chains with multiple individual actors, there is an existing need to amalgamate heterogeneous direct and indirect data sources considering varying data protection and usage rights (Zampou et al. 2022). As the demand for emission data grows, actors within value chains require reliable mechanisms for collecting, storing, transforming, distributing, and consuming this data (DalleMule and Davenport 2017). Additionally, diverse data capturing and processing standards further contribute to the complexity of obtaining the necessary data (Damsø et al. 2017; Stechemesser and Guenther 2012).

Energy Informatics provides technological solutions and tools (e.g., distributed data bases and digital identities) that are instrumental for preparing a verifiable and comprehensive data base that can be utilized to facilitate digital decarbonization across the full spectrum of energy flow along a value chain (Gramlich et al. 2023). The challenges and lack of solutions within the building sector particularly underscore the necessity for accurate, verifiable data in decarbonization, positioning research on Energy Informatics and Digital Decarbonization to enable emission-based actions in this sector (de Groot et al. 2001; Zampou et al. 2014).

Emission-based energy management in the building sector

Energy Informatics has already delved into analyzing technology-aided solutions for GHG-related energy management within the building sector, pointing toward the relevance of energy transition, decarbonization, and emission-based decisions (Camarasa et al. 2022; Fiorini and Aiello 2018; Jradi et al. 2021). Thereupon, efforts are made to reduce buildings' GHG emissions, including reducing energy consumption and switching to renewable energy sources (Ahlrichs et al. 2020). However, the complexities of diverse building uses (Jradi et al. 2021), communication barriers among stakeholders (Allouhi et al. 2015), and the challenge of verifiably attributing energy consumption related GHG emissions (Woo et al. 2021) necessitate advanced technological solutions.

The evolution of Energy Management Systems (EMSs) to EEMS (Zampou et al. 2022) has already been conceptualized and is defined as a class of IS that receive heterogeneous types of environmental data (e.g., electricity and fuel use, emission factors) as inputs, process them to calculate energy-key performance indicators and derive GHG emissions while offering functionalities like analytics, workflow management and automated reporting (Melville and Whisnant 2014; Zampou et al. 2022). EEMSs have laid the groundwork for the development of BEMSs (e.g., Cavalheiro and Carreira 2016; Fiorini and Aiello 2018; Woo et al. 2021), which are context-specific EMSs in the building sector. BEMSs can be understood as systems that monitor and control buildings' energy requirements while providing user feedback and information on how energy is used (Cavalheiro and Carreira 2016; Hannan et al.

2018). BEMS are intended to attain improved energy efficiency and optimal energy utilization by incorporating energy utilization strategies and methods (Bonilla et al. 2018). The first approaches encompass automatic demand side management, energy cost management, identification of energy consumption anomalies, or providing information for reporting purposes (Jota et al. 2011). However, besides steering a buildings' energy consumption deriving effective measures for sustainable building energy management is also crucial. Despite the advancement in Energy Informatics when acknowledging verifiable GHG-emission data to effectively facilitate digital decarbonization, GHG emissions considerations within BEMSs remain an underexplored area (Fiorini and Aiello 2018; Jradi et al. 2021; Sou et al. 2013).

In response to these challenges, our research advocates for a collaborative approach between the academic community and industry practitioners to design and develop a BEEMS. Such a system would address the current market demands and standards and bridge the gap between theoretical research and practical applications in sustainable building management. This endeavor aligns with the foundational principles of Energy Informatics and the urgent need for digital decarbonization strategies, offering a pathway toward mitigating climate change through innovative, data-driven solutions in the building sector.

Method

As noted above, we identify a noticeable gap in research on how to design a BEEMS that enables verifiable GHG accounting in the building sector (Step 1). Consequently, our study focuses on formulating DPs as essential criteria for developing a BEEMS. BEEMS have already been discussed and investigated in current literature and the building industry. In order to leverage existing research and ensure the practical relevance of our work, we use a multi-stage approach that includes a systematic literature review, expert interviews, and qualitative content analysis to synthesize DPs (cf. Figure 1). Therein, we follow existing studies applying a similar approach (e.g., Heeß et al. 2024; Mueller et al. 2023) when aiming for rigorously conceptualized and applicable research. Their methodology is based on Hevner et al. (2004) design cycle research framework, with a particular focus on the early stages of the process.

After identifying the need for a BEEMS, we conduct a systematic literature review in Step 2 (vom Brocke et al. 2015) to define our design objectives while deriving challenges and MRs for GHG emission accounting in the building sector (see Step 3). We develop a search string and explore most relevant databases of the IS research domain such as Web of Science, IEEE Xplore, and the AIS eLibrary. Since our research topic combines aspects from the general IS domain and specifically from the Energy informatics and Green IS fields, we particularly

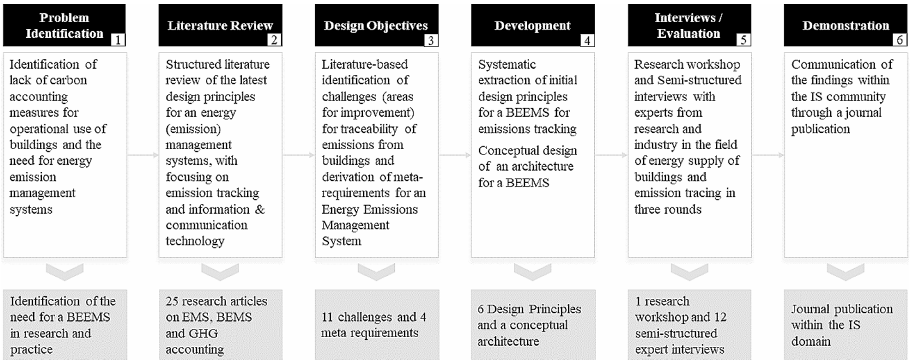

Fig. 1 Executed research approach

filter for related journals. Further, to ensure the quality of the results, we select English and peer reviewed articles while specifically focusing on descriptions and concepts on EMS and EEMS or related topics. Consequently, our search returns a total of 480 research articles. By screening titles, abstracts, and article content, we refine the selection based on our inclusion and exclusion criteria (see Fig. 2), resulting in 23 relevant publications. Lastly, by conducting both forward and backward searches, we identify two additional articles, leading to 25 articles.

To establish a robust foundation for our work and the formulation of our DPs, in Step 3, we analyze the 25 identified articles to discern the challenges associated with EMSs in general and in the building sector in specific. This analysis takes into account the obstacles related to energy flow-related GHG accounting. Through this process, we pinpoint ten design challenges. To adequately address these challenges, we formulate the following research objective: *Develop DPs for a BEEMS to facilitate verifiable end-to-end energy and emission-related data processing, enabling emission-based energy-utilization measures.* Following the framework proposed by Peffers et al. (2007) and Walls et al. (1992), we derive three MRs as design objectives for an EEMS based on the identified challenges.

In the subsequent Step 4, we develop our DPs for a BEEMS, following the approach outlined by Gregor et al. (2020) of a DP scheme. This scheme allows us to summarize various aspects of the statements, including aim, context, mechanism, and rationale. Building on the literature review, identified challenges, and derived MRs, we formulate an initial set of DPs. While the identified challenges and MRs are sector-agnostic, focusing on general challenges and objectives of EMS design, the DPs are specifically tailored to the design of a BEEMS, narrowing the scope of requirements.

Following the initial DPs' development, we evaluate them in Step 5. Initially, we present the set of DPs to a group of sixteen Green IS and Energy Informatics researchers during a research workshop, gathering comprehensive feedback and adjusting the DPs accordingly. After refining the DPs, we conduct two rounds of interviews (see Table 1), both within the author's team and with experts, to further evaluate the DPs against criteria such as ease of use, understandability, simplicity, elegance, and completeness (Sonnenberg and vom Brocke 2012). We carefully include stakeholders from different areas of building energy supply and end-user level (i.e., landlords, operators, tenants) to ensure a comprehensive assessment, whereby the focus of the interviews is on industry experts. The aim is to increase the relevance of the BEEMs by incorporating the requirements, challenges and input from the field into the design-oriented research approach, in addition to the consideration of the scientific literature throughout the structured literature review. Individual interviewees are selected based on their individual expertise, business areas and experience in the heating transition and property sectors, as shown in Table 1. The semi-structured interviews provide flexibility for nuanced exploration, while structured sections ensure vital parameters (i.e., DPs) are rigorously evaluated. The feedback gathered during the interview cycles is then thoroughly discussed within the author's team, leading to the finalization of the six DPs. To do so, we analyze the expert's input and derived relevant aspects for the design principles following the approach of Mayring (2000) for qualitative content analysis. The interviews allow us to demonstrate the developed framework to practitioners and researchers, ensuring its relevance and rigor. The interviews entail a questionnaire designed to guide the interviewees through the predefined design objectives and dedicated sections for open-ended feedback to offer

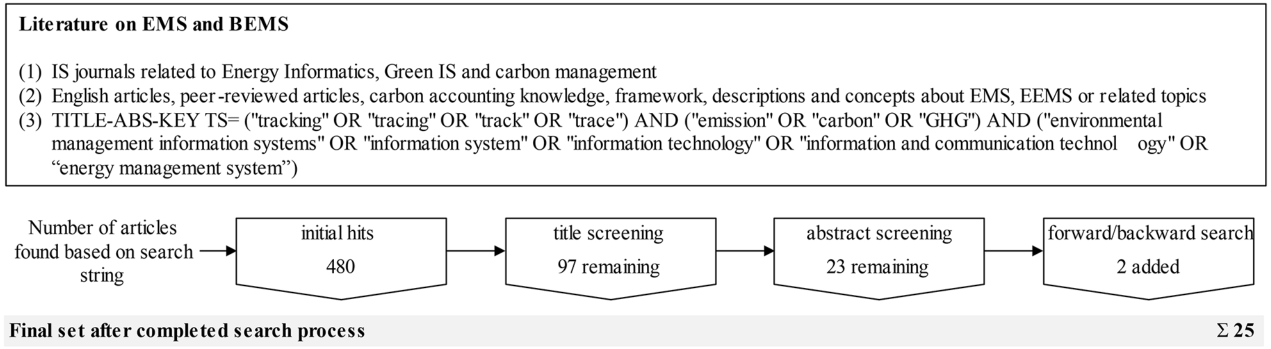

Fig. 2 Systematic literature review

the interviewees a significant degree of autonomy in shaping their responses (Drever 1995; Myers and Newman 2007).

Adhering to the iterative nature of the DSR scheme (Gregor et al. 2020), we iterate back to the development phase (4) and deductively develop a first conceptual, technical architecture of the envisaged BEEMS which is based on the DPs and current research on EMSs and BEMSs (Al-Ghaili et al. 2021; Cavalheiro and Carreira 2016; Zampou et al. 2022). Due to the focus of this work on identifying DPs for a BEEMS, the conceptual architecture needs to be evaluated in a consecutive cycle.

Design of building energy emission management systems

Within this section, we present our findings in three sub-sections. First, through our systematic literature review on BEEMS, we identify ten challenges for designing and implementing a BEEMS. Based on these challenges, we derive three MRs that provide guidance and structure on the requirements a BEEMS must fulfill. Second, we present the final set of six comprehensive DPs for a BEEMS. Third, building on the DPs, we design the first conceptual architecture of a BEEMS, highlighting the interplay of components and functions.

Challenges and MRs for a building energy emission management system

Below, we provide a concise overview of the challenges associated with verifiable GHG emissions in the building sector as identified in the literature. Subsequently, we introduce MRs that address these challenges. It is important to note that these challenges and MRs may extend beyond the building sector. Table 2 offers a comprehensive view of these challenges, demonstrating their alignment with the MRs. It further depicts which functionality of the BEEMS architecture (cf. Figure 3) addresses the specific challenge.

First, research finds that *efficient data processing and usage protocols* are a major obstacle to developing an EEMS in various industries (Hoang et al. 2017; Tranberg et al. 2019). As the status quo of BEMs unveils, the energy production and distribution process to individual buildings is marked by a fragmented system and data landscape that limits data flows and, thus, the verifiable derivation of information (e.g., GHG emissions) and efficient actions. The lack of data processing efficiency while following standardized overarching usage protocols of the system and the processed information may hamper current systems' overall performance and the outcome's value. This aspect is strongly related to *inconsistent data quality and granularity across multiple systems*. As highlighted by Melville and Whisnant (2012), the related data challenges of energy and emission management are mainly caused by heterogeneous and secondary data that diminish information's reliability and accuracy. Gräuler et al. (2013) support this aspect by defining data quality as a key enabler for energy-related management systems' long-term success. Zampou et al. (2022) further outline an EMS as a data-intensive process that requires system operators along the value chain to go beyond their existing infrastructures to provide a standardized and granular data input. Therein lies the obstacle of capturing and integrating the (emission) data across the entire value chain at sufficient granularity while following industry-wide standards to enable a consistent end-to-end data flow (Melville and Whisnant 2014). However, limited data sharing and interoperability among systems are hampered by the need to ensure high and consistent data quality and granularity across the entire building-related energy flow. Here, Zampou et al. (2014) highlight the importance of communicating different information formats captured through multiple primary and secondary data sources. Overcoming this obstacle and ensuring

Table 1 Overview of interviewed experts

Cycle	ID	Professional Title	Field of Expertise	Organization Type	Mainly discussed the following DPs
1	EXP1	Researcher	GHG Accounting; Energy Management	Research Institute	DP1; DP3; DP4
	EXP2	Researcher	GHG Accounting; Energy Management	Research Institute	DP1; DP2; DP3
	EXP3	Senior Associate	Smart Building Technology	Real Estate Investment Manager	DP3; DP5; DP6
	EXP4	Researcher	Energy Management; Technology Acceptance	Research Institute	DP2; DP3; DP6
	EXP5	Head of Product	Smart Building Technology; Building Management	Real Estate Investment Manager	DP1; DP2; DP6
	EXP6	Head of Data Intelligence	Data Intelligence; Building Management	Real Estate Investment Manager	DP1; DP3; DP6
2	EXP7	Project Manager	Data management, Sustainability; Energy Supply	Municipal Utility Cooperation	DP1; DP2; DP6
	EXP8	Strategic Energy Manager	Energy Management; Corporate Real Estate management	Energy Provider	DP2; DP4; DP5
	EXP9	Senior Renewable Energy Consultant	Energy Management; Decarbonization; Renewable Energy	BEMS Service Provider	DP1; DP4; DP5
	EXP10	Head of Sustainability and Innovation Fund	Energy Management; Energy market; Energy Systems	Energy Provider	DP1; DP2; DP6
	EXP11	Head of Supply Solutions	Energy Management; Building Management; Energy Systems	Energy Service Provider	DP1; DP3; DP5
	EXP12	Founder and CEO	Emission Management; Building Management; Decarbonization	Emission Accounting Solution Provider	DP2; DP5; DP6

interoperability and consistent data flow among multiple internal parts of the system and additional external sources requires transforming raw and arbitrarily formatted data into a standardized overarching format Zampou et al. (2014). Thus, this challenge relates strongly to the second challenge of data quality and is highly important for the long-term success of GHG-related EMSs (Gräuler et al. 2013). Besides the need for standardized data formats, C1-C3 align with *insufficient data processing and system operations automation*. Hoang et al. (2017) highlight the importance of automation within GHG emission-related EMSs, particularly for the real estate sector, due to the necessity of transforming building energy management processes into energy management processes that strongly rely on manual installation or operational tasks (e.g., installation and calibration of sensors). These manual tasks are inherent to the nature of the building and may only partially be automated. Consequently, a system must automatically identify anomalies in the processed data to ensure a consistent data and information flow (Hoang et al. 2017). Despite a large number of tasks already being automated within current EMSs, operations such as verification and validity checks of the processed data and workflow tracking still rely on manual interactions, thus limiting the reliability of and trust in the system (Melville and Whisnant 2014). Moreover, we identify a *lack of traceability of processed data and calculations* as a relevant problem to be considered within the design and development (Melville and Whisnant 2014; Tranberg et al. 2019). As the energy-related GHG emission data must be communicated among multiple stakeholders and system components, traceable information and data are considered key facilitators of an EEMS. Gräuler et al. (2013) highlight the importance of enabling

Table 2 Overview of identified challenges for EEMS and BEEMS

ID	Challenge	Meta-Requirement	BEEMS Architecture (cf. Figure 3)	Related Literature
C1	Efficient data processing and usage protocols	MR1	1st layer: Data collection, storage and further processing from heterogenous data sources through numerous APIs.	Arnesano et al. 2018; Hilpert et al. 2013; Hoang et al. 2017; Melville and Whisnant 2014; Tranberg et al. 2019; Zampou et al. 2022
C2	Inconsistent data quality and granularity and lack of emission data	MR1	1st layer: incorporation of Emission data and standardization of multiple external data sources.	Hilpert et al. 2013; Silpa et al. 2020; Sjödin and Grönkvist 2004; Tranberg et al. 2019; Zampou et al. 2022
C3	Limited data sharing and interoperability among different systems	MR1; MR2	3rd layer: BEEMS workflow engine incorporates data from individual (existing) system components.	Gräuler et al. 2013; Hilpert et al. 2013; Hoang et al. 2017; Zampou et al. 2022
C4	Insufficient automation in data processing and systems operations	MR2	1st– 4th layer: Automated data and operations flow.	Gräuler et al. 2013; Hilpert et al. 2013; Hoang et al. 2017; Melville and Whisnant 2014; Zampou et al. 2022
C5	Lack of traceability and verifiability of processed data and calculations	MR1	1st– 4th layer: transparent and traceable data collection and display to selected stakeholder groups (4th layer).	Gräuler et al. 2013; Kranz et al. 2021; Melville and Whisnant 2014; Tranberg et al. 2019; Zampou et al. 2022
C6	Missing trust in the systems operations and reliable data processing	MR3	1st layer: Data storage envisaged to leverage advanced technological solutions to verify and protect sourced data.	Hoang et al. 2017; Melville and Whisnant 2012, 2014
C7	Vulnerability to unauthorized data use and system compromise	MR3	BEEMs as closed system with permissioned access for external parties	Albizri 2020; Goebel et al. 2014; Hannan et al. 2018; Zampou et al. 2022
C8	Missing robust privacy-preserving measures and protocols	MR3	1st layer (sourced data) and 4th layer (stakeholder-interaction): data and privacy preserving measures.	Goebel et al. 2014; Melville 2010; Zampou et al. 2022
C9	Limited usability of the system for involved stakeholders	MR2	4th layer: Stakeholder specific and adjustable user platforms.	Albizri 2020; Corbett 2013; Hilpert et al. 2013; Kranz et al. 2021
C10	Lack of modifiable system components	MR2	1st– 4th layer: modular and layered BEEMS core architecture.	Kranz et al. 2021; Melville et al. 2017; Zampou et al. 2022

traceable data and information flows to contribute to the transparency and reliability of the system. Traceability plays a significant role in overcoming *missing trust in the systems operations and reliable data processing* (Hoang et al. 2017; Melville et al. 2017). This aspect unfolds in two dimensions. On the one hand, system stakeholders need to trust the processed data and derived information. On the other hand, this aligns with trust in the other stakeholders providing data to the system. Thereupon, we derive two cornerstones for trust in the system. First, reliability in the processed data (Hoang et al. 2017; Zampou et al. 2014) and second, trust in the stakeholders provide the data input and use the system. If stakeholders do not trust the GHG-related data processed by the system and the operations conducted by other stakeholders, the adoption and usage of the system may be limited. In addition, ensuring trust in the EEMS is closely connected to limiting the *vulnerability to unauthorized data use and system compromise* (Goebel et al. 2014; Zampou et al. 2022). Hannan et al. (2018) stress the importance of robust security measures for environmental systems, highlighting the need to maintain data integrity, ensure privacy, and keep track and record data consistently (Hannan et al. 2018). System operators must ensure that the data being processed, and the information derived is not altered or compromised by external malicious parties. Therein lies the challenge of protecting systems boundaries, especially at the various interfaces to legacy systems at the different stakeholder levels. A BEEMS is subject to specific challenges regarding processed data. To one extent, the system builds on data captured from energy producers and suppliers, which can be, to some extent, sensitive internal data which should not be shared with other entities in the supply chain (Mueller et al. 2023). On the other hand, the system must incorporate data about the tenant's energy consumption behavior to derive a thorough energy-emission profile on the asset level and enable focused emission-based actions. However, data and information on the tenant's energy consumption behavior may be subject to overarching data protection regulations (e.g., General Data Protection Regulation) and requiring *robust privacy-preserving measures and protocols* to ensure information of individual stakeholders is not shared outside the boundaries of the system and only abstracted information is used for the systems operations without unveiling sensitive data such as user consumption behaviors (Zampou et al. 2022). These privacy concerns align with the system's usability challenge for the stakeholders involved. We identify this aspect as crucial to ensure the adoption of the system and its proper use through the involved stakeholders (e.g., energy providers and building operators). Corbett (2013) emphasizes the need for usability and defines weaknesses as the main contributors to the limited effectiveness of an Zampou et al. (2022) further highlight user-friendliness and system usability as essential pillars in EMSs development. The system's usability directly points towards a need for *modifiable system components.* As current literature shows, the building sector already uses various systems to steer and manage building-related operations (e.g., BEMSs) (Kranz et al. 2021; Melville et al. 2017), thus the challenge results from establishing an EEMS and its additional functionalities that can communicate with existing systems and can be adapted to the individual user's needs. Consequently, a BEEMS cannot be understood as a one-fits-all solution but as an add-on to existing solutions and systems.

After having identified the challenges C1-C10, we cluster the challenges into three overarching MRs to establish a structured foundation for the development of our DPs:

MR1: Establish a robust and comprehensive data capturing and processing framework that follows current standards.

MR2: Enable an integrated automation and analytics infrastructure that enhances the system's modifiability and interaction.

MR3: Ensure the security and reliability of the processed data and derived information.

Besides the listed challenges, our literature review also yields additional obstacles, such as the need for standards for emission metrics, infrastructure, and the costs related to the implementation (Hannan et al. 2018; Tranberg et al. 2019). These issues particularly pertain either to the surrounding infrastructure or the implementation phase of an EEMS and are thus not considered during the development of our DPs. However, we acknowledge these challenges in the discussion section.

Design principles for a building energy emission management system

We iteratively refine the DPs using a research workshop and semi-structured expert interviews. The research workshop first reveals the necessity to refine the initial set of DPs to encompass pertinent aspects of a BEEMS and enhance clarity and simplicity. Generally, the researchers focus on the formulation and the intersection of current literature. In contrast, industry experts focus more on real-world applicability, scope, and comprehensibility about their area of expertise. A key result of the first evaluation cycle is merging the former DP7 "Application in future use cases" with DP2 into the current DP2 "Interoperability and flexibility."

Table 3 depicts the final set of six DPs, following the scheme of Gregor et al. (2020) to structure the DPs in title, aim, context, mechanism, and rationale. The aim describes the desired outcome when applying the DPs, whereas the context defines at which stage of the development of the BEEMS the DP is most relevant (Alter 2013). Further, the mechanism outlines how the aim of the DPs can be achieved, while the rationale justifies the necessity of the DP.

DP1– *End-to-end energy and emission data collection*: The first DP ensures energy and emission data are collected along the entire energy flow from the energy provider to the end-user in the building. This aspect is most relevant to reliably display the actual GHG emissions of the energy consumed on the user's level, thus building the foundation of BEEMS. Ensuring end-to-end data collection aims at collecting, receiving, and pre-processing production and energy consumption-related data at a sufficient level of granularity. The granularity and holistic data capture prevent erroneous estimations, as currently applied (Silpa et al. 2020), and enable the involved stakeholders to utilize the collected data for their use cases to some extent. The scope of collected data comprises the energy consumption and the emissions related to the value chain of the produced energy while also considering building-specific data (e.g., data from a building information system). EXP 7 highlights that "capturing energy-related *data and emission data, in particular, is the most difficult challenge due to the inconsistent data and system landscape."*. Consequently, a high-quality database with sufficient accuracy is crucial to adequately address the challenges C1 and C2 and adhere to MR1.

DP2– *Interoperability and flexibility*: The second DP underlines the importance of designing a system that can integrate into existing and future solutions. On the one hand, this DP refers to integrating existing data- and workflows from systems that run parallel to a BEEMS. On the other hand, the system components should be adaptable to allow modification to meet future market demands and regulations. EXP8 outlines, "*We already have several systems, such as an SAP System, a CRM system, and a building and energy monitoring system. Thus, the BEEMS and the ability to track GHG emissions should be designed as an add-on we can integrate seamlessly into our current suite*". Consequently, a BEEMS must maintain and operate an interoperable and modular architecture that can connect with other systems and public resources (e.g., master data register) through well-structured interfaces and adhering to current standards (e.g., ISO 50,001 for EMS). This allows the design of a resilient system that can avoid fragmentation during the adoption phase and enables BEEMS functionality to be kept up to date. EXP12 added on this aspect *"Interoperability is an important aspect, however when designing such system, it is even more important to not only develop the next system but try supporting a certain existing standard or system such as the CRREM standard."* Hence, developing an open modular system landscape while focusing on established market standards is essential to avoid further fragmentation. As such, DP2 addresses C1, C2, and C10 while adhering to MR1 and MR2.

DP3– *Scalable and efficient data processing*: Besides fulfilling the fundamental task of providing energy-related emission data, a BEEMS holds the potential to autonomously manage energy data and corresponding actions to reduce the reliance on human

Table 3 Overview of DPs for a BEEMS

ID	Design Principle	Aim	Context	Mechanism	Rationale	Literature
DP1	End-to-end energy and emission data collection	The BEEMS should collect, receive, and pre-process production and energy consumption-related data at a sufficient level of granularity for the stakeholder's use cases and enrich this data to establish a solid foundation for comprehensive analysis and decision-making.	Initiation, Development, Operation	Monitor energy consumption, constantly collect operational data, and trace emissions and further information. Add additional information about energy input and outputs on the building level, forecast future emissions and energy consumption, and store building characteristics while leveraging accessible Building Information Management (BIM) data.	A high-quality database with reasonable accuracy is critical for attaining related objectives and use cases of the BEEMS.	Cavalheiro and Carreira 2016; Gräuler et al. 2013; Hilpert et al. 2013; Melville and Whisnant 2014; Zampou et al. 2022
DP2	Interoperability and flexibility	The BEEMS should be able to integrate and run in parallel with external work- and data flows from existing or future energy information systems and market requirements (i.e., regulations). Additionally, it should demonstrate adaptability to address both current and evolving requirements and objectives of the BEEMS effectively.	Initiation, Development	Maintain and operate an interoperable and modular architecture that can connect with other IT systems and other (public) resources (e.g., master data register) through clear and well-structured interfaces and enable flexible integration of new applications and functionalities.	Compatibility with related systems and public resources enables resilience, avoids fragmentation, and allows for keeping an innovative information system.	Gräuler et al. 2013; Hoang et al. 2017; Melville and Whisnant 2014; Zampou et al. 2022
DP3	Scalable and efficient data processing	The BEEMS, along with all its components, should autonomously manage (i.e., collect, store, and process) energy data and corresponding actions to reduce the reliance on human-operated tasks and enhance overall efficiency.	Development, Operation	Design of a BEEMS that acts highly autonomously executes workflows and processes automatically, performs complex analyses to calculate energy/emission key performance indicators, and derives a thorough data basis for emission-related actions.	Autonomous information systems reduce costs and avoid errors (esp. human error) and dependencies on third parties to provide frictionless processes and high data quality as a solid basis for following processes.	Arnesano et al. 2018; Hilpert et al. 2013; Hoang et al. 2017; Silpa et al. 2020; Wehkamp et al. 2020; Zampou et al. 2014

Table 3 (continued)

ID	Design Principle	Aim	Context	Mechanism	Rationale	Literature
DP4	Data sovereignty and zero trust policy	The BEEMS should follow a data sovereignty approach and ensure the confidentiality, integrity, authenticity, verifiability, and availability of the processed data and information according to the jurisdictional framework. Further, the system shall be enriched by a continuous verification (i.e., zero-trust) concept to prevent unauthorized access to the data.	Initiation, Development, Operation	Comply with applicable laws and regulations to guarantee the stakeholders' data sovereignty and privacy and protect the data and the BEEMS with a zero-trust model and state-of-the-art security mechanisms against malicious acts.	Protect the rights, interests, and data of tenants, landlords, and other stakeholders against third parties.	Goebel et al. 2014; Zampou et al. 2022
DP5	Data verifiability and information reliability	The BEEMS should enable traceability, validity checks, and verifiability of the energy and emissions data and the processing flow to enhance trust in the data and the information derived.	Initiation, Development, Operation	Operate according to defined and transparent standards and norms and control the correctness of the workflow and underlying data through internal self-mechanisms and external audit functions at any time while considering state-of-the-art technological solutions.	Establishing reliability and reliance on the system and comprehensibility and comparability of its data.	Hilpert et al. 2013; Kranz et al. 2021; Melville and Whisnant 2014; Zampou et al. 2022
DP6	Usability for all stakeholders	The BEEMS should provide sufficient usability to leverage the user's system acceptance. This entails ensuring that BEEMS adheres to the individual application purposes of the stakeholders and considers the different asset types.	Initiation, Development	Implement different user types related to the underlying asset types to follow the specific application purposes of (1) Building owners/residents (property manager; private owner; institutional owner); (2) Energy (service) provider (grid operator; energy producer); (3) External Stakeholders (Regulators; financial institutions) by providing different functionalities and visualization formats	Focus on the users' needs to foster the application of the information system.	Ali et al. 2020; Gimpel et al. 2020; Kranz et al. 2021; Melville and Whisnant 2014; Zampou et al. 2022

operations, enhancing the overall efficiency of the system (Hilpert et al. 2013). EXP1 emphasizes this: "Data *collection and processing must be conducted automatically. This is a prerequisite for processing large amounts of energy, building, and consumption-related data.*" Thus, it is of particular importance to design a BEEMS that acts highly autonomously, executes workflows and processes automatically, performs complex analyses to calculate energy and emission key performance indicators, and derives a thorough basis for emission-related actions. As highlighted by EXP11, therein lies the challenge of processing and storing large amounts of data in a decentral manner. However, automating these data capturing and processing tasks allows less dependency on third parties and further supports a high-quality database. DP3 contributes to C1, C3, and C4 and fulfills MR1 and MR2.

DP4– *Data sovereignty and zero trust policy*: As we highlight within the challenges section, preserving data protection and privacy rights, as well as the integrity of the system, is highly relevant for the functionality of a BEEMS, as it builds the foundation for the trust relationship between the users and the system, thus contributing to its adoption (Goebel et al. 2014; Scherenberg et al. 2024; Zampou et al. 2022). EXP8 points out that *"[data protection and the integrity of the system] are critical aspects that must be ensured. In particular, building owners and tenants are very conservative and want to decide who can access and use their data"*. According to the current legislation, this results in the requirement for a BEEMS to ensure the confidentiality, integrity, authenticity, privacy, and availability of the processed data and information. Moreover, a BEEMS must be enriched by a continuous verification (i.e., zero-trust) concept that prevents unauthorized access to the processed data. This implies that a BEEMS must actively implement a zero-trust model and employ state-of-the-art security mechanisms at both the data entry points and user interfaces, recognizing them as the most vulnerable components of the system. Following these aspects may foster the user's trust in BEEMSs and enhance interaction and usability. Consequently, DP4 addresses C7 and C8 while adhering to MR3.

DP5– *Data verifiability and information reliability*: Deriving emission-based actions related to the energy flow of a building requires a reliable database. More specifically, traceability, validity checks, and the verifiability of the energy and emission data and the processing flow must be guaranteed to enhance trust in the data and the information derived. EXP9 described the status quo of their energy monitoring and data verification process as "(…) *Employees manually verify the data received from meters installed in the buildings since the information is mostly erroneous."* The emission data captured at different levels of the energy process flow needs to follow current data standards and norms. In contrast, the correctness of the workflow needs to be ensured through self-mechanisms and external audit functions at any time. EXP11 highlights, *"external auditors still need access to the system. Hence it is important that the data capturing, processing and verification follows current standards and applies technological mature solutions"*. Smart meters are the first approach to ensuring automated consumption data capturing. However, concerning emission-related data, novel technological approaches must be developed to solve the data-capturing issues and provide a verifiable database (Babel et al. 2022; Heeß et al. 2024). This DP supports solving C5 and C7 and can be categorized in MR1 and MR3.

DP6– *Usability for all stakeholders*: Establishing a BEEMS along the current systems landscape of EMS, BEMS, and other systems relies heavily on the willingness of stakeholders to interact with the system. As a BEEMS covers the energy and emission flow from production to distribution to consumption and beyond towards external stakeholders such as regulatory authorities, the stakeholder landscape and the mode of interaction with the system is highly diverse. EXP 6 highlights that "*the benefit of using the system must be recognizable for the involved stakeholders. Otherwise, they will not use it*". EXP12 further outlines that "*most systems fail because they cannot translate the environmental impact into a feasible good for the users. This principle is fundamental and requires an in-depth stakeholder analysis at a later stage*". These aspects point toward implementing different user and asset types to follow specific application purposes and fulfill the users' needs accordingly. Therein, it might be applicable to distinguish between (1) energy (service) providers, (2) building owners and residents, and (3) external stakeholders (e.g., regulators and financial institutions). In essence, DP6 corresponds directly with DP1-DP5 as they build the technical foundation to ensure sufficient flexibility in designing different user interfaces and related tasks to cater to the needs of various stakeholders. The DP solves challenges C3, C8, and C9, fulfilling MR2 and MR3.

Conceptual architecture for a building energy emission management system

Based on the six identified DPs and current research (Al-Ghaili et al. 2021; Cavalheiro and Carreira 2016; Zampou et al. 2022), we develop the first conceptual architecture of a BEEMS as outlined in the method section. The architecture comprises four layers of modular system components. Figure 3 depicts the conceptual architecture of a BEEMS, its system components, and layers. It highlights the four essential layers for processing external emission, energy, building and third party data flows to facilitate emission-based actions for buildings operational energy consumption. Moreover, Fig. 3 outlines the necessity for different user interfaces according to the multiple stakeholder groups interacting with the system. Further, as exemplary use case for further use of the systems data, the reporting mechanism for the building owners is indicated.

A BEEMS architecture may consist of multiple interconnected layers, with modifiable system components, which we outline below. External data from multiple sources is initially collected and stored at the first layer before further processing. We suggest that aligning energy management, building management, and emission management on the second layer is essential to provide the required data input for the BEEMS workflow engine (third layer), which processes and analyzes the data and prepares the output to be presented at multiple

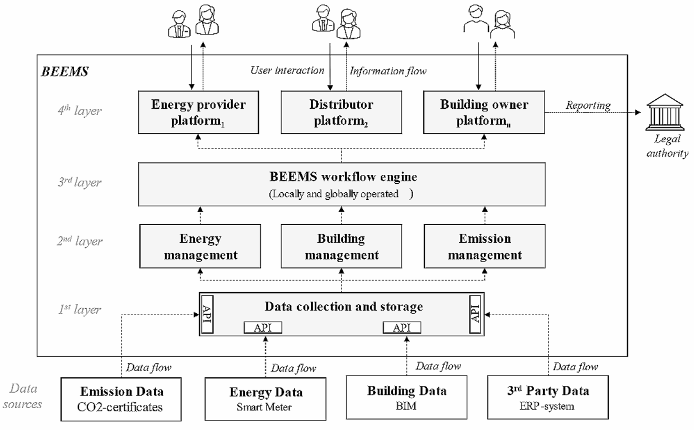

Fig. 3 Initial architecture of a BEEMS based on the six DPs (own illustration)

platforms (i.e., stakeholder interfaces). As we consider the system's usability to be essential for its adoption, the user platforms need to be modular components that are easily adjustable to the stakeholders' requirement, while being permissioned in their accessibility to limit the risk of fraudulent external interactions.

A *data collection and storage module* collects various data from external systems (e.g., BIM), tools (e.g., Smart Meter), and certificates (e.g., GHG certificates). Further, it takes care of handling multiple information flows. As emphasized by our interview partners, the availability and quality of building and emission-related data varies among multiple related systems (e.g., ERP; BIM); thus, the BEEMS needs to handle various heterogeneous data sources by providing numerous interfaces. Having a standardized data basis is crucial for the seamless functionality of the BEEMS; hence, collecting and storing granular data can be seen as the foundation of the BEEMS's functionality.

An *energy management module* processes energy consumption-related data from the building through smart meters and other sensors. The module assigns the energy consumption to pre-defined user profiles (e.g., building, unit, tenant) to create a granular and use-case-specific overview of the consumed energy. Within our architecture, we assume that sustainable energy consumption behavior needs to be aligned with an individual's consumption behavior while considering the profile of each building (e.g., multi-family house, shopping center). Thus, the BEEMS must allocate the consumed energy on multiple levels to enable further calculations for individual stakeholders.

A *building management module* handles data and information allocated through actuators, meters, or sensors that collect data from the building environment or the space activity (e.g., heating, ventilation, and air conditioning system). Besides, this module considers data input from the BIM, which creates a digital twin of the building's infrastructure based on floor and construction plans. The building management module processes the related data and, depending on the asset type (e.g., commercial or residential), creates individual usage profiles and parameters for a building. The main functionality of this module is to provide the basis for mapping energy and emission-related data to the operational use of an asset. This allows us to derive metrics for later decision support mechanisms (e.g., emission-related energy reduction) (Cavalheiro and Carreira 2016).

An *emission management module* handles the energy-related emission data to create the emission-related usage profile. As such, this module must collect emission data captured and processed along the entire energy flow from production to consumption on an individual tenant level. The emission management module handles data of emission certificates or other proofs. Like the energy management module, it allocates the GHG emission on multiple levels to enable further calculations or reports for individual stakeholders.

A *BEEMS workflow engine* depicts the core of the BEEMS. It combines the information derived from the second layer modules, materializes the previously processed data and information regarding their scope and intended usage, and calculates required metrics and KPIs. The results of the workflow engine are then displayed on multiple user platforms (*energy provider-, distributor-, building owner platform)* representing the stakeholders' points of interest. As such, these interactive platforms display previously calculated energy-consumption-related information added by emission data and provide the end users' KPIs and decision support metrics. This functionality also aligns strongly with the reporting mechanism that supports the creation of sustainability reporting for third parties (e.g., regulators). Besides these four layers and the system components, we indicate the permissioned nature of a BEEMS as an essential building block to ensure the integrity of the processed data and information and adequately protect users' and stakeholders' privacy. This feature indicates that only accredited users can access data assigned to their role within the system, and only data owners can decide upon using the information.

We develop this architecture as the first instantiation of our DPs and discussed further technological and future design features in the following section.

Discussion and implications

Our research yields six DPs for a BEEMS that promotes end-to-end verifiable energy and emission data collection, enabling emission-based actions to steer energy consumption within buildings. Thus, our concept contributes to reducing GHG emissions within the building sector. The final set of evaluated DPs, along with the conceptual architecture, guides the development of a BEEMS that allows for reliable GHG emissions tracking along the entire energy flow chain for the operation of buildings. Implementing a BEEMS will enable us to track energy-related GHG emissions and allocate them to energy consumption on an individual level (e.g., tenant). It, therefore, provides a technological solution that reaches beyond energy-saving methods to reduce GHG emissions within building operations, aligning with individual energy consumption patterns.

The core of our developed artifact lies in designing an IS that enables verifiable and efficient sharing of energy-related emission data to steer sustainable energy consumption within the building sector. We provide insights for the IS domain on how to design such systems related to the already researched category of EEMSs (Zampou et al. 2022). To ensure the applicability of our findings outside the IS community, we incorporate the views of experts with backgrounds in energy production distribution and the building sector. The experts provide us with valuable interdisciplinary insights, enriching our findings. Consequently, we give fertile ground for Green IS and Energy Informatics researchers to align with the energy production and building management field to leverage the potential for reducing GHG emissions and promote more sustainable processes and practices. Table 4 provides a mapping of the objectives of the BEEMS (i.e., DPs) with the challenges to be addressed and the overarching meta requirements identified during the research process.

Table 4 Overview of design principles, challenges and MRs

ID	Design Principle	Addressed Challenges	Overarching Meta Requirements
DP1	End-to-end energy and emission data collection	C1; C2	MR1
DP2	Interoperability and flexibility	C1; C2; C10	MR1; MR2
DP3	Scalable and efficient data processing	C1; C3; C4	MR1; MR2
DP4	Data sovereignty and zero trust policy	C7; C8	MR3
DP5	Data verification and information reliability	C5; C7	MR1; MR3
DP6	Usability for all stakeholders	C3; C8; C9	MR2; MR3

Discussion

Recognizing the insights from existing literature on EMSs and BEMSs, our study underscores the imperative of a robust *end-to-end energy and emission data collection* framework to empower informed emission-based decisions (Arnesano et al. 2018; Hilpert et al. 2013; Zampou et al. 2014, 2022). In alignment with DP1 of enabling end-to-end energy and emission data collection, we extend the insights from Zampou et al. (2022) regarding EEMSs for supply chains to address the intricate energy flows within the building sector. Our approach transcends the limitations of existing BEMS by considering preliminary stakeholder data, such as that from energy providers and distributors, and crucial end-consumer insights, notably from tenants and building owners. This includes granular data like individual energy consumption patterns and onsite renewable energy generation (e.g., solar power). This comprehensive data integration strategy is pivotal for tailoring sustainability initiatives, ensuring they encompass the full spectrum of energy and emissions flows. The iterative feedback from expert interviews highlighted the paramount challenge of achieving holistic data acquisition within the inherently fragmented landscape of building energy systems. This underlines the necessity for a meticulously designed BEEMS that harnesses the latest advancements in IoT technologies for seamless data capture and processing from many sources, thereby enhancing system efficiency and stakeholder engagement (Fotiou et al. 2018).

Further, current literature already considers modular and flexible system components within the scope of EEMSs. Melville and Whisnant (2014) and Gräuler et al. (2013) highlight the need for EEMSs to seamlessly integrate with existing systems to avoid overly complex structures and errors. DP2 considers this imperative, focusing on the critical aspect of *interoperability and flexibility*. The insights from expert interviews further illuminate the diversity and fragmentation inherent in the building-related energy-flow landscape. This heterogeneity, compounded by varying standards and the pace of technological advancements, underscores the impracticality of a one-size-fits-all solution, which could hinder user adoption and system efficacy. In line with the recommendations from Zampou et al. (2022), which initially applied these considerations within the supply chain context, our study validates their applicability and critical relevance within the building sector. The feedback from experts, particularly EXP7, EXP8, and EXP11, emphasizes the fragmented nature of the ecosystem encompassing energy producers, providers, and building operators. This fragmentation necessitates the development of a modular BEEMS solution capable of integrating into the existing diverse system landscape. This enhanced perspective on DP2 addresses the immediate challenges identified (C1, C2, and C10) and posits the modular and interoperable architecture of BEEMSs as a transferable concept for other industries facing similar fragmentation.

Regarding the data and information processed, current research proposes automating data and validity checks to reduce the reliability of manual interactions (Melville and Whisnant 2012). Silpa et al. (2020) point towards the complexity of manual tasks (i.e., collecting, processing, curating, and sharing data) and thus the need for automated workflows. As our proposed BEEMS relates not only to the energy flow but also integrates data from the building as well as the consumption patterns of tenants, the number of manual tasks and reliance on human interaction increases significantly. Thus, the scope of DP3 goes beyond current research and proposes a fully automated data processing system that operates without relying on human interactions to enable *scalable* *and efficient data processing*. However, as determined throughout the evaluation phase, human interaction should be possible at any system stage. This is essential in case of data misinterpretation and to increase trust in the system from a user perspective (Hilpert et al. 2013). Consequently, we build on current research while going beyond the proposed degree of automation as a rationale derived from the even greater complexity of systems added through interaction with the building sector. Further, we emphasize the importance of allowing manual interactions as a fundamental pillar to support the adoption of the BEEMS.

Considering *data sovereignty and zero trust policy*, prior research on EEMS only partially discusses this aspect. Zampou et al. (2022) highlight this facet relating to the reliable interaction between multiple supply chain partners, while Goebel et al. (2014) point towards the general need for secure ICT infrastructure. However, considering the sensitivity of tenant-related energy consumption data and current data protection laws, we assume DP4 is particularly important. The challenge lies in finding a way to adhere to current rules and regulations on data protection to guarantee the stakeholders' data sovereignty and privacy while protecting the BEEMS itself against unauthorized data access. We go beyond current proposals for data protection and expand our DP towards the theorem of data sovereignty as the most advanced theoretical IS perspective on data protection. This requires a BEEMS to apply current standards and implement state-of-the-art security mechanisms, such as user authentication and certificate management. DP4 points directly to DP5, data verification, *and information reliability* - an aspect considered within Energy Informatics in light of emission tracking (Fiorini and Aiello 2018; Hilpert et al. 2013; Kranz et al. 2021; Melville and Whisnant 2014). As this aspect is of particular importance to ensure the adoption and use of the system while building users' trust, we focus on this angle. Throughout the literature review and interview phase, we could identify several technological concepts that support developers of a BEEMS in implementing these DPs. DP4 and DP5 point developers towards considering emerging technologies, such as distributed ledger technologies (DLT) and decentralized data storage systems, to facilitate the development of verifiable energy and emissions data tags that serve as the foundation for the BEEMS functionality (Heeß et al. 2024). We therein identified the need for verifiable data to be of particular importance for the design of the BEEMS. Consequently, we consider recent approaches of Körner et al. (2023a) regarding the need for novel technological solutions to ensure the verifiability of emission data. Further, regarding the sovereignty of user data, DP4 guides towards approaches for emission certificates combined with Zero-Knowledge-Proofs (ZKPs) to align with DP5 for the verifiability of the processed data (Babel et al. 2023). The approach of an underlying DLT as a storage system for the reliability proof of the processed data follows the most recent findings within the IS field, simultaneously adhering to DP5 for data verification through concepts such as ZKPs (Babel et al. 2022; Heeß et al. 2024; Körner et al. 2023b).

Reflecting on DPs 1–5 reveals that they collectively enhance the functionality of BEEMSs by ensuring secure and comprehensive data collection and processing. This holistic approach caters to energy and emission monitoring and significantly boosts the system's usability for diverse stakeholders. Recognizing the pivotal role of human interaction in the system's adoption, it is crucial to prioritize usability across all facets of BEEMSs implementation. Previous research in the EEMS domain has begun to address these considerations, underscoring the necessity for these systems to cater to varied use cases and the distinct needs of different stakeholder groups (Hoang et al. 2017; Kranz et al. 2021; Zampou et al. 2022).

Building upon these insights, DP6 emerges as a critical addition, advocating for developing tailored user interfaces. These interfaces are designed to meet the specific requirements and expertise levels of the BEEMS's primary stakeholder groups, ensuring an intuitive and practical user experience. This principle aligns with the current discourse on EEMSs design, which emphasizes the creation of user-centric interfaces that adequately address the users' need (Arnesano et al. 2018; Kranz et al. 2021). Essential considerations under this principle include the customization of data presentation and the extent of interactive capabilities offered to users, ensuring that the system remains accessible and valuable to all users, regardless of their technical proficiency. In summary, DP6 underscores the importance of user interface design in enhancing the usability and adoption of BEEMSs, catering to the diverse needs of its stakeholders.

With regard to the implementation of a BEEMS, our research provides initial insights. The defined DPs and the conceptual architecture can serve as a valuable guide in the process of prototyping and field testing the BEEMS. As indicated in the individual DPs, different approaches are either already in existence or are being developed to fulfil the various characteristics. Nevertheless, as disruptive technologies such as artificial intelligence, the Internet of Things, and distributed ledger technologies continue to advance, both the DPs and the conceptual architecture of BEEMS may change rapidly. Accordingly, as described in DP2 the flexibility of the BEEMS also regarding the adjustment of system components to technological advancements should be considered during piloting and implementation.

Theoretical and practical contribution

With our work, we extend the existing body of knowledge concerning the design of EEMSs and the consideration of emission-related data to improve the ecological sustainability of the building sector. While research on EEMSs is growing steadily (Arnesano et al. 2018; Corbett 2013; Hoang et al. 2017; Zampou et al. 2022), it leaves space for investigating the design of a BEEMS. The traceability and verifiability of energy-related emission data and integration into the existing organizational internal ERP and EMS system landscape remain only partially investigated and stand out as primary limitations of the adoption of BEEMS in the building sector. Our aims to overcome these limitations and contributes to the current field by building on existing EEMS research with novel insights into a complex yet under-investigated industry, the building sector. As this area has already been partially investigated through the technological lens of BIM with a particular focus on the construction side of a building, analyzing the operational energy and emission flow of a building remains still underrepresented in current Energy Informatics research. Thus, developing a conceptual architecture for a BEEMS provides practical insights into opportunities and challenges of implementing central management systems for enabling emission-based actions aligned with the operational energy flow of a building and to align multiple stakeholder interests within the complex interplay of energy provision and consumption. We contribute to energy system-based research and scholarly work in Energy Informatics by providing insights on data sovereignty and systems integrity and on how EEMSs may be designed technically in a complex multi-stakeholder environment. With our results, we continue to expand Energy Informatics research by laying a structured foundation for how IS may contribute to sustainable development through BEEMS, providing a solution to the pressing global challenge of mitigating climate change-related challenges.

Finally, we contribute to the overall design theory of EEMSs by pursuing the development of technology-agnostic generalizable DPs to enrich the future development of EEMSs. As identified throughout the problem identification and evaluation phase, the design of tools and methods to track GHG emissions reliably and utilize the generated data to derive emission-based actions is a relevant aspect for various industries, thus of particular importance for the field of Energy Informatics in pursuing the reduction of environmentally harmful emissions and particularly incorporating most current research on technological solutions for verifiable emission accounting (Babel et al. 2022; Heeß et al. 2024; Körner et al. 2023b) enriches the research stream on EEMS. Moreover, our DPs for a BEEMS highlight the necessity of considering the usability perspective to ensure adoption by the system users, which reflects the socio-technical aspect of the system design. In doing so, our DP for a BEEMS provides a solid foundation regarding the end-to-end data collection, data sovereignty, and sustainable transformation of the building sector. We further extend the findings illustrated through our DPs by developing an initial technical architecture of our BEEMS. This allows future researchers to identify the essential components of the system more easily and derive helpful starting points for the systems development and implementation within additional DSR cycles.

Concerning the practical contribution of our work, all our interviewees acknowledged the necessity of reducing GHG emissions in the building sector. They further agree on the importance of going beyond lowering energy consumption while considering the versatility of energy sources as a distinguisher for the emission footprint of individuals and buildings. As imposed by current regulations, the need to report and reduce the emissions related to processes and tasks is gaining more importance. The alignment of energy consumption and GHG emissions appears to be a significant starting point for facilitating the sustainable transformation of the building sector, particularly of existing buildings. As industry already implements EEMS on isolated levels of building-related energy flows, our expert interviews unveiled that practitioners can confirm the challenges we identified throughout the problem identification phase (e.g., inconsistent data quality and granularity and lack of emission data). Thus, having a systematic approach to designing such an efficient BEEMS that maps DPs to the identified challenges provides valuable guidance for those tasked with implementing comprehensive BEEMSs and overcoming the fragmented data landscape. As we identified throughout the expert interviews, the DPs and conceptual architecture might be most relevant for building owners in the residential (e.g., multi-tenant homes) and commercial (e.g., shopping-malls) sector. Therein, we assume large potential of verifying the applicability of our proposed DPs through large tenant structures and a heterogenous field of applications. Consequently, we also note that single-family homes may currently not be the focus of the proposed BEEMS. Our DPs emphasize the data privacy concerns of the stakeholders involved, particularly pointing towards the sensitivity of the tenant's consumption data. As data protection is a paramount concern, our DPs regarding data sovereignty and zero trust policy, as well as data verification and reliability, are particularly interesting for practitioners and future research. By providing insights on technological concepts and ensuring the validity of the processed data, we equip both stakeholders with valid starting points to be considered within the actual development of BEEMSs. Through a combined industry view on developing a joint system or system component, we strongly contribute to the joint development by overcoming communication barriers in the current energy and building sector. Our DPs and initial architecture of a BEEMS highlight the possible points of action for practitioners aiming to implement such a system sustainably and in a future-oriented manner. This is essential for enabling a collaborative approach in which trust in the system is based on the reliability of its technical components to leverage the adoption on a local and global scale. Through our multi-step approach, we transparently unveil the status of current research on BEEMS and the industry. Therein, we highlight the limitations of industry-wide implementation of BEEMS mainly stemming from the lack of scalable technological solutions, data verification mechanisms and the lack of systems to adapt to changing regulatory requirements, such as the European directive on energy efficiency (Directive 2023/1791). Consequently, we pave the way to build on our comprehensive and evaluated DP to further investigate and develop the technical design of BEEMS, that builds on technological advancements and be implemented as and industry wide solution in the building sector.

Practitioners, who implement a BEEMS, should first aim for creating an industry-wide network considering the mentioned stakeholders of the BEEMS and align their efforts with broader sustainability initiatives, such as renewable energy adoption and carbon offsetting as these aspects are crucial for the long term and industry wide implementation of the envisaged BEEMS architecture. Second, the industry may prioritize comprehensive data collection using advanced data capturing methods and standards as this forms the basis for the later processing. Third, as the success of the BEEMS strongly relies on fostering technological solutions (e.g., distributed data bases; ZKPs) to ensure the verifiability of the utilized emission data, these technological concepts may be considered during the specification and further development of the system. Building on the identified six DPs is essential and already paves the way for a stakeholder-centric and emission-data based system.

Conclusion and outlook

Our work aims to shed light on the highly-relevant topic of decarbonizing the operation of buildings against the background of Energy Informatics research by focusing on developing DPs for BEEMSs. Grounded in a design oriented research approach, we establish six DPs and a conceptual architecture for a BEEMS that underpins emission-reduction initiatives through comprehensive data collection and verifiable data processing. By answering our research question and conducting a structured literature review, we synthesize existing concepts for BEEMSs, thus contributing to the body of knowledge on the steadily increasing Energy Informatics domain concerning the design and development of BEEMSs. Moreover, we enrich existing knowledge with practical insights from research and industry experts, such as energy production and management. Therein, we focus on the energy-related GHG emissions within a buildings' operational use and contribute to the field of Energy Informatics as provider of applicable tools and mechanisms to facilitate the sustainable transformation of the building sector. With our work we single out the need for verifiable data as the underlying imperative to facilitate the functionality of BEEMSs. Furthermore, our findings unveil the importance of protecting the collected data (e.g., individual energy consumption behavior) and highlight the systems usability as a critical enabler for its successful adoption. By doing so, our work is the first to significantly underline the obligation to combine verifiable, yet privacy-preserving data of energy flows with decarbonizing the operation of buildings.

As this study offers valuable insights, it is essential to acknowledge its limitations. First, following a sequential DSR-oriented approach poses limitations in the applicability of the derived DPs and the conceptual architecture. Although we referenced initial technological concepts (e.g., Babel et al. 2022), the practical viability of our DPs remains unexplored. Moreover, during the interviews, the experts discussed additional design considerations and obstacles for creating and deploying a BEEMS. In particular, they mentioned aspects such as the incorporation of tenant-side energy provision and the integration of the system into current energy markets. However, given the study's objective to establish foundational DPs and outline the BEEMS conceptual architecture, these challenges were not examined in depth. Therefore, future research should carry out a pilot implementation to test and validate the principles and architectures' effectiveness and practical applicability. In this context, first a detailed analysis on suitable technologies must be carried out, taking into account the results of this research article. Further, despite having interviewed experts from industry and research with diverse fields of expertise, their opinion on the presented DPs is driven by their personal background and assumptions thus limiting the generalizability of the results. As a result, we urge further research to explore the technological advancements and practical implementation of BEEMSs and foster partnerships with energy suppliers and distributors to test the relevance and thoroughness of our identified DPs. Future studies should consider broadening the field of experts and evaluation methods (e.g., user surveys or mockups) to accurately verify the applicability of their findings and incorporate novel view points on the DPs and the conceptual architecture. In addition, the siloed storing of building related data and the lack of verifiable energy and emission-related data in the building sector is a major limitation when developing a BEEMS. Thus, future research could provide helpful insights by identifying means and pathways to address the lack of available data, develop standards and overarching best practices to provide a comprehensive data base for BEEMS. Additionally, the implementation of BEEMS might cause additional costs for individual stakeholders and raise questions of hosting and managing its infrastructure. As already identified during the interviews, this might be a major limiting factor for the system's adoption. Consequently, future researchers might delve into a long-term cost benefit analysis of the systems implementation from different stakeholder perspectives to provide a sound argumentation for the implementation of the BEEMS. As highlighted through DP6 the usability of the BEEMS is essential to ensure its adoption among different stakeholder groups. Therein it is essential to understand the role of building occupants and their energy consumption behavior to carefully design the user interface and adjust the system's functionality accordingly. Accordingly, future research on the development of a BEEMS should also consider theoretical foundations outside the IS research domain, such as behavioral science, to understand the tenants' energy consumption behavior and patterns better and incorporate the findings into the design of the BEEMS.

BEEMSs hold the potential to support the building sector's sustainable energy transition by facilitating energy consumption decisions based on emission data. The accurate and end-to-end tracking of energy-related emissions on a unified and standardized data platform would significantly reduce emissions associated with building operations. Integrating modular BEEMS components into the existing systems sector could substantially benefit energy providers and consumers and improve data quality and accessibility. Leveraging technological innovations such as Distributed Ledger Technologies and Digital Identities could enable secure and reliable data exchanges, enhancing the management of energy consumption within the sector. This approach aligns with the sustainability goals of the building sector and opens avenues for increased efficiency and accountability in energy consumption.

Abbreviations

BEEMS	Building Energy Emission Management System
BEMS	Building Energy Management System
BIM	Building Information Management
DSR	Design Science Research
DP	Design Principle
EEMS	Energy Emission Management System
EMS	Energy Management System
GHG	Greenhouse gas
Green IS	Green Information Systems
IS	Information Systems
IT	Information Technology
MR	Meta-Requirement

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Author contributions

M.K.: Conceptualization. Supervision, Validation. Writing—Review and Editing. T.K.: Conceptualization, Design. Writing—Original Draft. J.R.: Project administration, Conceptualization, Design. Writing—Original Draft. J.S.: Supervision, Writing—Review and Editing. All authors read and approved the final manuscript.

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Data availability

No datasets were generated or analysed during the current study.

Declarations

Competing interests

The authors declare no competing interests.

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