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Impact of space utilization and work time flexibility on energy performance of office buildings

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ABSTRACT

This study investigates the impact of different space utilization on energy use intensity, heating load, cooling load, and thermal comfort of occupants using a combination of empirical data gathering and simulation-based studies. The increasing worldwide preoccupation with energy consumption and environmental sustainability has led to increased attention on optimizing interior spaces to mitigate total energy demand. The considered case study for conducting this research was the Norwegian living lab namely Zero Emission Building (ZEB) Flexible Lab in Trondheim, Norway. In this study, 10 different scenarios of occupancy schedules based on flexible arrangements from standard workweeks to extensive remote work configurations were designed and analyzed using IDA ICE 5.0. The findings demonstrate significant reductions in energy use across scenarios with increased teleworking and compressed work weeks. The remote scenario achieved the most significant decrease in Energy Use Intensity (EUI), with a reduction of 46 % compared to the base case. Similarly, the implementation of flexible hours and remote working in scenarios resulted in a reduction of electric heating demand by up to 23 %, underscoring the potential of occupancy-based strategies in enhancing building energy efficiency. However, uncomfortable hours increased by 59 % in the 2-day remote working scenario compared to the base case, demonstrating the need to consider climate conditions when implementing remote work. The research offers valuable insights into the complex connections between flexible arrangements and energy efficiency, considering many elements such as occupancy schedule and use dynamics. This article offers a comprehensive analysis that may give architects, building managers, and policymakers valuable insights. This study contributes to the developing sustainable architecture by emphasizing the impact of dynamic occupancy on the energy performance of office buildings.

Abbreviations:

The National Telecommuting Initiative	NTI	The American Society of Heating, Refrigerating and Air-Conditioning Engineers	ASHRAE
Economic Cooperation and Development	OECD	Phase Change Material	PCM
Gross Domestic Product	GDP	Photovoltaic	PV
Flexible Work Arrangements	FWA	Domestic Hot Water	DHW
Activity-based (flexible) Offices	A-FO	solar heat gain coefficient	SHGC
Energy Performance in Buildings Directive	EPBD	Expanded Polystyrene	EPS
Zero Emission Buildings	ZEB	Air Changes per Hour	ACH

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Heating, Ventilation, and Air Conditioning	HVAC	Normalized Mean Bias Error	NMBE
Carbon Dioxide	CO2	Coefficient of Variation of the Root Mean Square Error	CV(RMSE)
Indoor Climate and Energy	IDA ICE	Root Mean Square Error	RMSE
Energy Use Intensity	EUI	Scenario	SC
EnergyPlus Weather File	EPW	Indoor Overheating Degree	IOhD
Norwegian University of Science and Technology	NTNU	Indoor Overcooling Degree	IOcD
Variable Air Volume	VAV	Building Management Systems	BMS

1. Introduction

1.1. Background

Energy efficiency in office buildings has become a critical focus in contemporary architectural design and sustainability efforts. The configuration and utilization of office spaces play a pivotal role in determining energy consumption patterns and overall building efficiency. It is evident that offices are substantial consumers of energy, comprising 40 % of energy use in commercial buildings, and usually are the focus of cost-cutting measures involuntary by corporate facility owners and managers [1]. There has been a gradual but rising interest in making buildings more energy efficient and adding to a sustainable earth-friendly environment. In Europe, service buildings account for around a quarter of the total useable floor area, with office space accounting for another quarter [2]. In contrast to residential buildings, service buildings demonstrate a greater energy consumption per square meter, representing approximately one-third of the total energy used for space heating, ventilation, and hot water [3]. Office spaces that are primary users of energy in commercial buildings are the initial focus of the movement toward sustainability and thus are a prime target for energy reduction measures [4,5]. The study of energy performance in office buildings has become increasingly important in light of sustainability efforts and a desire to lower the costs of operating office buildings. As a result, the responsible management of resources needs to decrease the energy consumption of office buildings.

Various studies have delved into the intricate relationship between spatial design and energy performance [6–9]. This scholarly exploration investigates how different spatial layouts, configurations, and utilization strategies impact energy consumption within office premises. Research has highlighted the significant influence of space organization on heating, cooling, lighting, and overall energy use intensity [8,10]. Moreover, the interplay between architectural spatial design and energy efficiency in office buildings is analyzed by Papadakis et al. their results showed that the efficient utilization of space can directly affect occupants' thermal and visual comfort, further emphasizing its multifaceted significance [11]. Different studies explored various layout configurations and their respective impacts on energy consumption patterns, aiming to provide insights into optimizing office spaces for enhanced energy performance [12–15]. In this paper, 'space utilization' refers to how office spaces are occupied and utilized, including aspects such as number of occupants, occupancy density, and the duration of use across various work schedules. This study investigates the relationships between different occupancy patterns such as compressed workweeks, remote workdays, and flexible work arrangements with the energy performance of buildings, and how they affect the energy efficiency of office buildings.

1.2. Towards flexible working hours

The phrase "new way of working" specifically denotes flexible work arrangements, encompassing telecommuting, hybrid work schedules, and compressed workweeks. These work habits modify conventional office occupancy patterns by decreasing the frequency of employees' physical presence in the workplace. An examination of spatial arrangement frequently accompanies an evaluation of interactions. While an open layout may facilitate greater collaboration, it may also introduce disturbances and a dearth of privacy [16]. Conversely, confined cubicles offer opposing advantages in terms of commotion and privacy. According to the 2021 US Remote Work survey, only 21 % of employers believed that full-time employee presence in the office was mandatory, while 55 % of employees preferred to work remotely a minimum of three days per week [17]. Despite these findings, 87 % of employees maintained the belief that a physical workspace was indispensable for effective collaboration. The rise of flexible work setups, including remote work and co-working spaces, has revolutionized traditional office structures. These alternatives offer diverse and adaptable designs, allowing for multi-use spaces and cost-effective solutions [18,19]. Their impact on energy consumption within these varying work environments has become a pivotal consideration in optimizing energy-efficient building design [20].

In the public administration of the United States, experiments with remote work had already launched in the 1970s. The National Telecommuting Initiative (NTI), established by the US Federal government in 1996, aimed to facilitate part-time remote work for 160,000 federal employees by October 1998 and 160,000 by the end of 2002 [21–23]. The pandemic served as an impulse for transformation. Although flexible working options, such as the ability to choose one's work location and hours, were already prevalent in the Organization for Economic Cooperation and Development (OECD) countries before the pandemic, the COVID-19 pandemic and resulting lockdowns in several countries further increased the frequency of flexible working arrangements [24]. It is noteworthy to emphasize that the OECD comprises 38 member nations and Norway is one of these countries. The OECD collectively represents around 60 % of the worldwide Gross Domestic Product (GDP), 75 % of global commerce, over 90 % of global official development assistance, 50 % of global energy consumption, and 18 % of the global population [25,26].

The concept of 'flexibility' has become a fundamental element in contemporary work environments, signifying a significant departure from traditional approaches and aligning with the demand for flexible work arrangements [27]. The shift toward flexible working paradigms is propelled by significant societal and organizational changes, such as digitalization and decentralization, which have reshaped traditional workplace norms [28]. Digitalization and decentralization, which have collectively redefined where and how work can be performed, are the primary forces underlying these transformations. Working under the umbrella terms "Flextime" and "Flexplace," Flexible Work Arrangements (FWA) encompass a variety of work modalities that permit flexibility with regard to the timing of work [29]. Adopting the philosophy that work can be both an organized and flexible experience, this progressive approach seeks to harmonize work dynamics with the complicated framework of modern life. The advent of the 4-day workweek presents a transformative shift in the traditional five-day work model. Explored as a path to enhance employee well-being and productivity, this innovative approach alters office occupancy patterns and usage dynamics. Its potential to significantly influence energy consumption patterns within office spaces requires a re-evaluation of spatial design strategies [30]. These emerging paradigms of work represent compelling avenues for reimagining office spaces and resource utilization. Understanding their implications on energy efficiency is essential for architects, policymakers, and organizations aiming to create sustainable and adaptable office environments.

The concept of the 'Flexplace' highlights a shift in the physical layout of the workplace, which is exemplified by new office arrangements such as home offices, desk-sharing models, Activity-based (flexible) Offices (A-FO), and open-plan offices [31–33]. The above-mentioned spatial flexibilities underscore the capacity of diverse work environments to enhance collaboration and task-specific productivity. An instance of how A-FO designs facilitate various activities is through the provision of appropriate workstations, which can vary from quiet zones for focused tasks to areas suited for collaboration. Furthermore, in contrast to traditional office environments, telework and home offices allow people to operate from diverse locations, thereby promoting a workforce that is exceptionally mobile and technologically linked [34,35].

Additionally, work schedules have adopted a new rhythm due to temporal flexibilities such as 'flextime,' compressed working weeks, and part-time employment, which encourage work-life balance and independence [29,36,37]. The implementation of trust-based working hours serves as an exemplification of the transition from time-centric to output-centric employment models [38, 39]. These time-related practices are indicative of a paradigm shift. Moreover, aspects of 'Content/Process' such as job sharing and autonomy [40] serve to solidify this culture of adaptability by granting employees the ability to personalize their work schedules and methodologies. By combining these aspects of flexibility, traditional work environments are transformed into dynamic ecosystems that support innovative, resilient, and sustainable organizational strategies in public administration and the broader professional domain. Fig. 1 illustrates the work and organizational terms and definitions.

1.3. Flexible working hours and energy use in buildings

Table 1 discusses the literature on how occupancy affects office building energy use in office buildings. The relationship between energy consumption and telecommuting is receiving considerable attention, especially regarding evolving work paradigms that alter conventional energy use profiles. O'Brien & Yazdani Aliabadi [41]. conducted a thorough evaluation of the energy-saving benefits of telecommuting. Their analysis revealed a complicated situation where telework can lead to energy savings in specific situations. However, it can also have rebound effects in other cases, such as an increase in residential energy consumption due to changes in commuting habits and the need for additional heating or cooling at home [41]. Kharvari et al. [42] examined the impact of telecommuting on reducing energy consumption in office buildings. They found that offices consume significant quantities of energy even when unoccupied, highlighting the need for occupancy-based technologies to optimize energy usage. Following the pandemic, the situation has become more complicated. Cortiços & Duarte [43]. reported a rise in energy use in large office buildings after COVID-19. They claimed that changes in occupancy patterns could be a potential reason for this increase.

In Norway, an amended administrative regulation pertaining to work performed in employees' homes was enforced as of July 1, 2022; it, among other modifications, strengthens the oversight of working hours. New regulations on 'home office' work (as it is referred to in Norway) replaced previous regulations with special working hours rules and specified that the same working time regulations must apply to telework and work performed from home as to work performed at the office [52]. Norway's energy policies, such as the Energy Performance in Buildings Directive (EPBD) and the Zero Emission Buildings (ZEB) initiative, emphasize reducing carbon emissions and increasing energy efficiency [53]. Although Norway is not a member of the European Union, it aligns closely with EU directives on energy efficiency for buildings. The current building regulation includes technical requirements (TEK17) for

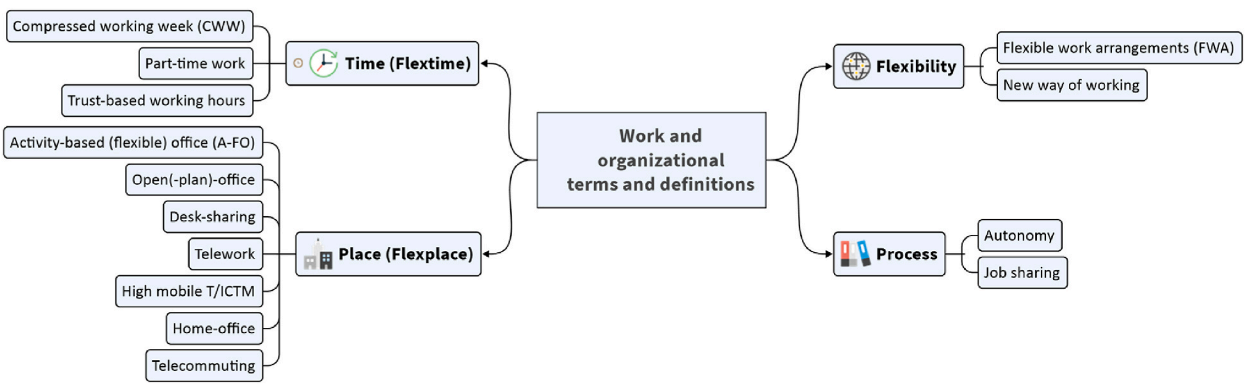

Fig. 1. Work and organizational terms and definitions.

Table 1
A review of the research on how different space utilizations affect building energy use.

Reference	Study parameters	Building type/s	Location	Study focus	Findings
[41]	Energy consumption and carbon emissions	Office, Residential	Various Locations	Telework-related changes in energy consumption	Telework's effects on energy consumption are complex, showing potential savings in some areas but rebound effects in others, depending on factors like commute distances and home sizes.
[44]	Energy consumption	Public buildings	Beijing, China	COVID-19 prevention measures	Demonstrated that personal preventative measures like mask-wearing could reduce the energy consumption for COVID-19 prevention by 20 %–60 %.
[42]	Energy consumption	Office	Canada	HVAC, partial occupancy	Offices consumed much energy even when vacant unless occupancy-based technologies were used to mitigate energy use.
[43]	Energy consumption	Office	Berlin, Germany London, UK, Paris, France Rome, Italy Madrid, Spain	Building operation post-COVID-19	Energy consumption tended to increase in large offices after COVID-19, possibly due to changes in occupancy patterns.
[45]	Lighting energy consumption	Office	Yongin, Republic of Korea	Lighting systems, automatic dimming control	Automatic dimming control can save up to 43 % in lighting energy consumption.
[46]	Cooling energy consumption	Office	Singapore	HVAC system, real-time occupancy data	An average saving of 21 % for cooling purposes was achieved by optimizing HVAC operations based on occupancy.
[47]	Energy Saving in Lighting	Office	Vienna, Austria	Lighting systems, occupancy sensors, dimming control	Energy savings of 66–71 % by using occupancy sensors combined with a dimming control system.
[48]	Occupancy	Office	Wisconsin, USA	HVAC interactions, ABM	Agent-based modeling estimated real-time occupancy accurately, improving interactions with building service systems.
[49]	HVAC energy consumption	Office	Pittsburgh, USA	HVAC system, occupancy diversity, climate conditions	Occupancy diversity has significant impacts on HVAC energy consumption in different climate conditions.
[50]	Energy consumption and thermal satisfaction	Office	Maryland, USA	HVAC strategies, occupancy	Implementing space match strategies resulted in up to 22 % cooling electricity savings and a 15.7 % increase in comfort probability across all simulated scenarios.
[51]	Energy consumption	University	Trondheim, Norway	Heating use profiles, scenarios for energy use	Unchanged heating use levels during the lockdown despite reduced occupancy and discusses scenarios to optimize heating efficiency, highlighting potential energy savings and adaptive strategies for future disruptions.

U-values of the building envelope as well as Heating, Ventilation, and Air Conditioning (HVAC) parameters and maxima of annual total net energy needs for different usages. These regulations are further reinforced by the Norwegian Standard such as NS 3700 and NS 3701 for low-energy and passive houses [54].

Norway has done its development of the definition ZEB, which not only involves energy consumption and energy production but also the carbon dioxide (CO2) balance of the building [55]. The Norwegian Research Center on Zero Emission Buildings defines five levels of ambition, from calculation of energy use in operation phases to comprehensive life cycle assessment including emissions from energy use, materials, construction processes, and waste scenarios [56]. This study contributes to this agenda by illustrating the potential for flexible occupancy arrangements to reduce energy use in office buildings, thereby aligning with national energy reduction objectives. Particularly as remote and flexible work becomes more prevalent post-pandemic, the findings could inform strategies that balance thermal comfort with energy savings, given the cold climate in Norway.

1.4. Scope of the study

This paper investigates the impact of flexible working hours on the energy performance of office buildings within the context of cold climate countries. Where, the potential of heating energy saving is usually limited in the residential buildings that are continuously heated regardless of the occupancy present. The authors focused on office buildings rather than residential buildings due to several reasons motivational in the context of Norwegian buildings, as well as other cold-climate countries. On the one hand, residential buildings exhibit a high level of insulation specifically in Norway, and maintain fixed heating set point throughout the day and night [57]. The enhanced insulation standards reduce heat loss, making residential buildings less prone to fluctuations in occupancy regarding heating demands. Therefore, the energy savings that could be realized through remote working in residential settings are limited.

On the other hand, office buildings exhibit more variability in energy use due to dynamic occupancy patterns, making them more suitable for evaluating energy-saving potential during remote work periods compared to residential buildings [41]. The "smart readiness" level of office buildings, particularly those that are modern, is generally higher than that of residential buildings [58,59].

Office buildings are equipped with smart building management systems (BMS) and intelligent controls that can dynamically adjust HVAC, lighting, and other systems following the occupancy schedule [60]. Consequently, the adaptability of office buildings in terms of energy management is much higher than residential and has a greater potential for energy savings when occupancy is reduced, such as during remote work scenarios. Last but not least, office buildings generally have higher energy use intensity (EUI) owing to the requirements of HVAC systems, lighting, and equipment [42]. The fluctuation in office occupancy during remote work directly affects energy use, while home energy usage remains relatively stable. The study of office buildings provides valuable insights into enhancing energy efficiency via flexible work arrangements, especially considering the growing prevalence of remote working.

1.5. Aim and contributions

Despite several studies on energy performance and occupancy effect in office buildings [41–43,45,49,61–64], there is relatively less research that couples both. In addition, very limited studies incorporate occupancy scenarios and building spatial layouts to forecast the impact of space utilization on energy performance in office buildings. The existing research is mainly focused on dynamic occupancy situations, examining patterns of space utilization across a given period based on a different space utilization pattern in real-world office spaces. Nevertheless, a few research studies exist regarding dynamic occupancy scenarios that accurately replicate the changes in office space use observed in real-world settings. The significance of these dynamic patterns is in their capacity to capture the fluctuations in energy use and provide prospective solutions for optimization that can effectively respond to changing occupancy requirements. This approach simplifies the complexity of office environments in the real world, where occupancy patterns frequently fluctuate throughout the day, week, and year. Inadequate research accurately modeling and simulating these dynamic occupancy scenarios creates a significant divide. Dynamic occupancy scenarios are essential for depicting the transitory nature of office spaces, which experience fluctuating levels of occupancy due to meetings, events, flexible work hours, and seasonal changes. To address this disparity, it is imperative for research to devise approaches that effectively capture the complexities associated with varying occupancy patterns and evaluate their direct influence on energy consumption. This will enable the development of more precise prediction models. Most research concentrates on the assessment of energy performance and occupancy patterns within short-term durations [41,42,47,65]. Nevertheless, there is a gap referring to the examination of the ongoing consequences of space usage techniques on the overall functionality of buildings. Long-term research, which investigates the long-term impacts of various consumption patterns, including flexible arrangements, can provide valuable insights into the sustainability and resilience of office buildings.

This research offers a novel perspective examining the impact of the “new way of working” trend on energy performance. As organizations adopt flexible working arrangements such as remote working models and compressed working weeks, new challenges and opportunities emerge that go beyond conventional energy consumption concerns. Examining the effects of remote work, reduced office hours, the new approach of the four-day workweek worldwide, and altered occupancy patterns, this paper provides unique insights into how these changes affect energy demand and building operations. Taking on the challenges and capitalizing on the opportunities presented by this new paradigm places the research at the pioneering of addressing the changing requirements of the built environment. Furthermore, the authors used the real case study office building, which was a high-performance building, and calibrated it with real data. Therefore, using a real case study allows for a detailed, site-specific analysis of energy consumption under different occupancy scenarios. Also, combining simulation-based studies with empirical data gathering provides a robust methodological approach that enhances the reliability of the study findings.

The novelty of this research lies in its focus on the dynamic interplay between flexible work arrangements and energy performance in office buildings, particularly within the context of Norway’s cold climate. This study aims to provide a comprehensive analysis of how different occupancy scenarios affect energy use intensity, heating, cooling loads, and thermal comfort. Our innovative approach extends beyond traditional energy studies by linking the adoption of flexible working arrangements to broader socio-economic factors, such as energy availability and international policy shifts. By analyzing the interaction between these elements, our research offers strategic insights into how office buildings can be designed and operated to remain resilient against both current and future energy challenges. This paper not only advances the theoretical framework of building energy efficiency but also provides practical guidance for architects, policymakers, and facility managers looking to navigate the evolving landscape of work and its impact on the built environment.

The structure of this paper is as follows: Section 1 reviews the literature on energy performance and occupancy in office buildings, identifying gaps our study seeks to address, especially in terms of dynamic occupancy scenarios. Section 2 details the methodology, including data collection and simulation processes using Indoor Climate and Energy (IDA ICE) 5.0, focused on the ZEB Flexible Lab case study. Section 3 presents the simulation results, analyzing the energy and thermal impacts of various flexible work scenarios. Section 4 discusses the findings, emphasizing their implications for sustainable building management and design, suggesting future research directions, and discussing policy implications derived from the results. Finally, Section 5 concludes by summarizing the study’s contributions and findings. This organization ensures a systematic exploration of the effects of flexible work arrangements on building energy efficiency.

2. Methodology

The methodology of this paper outlines a systematic framework that incorporates simulation techniques and empirical data to evaluate the energy performance of buildings. Methodological rigor and analytical depth are ensured through the sequential development of each phase of the approach. The methodology encompassed three main steps, commencing with the data collection. Subsequently, the creation of a simulation data set and data analysis, including the investigation, progressed with a parametric simulation and subsequent analysis of the obtained data, culminating in the formulation of specific suggestions, as depicted in Fig. 2.

Data collection involved gathering empirical data and climatic data related to the case study building; simulation involved creating energy models with differing occupancy scenarios; and analysis involved evaluating the impact of different occupancy scenarios on energy performance using key indicators such as EUI, heating, and cooling loads which elaborated upon in the following sections.

2.1. Data collection

Data collection utilized sensors to monitor indoor temperature, outdoor temperature, and metered data regarding energy use within the living laboratory. The sensors delivered real-time data regarding temperature, HVAC utilization, and lighting conditions.

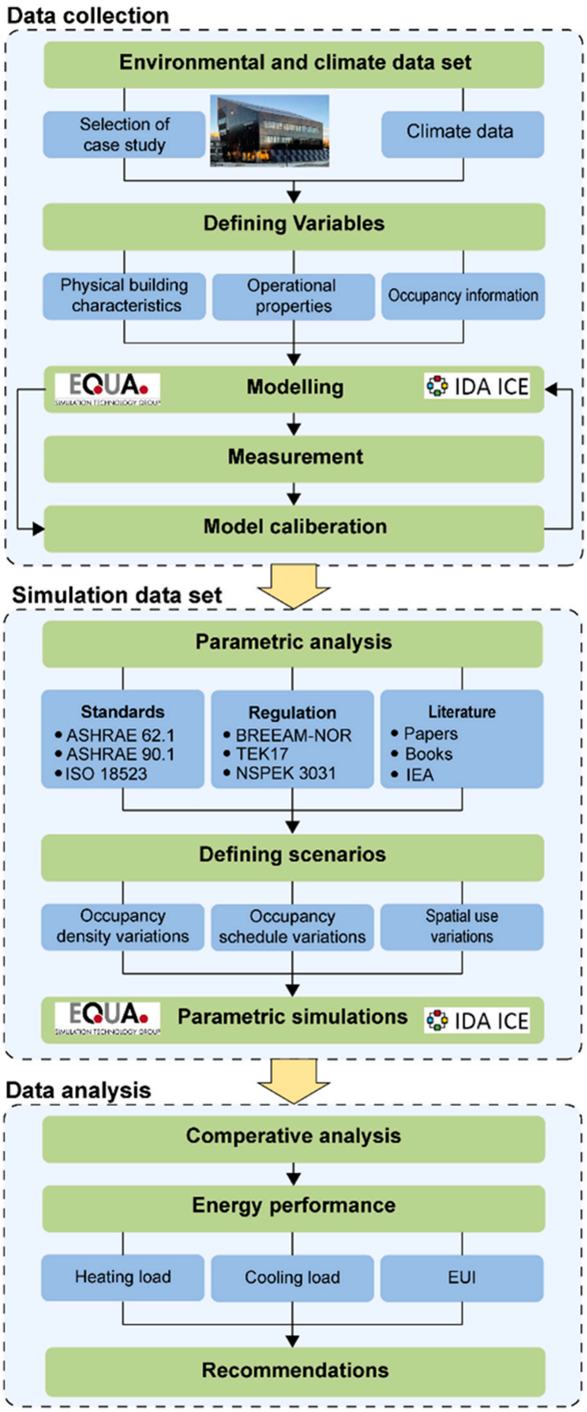

Fig. 2. Detailed conceptual study framework.

Data verification was conducted through cross-referencing with metered data and other statistical validation methods to assure precision. In the first step of the methodology, environmental and climatic inputs were gathered through data collection. The process begins by choosing a suitable building as a case study, which is subsequently followed by gathering climate data that is pertinent to the location of the building. To this end, ZEB-lab, a nearly zero-energy [66] and zero-emission building in Trondheim was chosen as a case study. Afterward, we carefully establish the variables expected to impact the energy efficiency of the case study building. Apart from climate data, the physical characteristics of the building, operational properties, and occupancy information of the case study building were gathered based on the real data collected and used as input variables for the building's energy simulation model. Then, the simulation model was calibrated based on the real input variables. The variables are categorized into three distinct groups: the physical features of the building, its operational properties, and the occupancy information.

2.1.1. Environmental and climate data set

2.1.1.1. Climate data. The climate files from the weather station located at the Gløshaugen campus near the ZEB Flexible LAB have been compiled and utilized as EnergyPlus Weather File (EPW) in the building simulations for the implementation of different scenarios. Norway has a cold climate, and more than half of the building's energy roughly is used for space heating [67,68]. The cooling demand is low but has increased during the past decades [69].

This research was conducted on the Norwegian University of Science and Technology (NTNU) campus in Trondheim, Norway. The city is located at a latitude of 63.4° North, has a population of 200,000, and is situated on the coast of a large fjord. The NTNU campus (Gløshaugen) is located approximately 1.5 km south of the city center at an elevation between 38 and 49 m above sea level. The Koppen-Geiger climate classification for Trondheim is oceanic (Dfb), but it boarders continental, subarctic, and subpolar climates [70]. From November to March, moderate snowfall is typically interspersed with periods of pleasant weather and rain. With a mean annual temperature of 4.8 °C (1961–1990), the climate is quite cool, with relatively brief and mild summers and lengthy and calm winters [71]. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE)169–2013 classification [72] provides additional information about the climatic conditions of Trondheim. Fig. 3 depicts dry bulb temperature during a year. As presented in Fig. 3 the dry bulb temperature, it becomes evident that the highest temperatures occurred in July, approaching 25 °C. Conversely, the lowest temperatures were recorded in January and February, dropping to approximately −5 °C.

2.1.1.2. Case study selection. A structured form of telework may be provided, whereby staff members habitually spend one to two days per week away from the workplace or work sporadically. Telework allows most employees to work from home [73]. Nevertheless, a few countries, such as Nordic countries, also provide telework stations in various regions for the benefit of their personnel. Teleworking is the most prevalent form of spatial flexibility offered. Telework can be provided to employees in a structured or ad hoc fashion, with employees working remotely for one to two days per week on average or on an as-needed basis. Based on this research, telework options are utilized by approximately 75 % of public administration personnel in Denmark, the Netherlands, and Norway which represented the high potential of this method in Norway as our case study (see Fig. 4).

The beginning of the design project can be traced back to 2016, marking the commencement of a precise and challenging creative endeavor. The construction phase commenced in May 2019, followed by the laboratory's official opening and operational preparedness in March 2020. The ZEB Flexible Laboratory is a full-scale building with several interchangeable façades, parts, and technology components. The system's versatility enables the exploration of many configurations, technologies, and functionalities. Currently, the building serves dual duties as a conventional office building and a facility for educational activities. It plays a crucial role in supplying ongoing and up-to-date experimental data, essential for testing and validating emerging technologies.

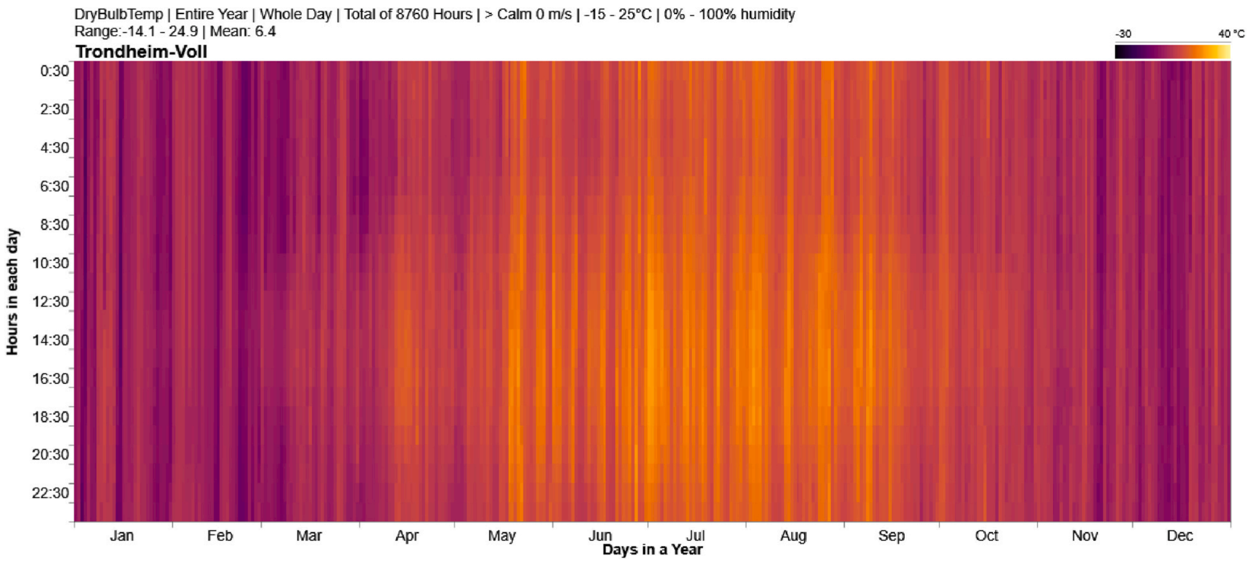

Fig. 3. Dry bulb temperature during a year.

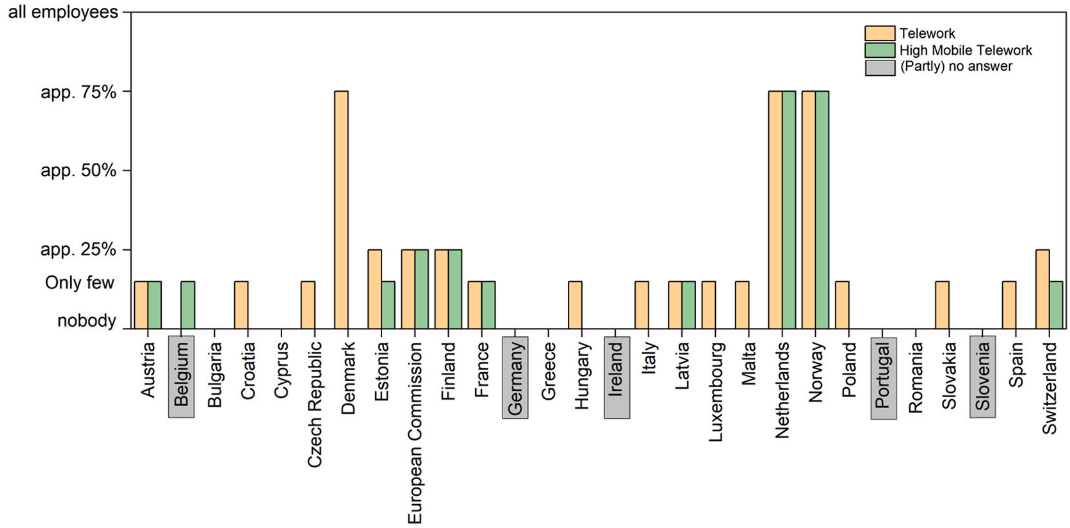

Fig. 4. Telework and high mobile telework in European countries (modified from Ref. [73]).

Moreover, it facilitates mitigating the potential risks associated with implementing zero-emission buildings in the future [74]. The building element comprises a four-story living laboratory, encompassing a total floor area of 1742 m^2. The facility plays a role in advancing knowledge related to ZEB. It serves as a platform for conducting experimental research on the interaction between users and buildings, as well as a large-scale laboratory for testing new technologies [74]. Fig. 5 represents an overview of ZEB Flexible Lab.

Photovoltaic (PV) panels are strategically included over the entirety of the roof surface and extensively envelop various sections of the façade, therefore facilitating the acquisition of ample renewable energy. The ZEB-lab is characterized by its small physical footprint

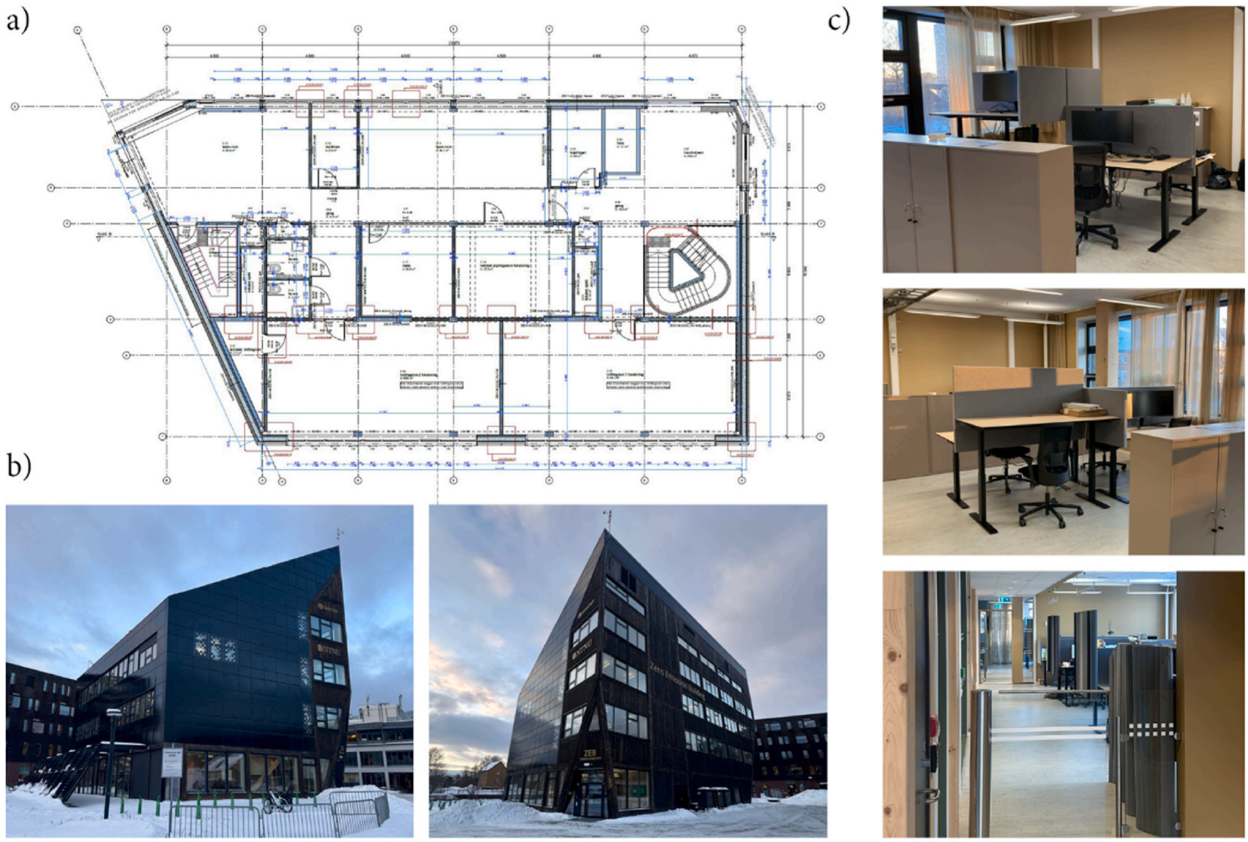

Fig. 5. Overview of the case study building (ZEB Flexible Lab) located in Gløshaugen campus; a) Second-floor plan; b) Exterior views; c) Interior view of office rooms.

and its structural framework constructed from wood, which serves as a load-bearing system. Additionally, the building envelope of the ZEB-lab exhibits exceptional insulation properties and airtightness. The provision of space heating is facilitated by utilizing a waterborne system powered by an air-source heat pump and connected to a nearby heating grid. The heat pump further offers space cooling to a pair of modest research facilities known as the twin rooms. The ZEB Flexible Lab employs a hybrid ventilation strategy that integrates both natural and mechanical ventilation, complemented by a remarkably efficient heat recovery system. Mechanical ventilation primarily relies on a Variable Air Volume (VAV) system that delivers air flows in response to temperature and CO2 levels.

2.1.2. Defining variables and modeling

This step defined various variables to model the case study building. The building model was created based on the gathered data in the previous step. In the dynamic simulation software IDA ICE, version 5.0 beta [75], a full model of the case study building was developed for all scenarios. IDA ICE was validated in numerous studies following CEN and ASHRAE standards [76,77]. Several studies [78,79], examined the possibility of modeling different strategies to improve the energy performance of buildings in IDA ICE [80,81]. evaluated and validated the prediction accuracy of IDA ICE for Phase Change Material (PCM) simulation compared to experimental results. In addition, IDA ICE's PV energy generation calculation accuracy was validated, as shown in Ref. [82].

The energy simulation inputs for the case study building model are shown in Table 2. The heating set points are dynamically modified based on occupancy. For simulations, the effect of varying occupancy schedules on energy performance in different scenarios is considered. Although occupancy schedules are the main variable, the heating and cooling loads are also considered and affected by the patterns of occupancy. The cooling operations are designed to regulate the indoor temperature at 24 °C. The ventilation parameters consist of 25 L/s/m^2 supply flow rates and supply air temperatures ranging from 17 °C to 24 °C. These parameters are adjusted according to the exhaust air temperature. The system functions with a defined fan power of 1 kW/m^3/s°C and includes a rotary heat exchanger that achieves an 85 % efficiency in recovering heat. The estimated annual Domestic Hot Water (DHW) usage is 5 kWh/m^2. The building has a PV panels system that covers 502 m^2 on the façade and 456 m^2 on the roof. The average efficiency of the panels on the façade is 16.90 %, while the panels on the roof have an average efficiency of 21.50 %. These panels are made of monocrystalline silicon. The building's design incorporates 83 kWp of installed capacity for the façade and 98 kWp for the roof, effectively maximizing the utilization of renewable energy. These simulations are essential to our approach to evaluating the energy efficiency and sustainability measures of the building.

Table 2
Input properties of case study building for energy simulation.

Energy simulation input Parameters	Value	Note
Heat pump, COP	3.8	Air-to-water heat pump
Heat pump, total heating capacity	30 kW	
Heating setpoint	21 °C (07:00–17:00 Monday-Friday, occupied building) 20 °C 07:00–24:00 Monday-Friday, non-occupied building, 15 °C 22:00–07:00 every day	
Heating distribution system (supply/return temperatures)	47/35 °C	Waterborne radiator system
Cooling setpoint	24 °C	
Ventilation supply flow rates	25 L/s/m^2	
Ventilation, supply air temperature	17–24 °C	Based on the exhaust air temperature
Ventilation, specific fan power	1 kW/m^3/s °C	
Ventilation, heat recovery efficiency	85 %	Rotary heat exchanger
DHW, average hot water use	5 kWh/m^2/year	
PV area	502 m^2	
PV roof, area	456 m^2	
PV facade, average efficiency	16.90 %	Monocrystalline silicon
PV roof, average efficiency	21.50 %	Monocrystalline silicon
PV facade installed capacity	83 kWp	
PV roof, installed capacity	98 kWp	
U-value, external walls	0.15 W/(m^{2}K)	Wooden frame with 300 mm mineral wool insulation
U-value, windows/door	0.77 W/(m^{2}K)	Triple-glazed with argon filling and wood frame
The solar factor of windows	0.53	
Visible transmittance	0.71	
Windows	0.09 W/(m^{2}K)	
U-value, roof	0.10 W/(m^{2}K)	Wooden structure with 450 mm mineral wool insulation
U-value, slab on ground	0.04 W/(m^{2}K)	The concrete slab is on 250 mm of EPS insulation. Equivalent U-value for ground transmission
Infiltration rate at 50 Pa	0.3 ACH	
Window-to-wall ratio	27 %	

The U-value of the external walls is 0.15 W/(m^2K), which is achieved by using a wooden frame with 300 mm of mineral wool insulation. The windows and doors possess a higher U-value of 0.77 W/(m^2K), which can be attributed to the utilization of triple-glazed units with argon filling and wooden frames. The windows have a solar heat gain coefficient (SHGC) of 0.53, which is also referred to as the solar factor. Additionally, they have a visible transmittance of 0.71, allowing for the use of natural daylight while controlling the amount of solar heat entering the space. The U-value of the windows is significantly low, measuring at 0.09 W/(m^2K), which indicates a high level of thermal resistance. The roof has a U-value of 0.10 W/(m^2K), which improves the building's ability to retain heat. The ground floor consists of a concrete slab that is insulated with 250 mm of Expanded Polystyrene (EPS) insulation. This insulation has a U-value of 0.04 W/(m^2K), indicating that the floor is well-insulated and effectively reduces heat loss to the ground. The quantification of the building's air tightness is determined by an infiltration rate of 0.3 Air Changes per Hour (ACH) at 50 Pa, which serves as an indication of high construction quality and effective sealing. Finally, the window-to-wall ratio stands at 27 %, which is a well-proportioned value that ensures sufficient natural light and views without significantly compromising the building's thermal insulation.

The number of occupants in each zone is measured based on the number of chairs and the room/zones of the case study. For office rooms, each chair is assumed to represent a single occupant. Based on the logical assumptions of each zone, it is presumed that 80 % of the seats in meeting rooms are occupied and that the total number of occupants in other zones, such as hallways, restrooms, and stairwells, is generally between one and three. The number of occupants in each zone is presented in Table 3.

2.1.3. Measurements

The on-site inspections encompassed the collection of data pertaining to several physical features, including the thermal conductivity of materials, window properties, and specifications of the HVAC system. In addition, the authors monitored the number of occupants and occupant's presence on a room level to determine actual occupancy in real-world settings. The measurements presented in this study were implemented to calibrate simulation based on ASHRAE 14–2002 [83]. Then, the simulation was employed to establish the effectiveness of various flexible arrangements.

2.1.4. Model calibration

Two evaluation metrics have been employed to assess the validity of the building energy model [84,85]. The initial index is denoted as the Normalized Mean Bias Error (NMBE), as presented in the primary equation. In contrast, the second equation represents the Coefficient of Variation of the Root Mean Square Error (CV (RMSE)) [83].

$$\mathrm{NMBE} = 100 \times \sum_{i=1}^{Np} (m_i - s_i) \Big/ \sum_{i=1}^{Np} m_i \ [\%] \tag{1}$$

$$\mathrm{CV\ (RMSE)} = 100 \times \frac{\sqrt{\sum_{i=1}^{Np} (m_i - s_i)^2 \Big/ Np}}{\overline{m}} \ [\%] \tag{2}$$

where ***mi***: (i = 1, 2, 3 …, Np) denotes the monitored data points and ***si***: (i = 1, 2, 3 …, Np) denotes the simulated data points. The NMBE is a dimensionless measure that quantifies the difference between predicted and observed data at a specific time scale. The CV(RMSE) is a crucial statistical measure used widely in fields like engineering and forecasting to assess the accuracy of models and simulations. The root mean square error (RMSE) is essentially the square root of the average of the squared differences between predicted and

Table 3
Number of occupants at each zone in the case study building.

Modeled Building Zones	Number of Occupants
Ground floor south, canteen	78
Ground floor, middle zone, auxiliary	1
Ground floor, north zone, auxiliary	1
1st floor south, Tween room 1, working zone	7
1st floor south, Tween room 1, working zone	7
1st floor south, middle zone, auxiliary/meeting	1
1st floor north, working zone	9
1st floor north, auxiliary/lobby	2
2nd floor south, working zone	8
2nd floor south, meeting room 1	3
2nd floor south, meeting room 2	1
2nd floor middle, auxiliary/meeting	3
2nd floor north, working zone	12
2nd floor north, auxiliary/lobby	2
3rd floor north, teaching room	28
3rd floor north, auxiliary/meeting	15
3rd floor middle, auxiliary	0
3rd floor south, auxiliary	0
Secondary stairway	0

actual values. After adjusting for the average of the observed data, this measure is referred to as the Coefficient of Variation of RMSE. Normalization enables the comparison of error magnitudes in different datasets and models by expressing the RMSE as a proportion of the mean. This provides a relative error metric for comparative analysis. More precisely, in the context of ASHRAE 14–2002 and 2014, the CV(RMSE) is used as an important standard for evaluating the accuracy of building energy models compared to actual energy consumption data. ASHRAE 14–2002 recommends a maximum NMBE threshold of 5 % for monthly calibrated data points and 10 % for hourly calibrated data points. Moreover, the maximum thresholds for CV(RMSE) are 15 % and 30 % for monthly and hourly calibrated data points, respectively [83].

The accuracy of the simulation model was guaranteed by calibrating it against measured data. The iterative procedure encompassed the modification of factors such as thermal transmittance, solar heat gain coefficients, and HVAC system efficiencies to match the model's predictions with empirical findings. The case study model that underwent calibration has demonstrated its efficacy as a dependable instrument for forecasting the energy performance of the building across diverse scenarios.

The case study building has been monitored since it was built. The data on heating, cooling, and electrical lighting is constantly measured and stored in different time intervals. The monthly consumption data relating to the electricity (lighting, heating, cooling, and auxiliary electricity used by the HVAC system) of the whole case study building during 2023 were used to validate the simulation model. To this end, the entire building was modeled and simulated using IDA ICE, and the energy simulation and experimental measurement results are reported in Fig. 6. It is worth mentioning that the case study building energy model is studied and validated in the previous research by Moschetti et al. [86].

Fig. 6 presents a comparative analysis between measured and simulated monthly electricity usage for thermal energy in a case study building. The MBE and the CVRMSE for the electricity use were calculated as 3.70 % and 4.76 %, respectively. These values indicate compliance with the criteria outlined in ASHRAE 14–2002, demonstrating that the simulation model is adequately calibrated for the parameters of electricity consumption. Although the simulation matched the requirements, it did not accurately replicate the actual building's energy consumption patterns. The simulation results indicate an overestimation of electricity consumption during the year's initial months and an underestimation during the later months. These differences can be related to uncertainties in the simulation parameters, including fluctuations in the occupancy schedule and inaccuracies in the input weather data. Internal heat gains could have been diminished with a lower occupancy rate, which could have increased the amount of electricity used for thermal energy. Despite the observed deviations, the simulation model can be deemed adequately reliable due to the respect of calibration parameters for electricity consumption to ASHRAE standards.

The indoor air temperature of office room 1 in the case study was selected to calibrate of simulation model. Office room 1 is a south-faced façade room located on the second floor. The indoor air temperature in office room 1 was recorded via two sensors located on a wall at a height of 1.8 m, far from heat sources, at 15-min intervals. The average of measured data from both sensors was used at each time step. The hourly values were derived by averaging the 15-min measured data, as the monitoring frequency was 15 min. A sub-period of 18 days, from 6 p.m. January 1, 2023, to 3 p.m. January 18, 2023, was selected for this study. The outdoor dry bulb temperature was measured and obtained from a weather station near the ZEB Lab building (about 20m away from the case study

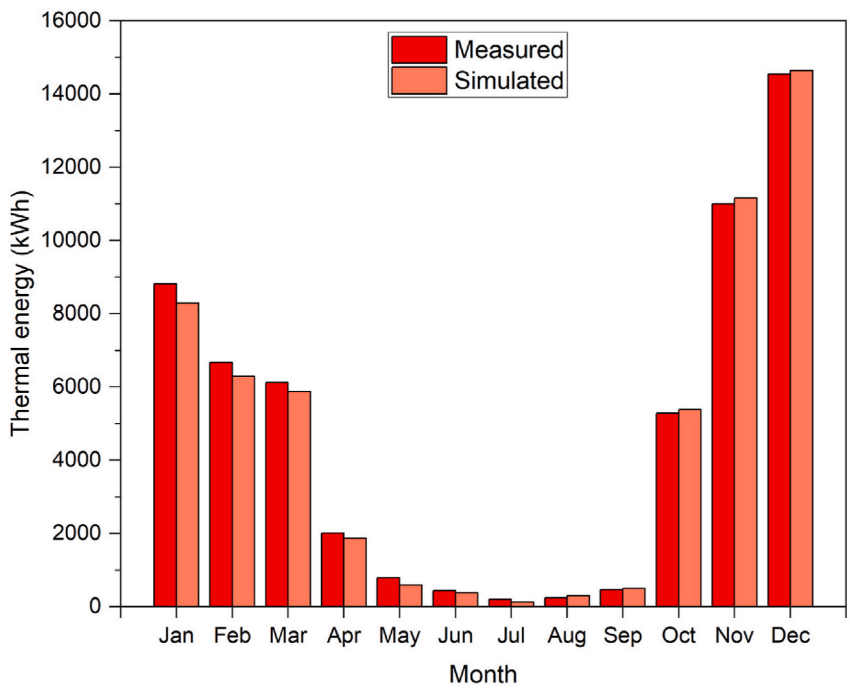

Fig. 6. Calibration values for monthly thermal energy demand.

building) on an hourly basis. The measured outdoor temperature was used in the simulation model to run the simulations. The RMSE was calculated to measure the differences between measured values for indoor air temperature and simulated ones. RMSE for the considered period was 0.156 indicating that on average the difference between measured and simulated temperature was about 0.16 °C. The different temperatures of 2 °C between the simulation and the measurement could occur, as stated by Refs. [87,88]. As shown in Fig. 7, the outdoor temperature fluctuated between −12 °C and 8 °C on January 7 and January 14, respectively. Comparing the indoor air temperature of the simulated showed satisfactory agreement with the measured data. Results depicted that simulated data predicted indoor temperature higher than measured data however the differences were smaller than 0.75 °C temperature in some hours such as January 17 at noon. These discrepancies could stem from uncertainty associated with occupancy behaviors and their actions for example opening widows during measurement periods. Consequently, the model is calibrated and suitable for conducting further energy performance assessments and implementing different scenarios.

2.2. Simulation data set of scenarios

2.2.1. Parametric analysis

This paper used different resources such as standards, regulations, and literature to define scenarios. ASHRAE 62.1 [89], ASHRAE 90.1 [90], and ISO 18523 [91] were used as standards related to occupancy and different schedules for the utilization of spaces in office buildings. Besides literature, various national standards and regulations of the energy performance of buildings in Norway, such as BREEAM-NOR [92], TEK17 [93], and SN/NSPEK 3031 [94], have been considered for scenarios.

2.2.2. Defining scenarios

As mentioned above, different scenarios were considered for this paper based on standards, regulations, and literature. Each of these scenarios is utilized in many office buildings in real practice across the world. The research examines ten specific occupancy scenarios to assess the influence of different occupancy patterns on the energy consumption of buildings. Considering these scenarios, which encompass both on-site and remote work schedules, is crucial better to understand the real-world effects of occupancy on energy consumption.

The base case scenario reflects the actual occupancy schedule of the case study building. This scenario establishes a benchmark for energy use against which other scenarios are compared. It is worth mentioning that the actual occupancy schedule is aligned with the recommended occupancy schedule of NSPEK 3031. Another scenario to consider is ASHRAE 90.1–2004 (SC02). Follows the standard occupancy schedule for office buildings as recommended by ASHRAE 90.1, serving as a guideline for optimal building operation hours.

SC03 to SC06 represent variations of a 5-day on-site workday with differing start and end times. The Early Bird Schedule (SC03) captures the energy profile for occupants who start the workday early, potentially affecting lighting and HVAC needs during morning hours. The Standard Workday Schedule (SC04) represents the standard work hours. The Late Morning Schedule (SC05) addresses the energy implications of occupants working later in the day, and finally, the Extended Day Schedule (SC06) explores the effects of a significantly late start to the workday, which may shift energy usage patterns towards the evening. Another occupancy schedule is the compressed working week (SC07), which investigates the energy consumption of occupants staying longer hours for four days in a week. Furthermore, scenarios 8 to 10 examine the impact of remote work strategies. The 1-day remote schedule (SC08) assesses the energy savings from having occupants work remotely for one day of the week. The 2-day remote scenario (SC09) offers a balance between on-site and remote work, reflecting the flexible work trends and their influence on energy consumption. Last but not least, the

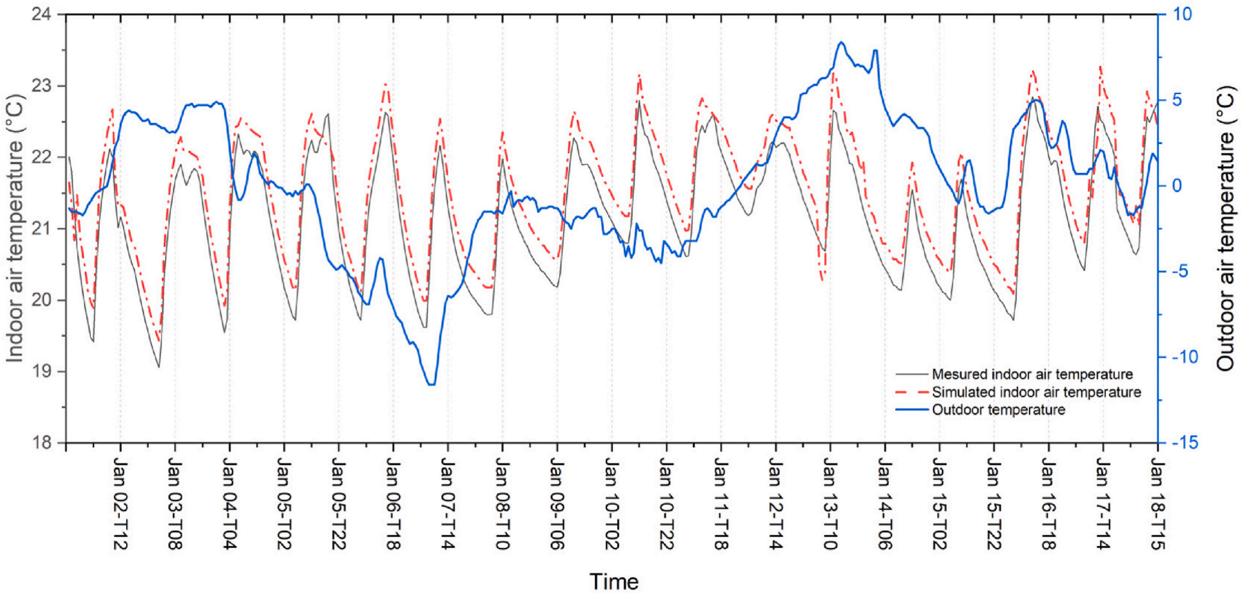

Fig. 7. Comparison simulated and measured indoor air temperature related to office room 1.

4-day remote scenario (SC10) provides insights into the energy impact of a predominantly remote work week with minimal on-site presence. Detailed information regarding each scenario is presented in Table 4. It is noteworthy that the heating setpoints for all scenarios, with the exception of the base case scenario, were taken as 21 °C and 15 °C during occupied and unoccupied hours, respectively. The heating set point for the Base case scenario was 21 °C during occupied hours from 07:00–17:00 Monday-Friday, 20 °C from 17:00–24:00 Monday-Friday when the building was unoccupied, and 15 °C from 22:00–07:00 during the nighttime every day. The ventilation supply air temperature of 17–24 °C was considered for all scenarios with different schedules based on their occupancy. The ventilation system was controlled based on indoor temperature and CO2 concentration at each thermal zone. Furthermore, lighting, heating, air conditioning systems, and office equipment for each scenario operated based on their occupancy schedules and considered set points.

2.3. Thermal comfort indices

There are two main categories of thermal comfort models: static and adaptive. In contrast to adaptive comfort models, which establish thresholds that are variable in response to outdoor weather conditions, static thermal comfort models establish fixed thresholds that indicate when an environment becomes too hot or too cold. A questionnaire is sometimes used as a tool for the adaptive thermal comfort model. In this study, ISO 17772-1 [95,96] was used for the calculation of the static and adaptive comfort model. For this study, Category II was selected, which is recommended for new and refurbished buildings. Based on ISO 17772-1, the recommended design values of the indoor temperature for buildings with mechanical cooling systems, the minimum and maximum thresholds for the operative temperature of a single office for category II were 20 °C and 26 °C, respectively.

Moreover, to evaluate the thermal performance of the building in a manner that is more comprehensive, intricate, and instructive, the Indoor Overheating Degree (IOhD) was utilized. According to Hamdy et al. [97], an asymmetric multizonal measure known as the IOhD [°C] is used to calculate cooling degree hours throughout the entire number of hours that the zones were occupied [97]. Formulas 3 and 4 are employed to calculate IOhD and Indoor Overcooling Degree (IOcD), respectively:

$$IOhD \equiv \frac{\sum_{z=1}^{Z}\sum_{i=1}^{N_{occ}(z)}\left[\left(T_{in,z,i} - T_{comf,upper,z,i}\right)^{+} \times t_{i,z}\right]}{\sum_{z=1}^{Z}\sum_{i=1}^{N_{occ}(z)} t_{i,z}} \tag{3}$$

$$IOcD \equiv \frac{\sum_{z=1}^{Z}\sum_{i=1}^{N_{occ}(z)}\left[\left(T_{comf,lower,z,i} - T_{in,z,i}\right)^{+} \times t_{i,z}\right]}{\sum_{z=1}^{Z}\sum_{i=1}^{N_{occ}(z)} t_{i,z}} \tag{4}$$

where Z [−] is the total number of building zones, z is the zone counter, $N_{occ}(z)$ [−] is the total number of occupied hours in zone z, i is the hour counter, $T_{in,z,i}$ [°C] is the indoor operative temperature in zone z at hour i, $T_{comf,upper,z,i}$ [°C] is the maximum comfort threshold in zone z at hour i, $T_{comf,lower,z,i}$ [°C] is the minimum comfort threshold in zone z at hour i.

The IOhD and IOcD are multi-zonal and asymmetric indices that enable the analysis of the occupancy profiles of each zone

Table 4
Details of considered scenarios.

Scenario	Occupancy schedules scenarios	Description	Operation hours
SC01	Base case	The actual occupancy schedule of the case study building	**Occupied Hours:** Monday through Friday, 07:00 to 17:00; **Unoccupied Hours:** Nights, weekends, and holidays
SC02	ASHRAE 90.1–2004	Occupancy schedule recommended by ASHRAE 90.1–2004 for office buildings	**Occupied Hours:** Monday through Friday, 8:00 to 18:00; **Unoccupied Hours**: Nights, weekends, and holidays
SC03	5-day (Early Bird Schedule)	Working in offices for 5 days in a week and starting to work from 07:00	**Occupied Hours:** Monday through Friday, 8 h working (07:00 to 15:00); **Unoccupied Hours:** Nights, weekends, and holidays
SC04	5-day (Standard Workday Schedule)	Working in offices for 5 days in a week and starting to work from 08:00	**Occupied Hours:** Monday through Friday, 8 h working (08:00 to 16:00); **Unoccupied Hours:** Nights, weekends, and holidays
SC05	5-day (Late Morning Schedule)	Working in offices for 5 days in a week and starting to work from 09:00	**Occupied Hours:** Monday through Friday, 8 h working (09:00 to 17:00); **Unoccupied Hours:** Nights, weekends, and holidays
SC06	5-day (Extended Day Schedule)	Working in offices for 5 days in a week and starting to work from 10:00	**Occupied Hours:** Monday through Friday, 8 h working (10:00 to 18:00); **Unoccupied Hours:** Nights, weekends, and holidays
SC07	4-day (Compressed Working Week)	Working in offices for 4 days in a week with longer stay	**Occupied Hours:** Monday through Thursday, 9.5 h working (08:00 to 17:30); **Unoccupied Hours:** Nights, Fridays, weekends, and holidays
SC08	1-day remote work schedule	Working in offices for 4 days in a week and one day remote working	**Occupied Hours:** Monday through Thursday, 8 h working (08:00 to 16:00); **Unoccupied Hours:** Nights, Fridays, weekends, and holidays
SC09	2-day remote work schedule	Working in offices for 3 days in a week and 2 days remote working	**Occupied Hours:** Monday through Wednesday, 8 h working (08:00 to 16:00); **Unoccupied Hours:** Nights, Thursdays and Fridays, weekends, and holidays
SC10	4-day remote work schedule	Working in offices for 1 days in a week and 4 days remote working	**Occupied Hours:** Monday, 8 h working (08:00 to 16:00); Unoccupied Hours**: Nights,** Tuesday to Friday, weekends, and holidays

independently. This method simplifies the utilization of zone-specific comfort models to accurately represent the occupant behavior and adaptation opportunities within a zone. This multizonal approach enables the representation of real-world conditions in buildings, including zones with variable thermal comfort models (namely, static and adaptive) and requirements (e.g., comfort categories), as well as the monitoring of the occupied hours in each zone [98]. For thermal comfort analysis, two indicators were considered: the number of uncomfortable hours based on the ISO 17772-1 recommended thresholds and IOhD [°C]. The findings of these simulations are outlined in the subsequent sections.

2.4. Data analysis

A comparative analysis is performed in the concluding stage, data analysis, to evaluate the outcomes across various scenarios. The data analysis employed dynamic modeling, empirical validation, and statistical analysis to evaluate the effects of different occupancy scenarios on EUI and thermal comfort in the ZEB Flexible Lab building. The selected tools and models, along with their corresponding approaches, were intended to guarantee precise simulation of real-world settings and to provide a comprehensive analysis of the results. Key performance indicators such as the heating load, cooling load, and EUI are thoroughly examined to assess the energy efficiency of the building. Based on the acquired insights, we develop specific recommendations to improve the building's energy efficiency. Potential recommendations could consist of modifications to the design, operations, or maintenance protocols. The framework has been carefully designed to offer a comprehensive methodology for our examination of the energy efficiency of buildings. The primary objective of the data analysis was to evaluate the energy savings and comfort implications of various occupancy scenarios in an office building. The analysis provided a clear understanding of the impact of various flexible work arrangements on the energy performance of buildings by simulating real-world conditions using calibrated models. The data analysis of findings contributes to the more extensive investigation by emphasizing on following points.

- The potential for substantial energy savings in office buildings through the implementation of flexible scheduling and remote work.
- The trade-offs between thermal comfort and energy savings, particularly in cold climates where reduced occupancy may result in increased heating demands.
- Practical insights for building managers and policymakers regarding the optimization of energy consumption through occupancy-based strategies while simultaneously preserving comfort standards.

3. Results

This section presents the results of our investigation into the energy performance and thermal comfort of case study buildings.

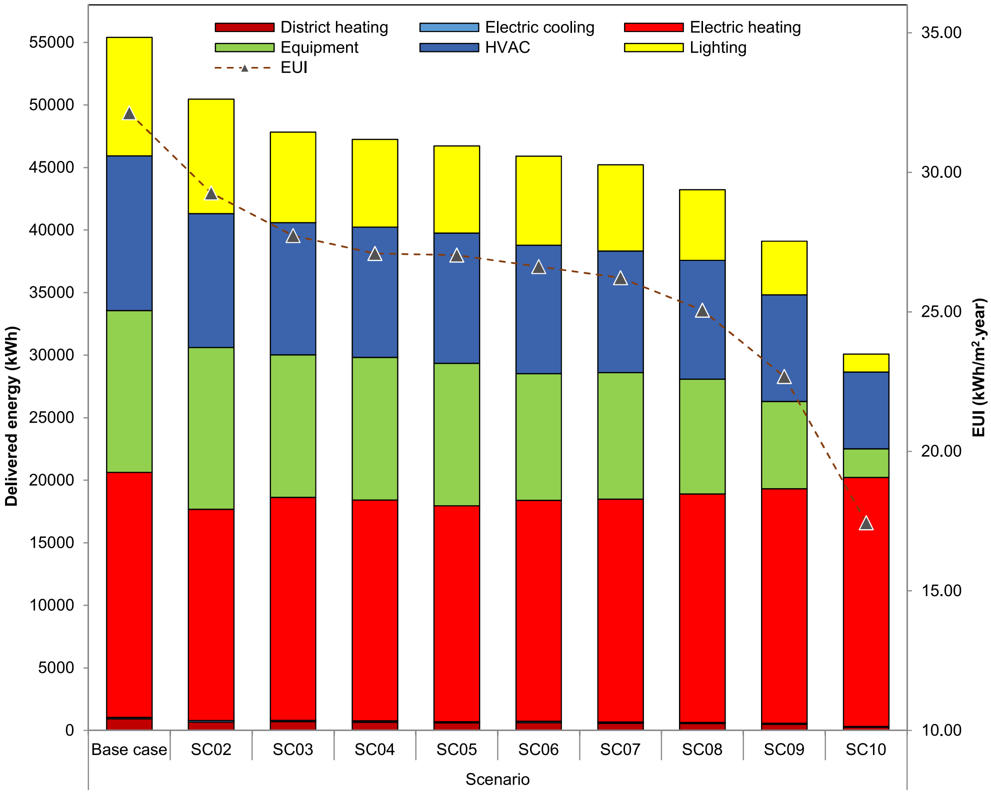

Fig. 8. Comparison of annual delivered energy and EUI in different scenarios.

Annual delivered energy, EUI, and thermal comfort analysis comprise the findings. The thermal comfort analysis is subdivided further into indoor operational temperature, indoor overheating degree, and indoor overcooling degree analyses. Each subsection details the impacts of flexible arrangements scenarios on the building's performance, providing insights into both energy consumption patterns and occupant comfort levels.

3.1. Annual delivered energy and EUI

A comprehensive analysis of the annual delivered energy and EUI in different occupancy scenarios is illustrated in Fig. 8. The analysis accounts for the intricate breakdown of energy usage into district heating, electric cooling, electric heating, equipment, HVAC and auxiliary, and lighting. The base case scenario SC01, reveals an aggregate annual delivered energy consumption of 55,401 kWh, which is followed by the ASHRAE 90.1–2016 (SC02) scenario with an annual delivered energy of 50,461 kWh. The 5-day scenarios (SC03 to SC06) have very close supplied energy with the exact value of 46,621 kWh, 47,833 kWh, 46,723 kWh, and 45,218 kWh, respectively. However, the 4-day scenario (SC07) with delivered energy values of 45,218 kWh had lower supplied energy than the 5-day scenarios. The remote working scenarios SC08, SC09, and SC10 delivered scenarios had the lowest supplied energy among all scenarios, with the values of 45,912 kWh, 39,114 kWh, and 30,083 kWh, respectively. It is evident that across all scenarios, SC01 consistently demonstrates a higher energy use, and each scenario observed a significant reduction compared to the base case. For example, the overall delivered energy of SC02 compared to SC01, with a mean difference of 8.92 %, highlighting the influence of standard occupancy practices on energy demand. To be precise, the total delivered energy for SC03 to SC10 decreased by 13.66 %, 15.66 %,15.85 %, 17.13 %,18.38 %, 21.99 %, 29.40 %, and 45.70 % compared to the base case scenario, respectively.

In district heating, the base case scenario consumed the highest amount of energy (927 kWh), while the SC10 demonstrated the lowest energy use (261 kWh), indicating a substantial reduction of approximately 72 %. This absolute difference underscores the effectiveness of remote work arrangements in reducing district heating demand. Electric heating consumption also exhibits a strong correlation with occupancy schedules. The base case scenario recorded the highest energy demand (19589 kWh), while the SC02 and SC05 consumed the least amount of electricity for heating by the value of 16889 kWh and 17254 kWh, reflecting a reduction of around 13.8 % and 12 % compared to S01, respectively. Equipment and HVAC auxiliary energy use patterns exhibit less dramatic fluctuations compared to district heating and electric heating. The base case scenario and the SC02 both showed similar energy consumption levels for these categories, with a mean energy use of 12930 kWh. As remote workdays increase, the mean energy use for these categories also decreases, with SC10 showing a reduction of approximately 46 % compared to SC01. The variation in cooling energy use is relatively modest across scenarios. The base case scenario and SC02 used similar amounts of electricity for cooling (116 kWh and 122 kWh, respectively), indicating that occupancy changes have a minimal impact on cooling demands. Lighting energy consumption, on the other hand, is highly sensitive to occupancy schedules. The base case scenario consumed the highest amount of electricity for lighting (9472 kWh), while the SC10 recorded the lowest consumption (1438 kWh), reflecting an 85 % reduction. This substantial decrease can be attributed to the reduced need for artificial lighting due to the lower number of occupants on-site.

In contrast to the anticipated pattern, the SC10 exhibited a rise in electric heating consumption to 19904 kWh, representing a 1.6 % increase compared to the baseline. Meanwhile, district heating showed a significant decrease of 72 %, indicating a more responsive adjustment to the reduced building occupancy. The SC09 led to district heating and electric heating demands of 18754 kWh and 495 kWh, respectively, representing reductions of 4.3 % and 46.5 % compared to the base case. The energy-saving potential of a hybrid work model that balances on-site and remote workdays is highlighted by these reductions. Upon examining the SC08, there was a significant decline in district heating to 552.5 kWh, indicating a substantial decrease of 40.4 % compared to the base case.

Nevertheless, the demand for electric heating experienced a notable rise of 8.3 %, reaching a total of 18251 kWh. This indicates that district heating systems exhibited a favorable response to the decrease in occupancy. In contrast, electric heating systems did not adapt as efficiently, potentially due to less adaptable control systems or the requirement to maintain specific baseline temperatures despite reduced usage. The SC07, characterized by prolonged working hours over four days, led to a decrease in electric heating and district heating by 9.1 % and 37.9 % from the baseline, respectively. Therefore, the results indicate that longer operating hours on fewer days can lead to overall energy savings, potentially due to lower heating ramp-up requirements.

Overall, the results presented in Fig. 8 underscore the significant potential for reducing energy consumption in buildings through optimized occupancy schedules and energy-efficient practices. While the consumed energy of various parts of the office is reduced by decreasing the presence of working days, the demand for heating of the building is increased by remote working. The main reason for this increasing trend is related to internal heat gains based on equipment, occupancies, and facilities activities. The heating system setpoint is considered 15 °C resulting in heating demand on remote working days. However, the setpoint in the presence of occupancy is considered equal to 21 °C, and the heat gained as a result of occupancies' activities and the other facilities contributed to these differences.

Results in Fig. 8 show that there is a significant difference in EUI between different occupancy scenarios. The base case scenario had the highest EUI of 32.13 $kWh/m^2/yr$. The implementation of ASHRAE 90.1 standards (SC02), resulted in an 8.93 % decrease compared to the base case scenario. This demonstrates the effectiveness of the strict energy performance criteria. In general, the scenarios with lower EUI involve employees working fewer days a week or working remotely. More precisely, the "5-Day" scenarios (SC033 to SC06) showed small decreases in EUI ranging from 0.22 % to 2.42 % compared to each other. However, the EUI compared to the base case decreased by 13.7 %, 15.7 %, 15.9 %, and 17.2 % in SC03, SC04, SC05, and SC06, respectively. This indicates that there are moderate energy savings linked to various occupancy and work schedule arrangements during a typical five-day workweek.

Implementing a compressed working week (SC07) resulted in a about 19 % decrease in EUI compared to the base case scenario. This suggests that operating the building for one less day leads to energy conservation benefits. In addition, the incorporation of remote workdays SC08, SC09, and SC10 resulted in more significant reductions in EUI of 22 %, 29.41 %, and 45.72 %, respectively, compared to the base case scenarios. As can be seen, the remote working scenario had the lowest EUI reduction among all scenarios. The notable decline highlights the influence of decreased building occupancy on energy use, resulting from decreased requirements for lighting, HVAC, and office equipment utilization.

3.2. Thermal comfort analysis

After conducting energy simulations and comparing the different scenarios, simulations were performed to analyze thermal comfort in the case study building. To this end, two office rooms were selected to compare the zone air temperature and indoor operative temperature to evaluate thermal comfort. The selected offices are south-faced and located on the second and third floors of ZEB Flexible Lab (see Fig. 9). Apart from floor differences, Office Room 1 and Office Room 2 were different in some physical and operational aspects. Office room 2 had a larger Window Wall Ratio (WWR) with a value of 52 % and 8 persons working in the room and the office was equipped with a 950 W radiator. The corresponding values for WWR, number of occupants, and radiator for office room 1 were 38 %, 7 persons, and 1100 W, respectively.

3.2.1. Indoor operative temperature

The indoor operative temperature of the selected rooms was compared among all scenarios. Fig. 10 represents the indoor operative temperature in office room 1. Each dot represents an hourly operative temperature during a year for a selected office room for each scenario. The numbers below each bar chart illustrate the number of hours in which operative temperature exceeded the lower limit of ISO 17772-1 (20 °C). For the selected rooms results were provided based on occupancy and only presented the occupied hours and excluded unoccupied hours.

In the “Base case” scenario, operative temperatures fell below the comfort level for 108 h throughout the year. When compared to the SC02, with 150 h below the threshold, suggests that the base case operational schedule is more effective at maintaining

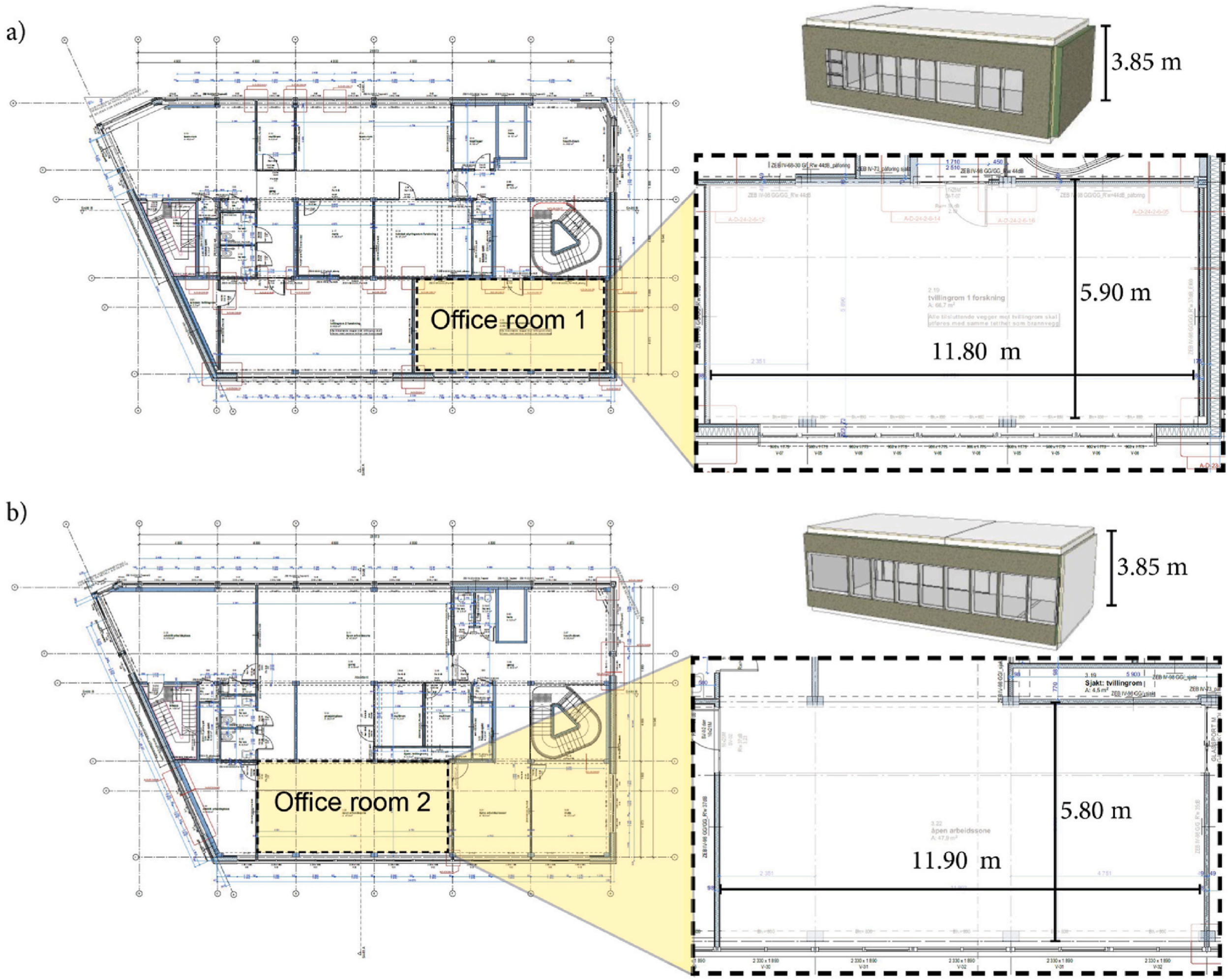

Fig. 9. Selected offices for thermal comfort analysis. a) Second-floor plan and 3D model with highlighting office room 1; b) Third-floor plan and 3D model with highlighting office room 2 and.

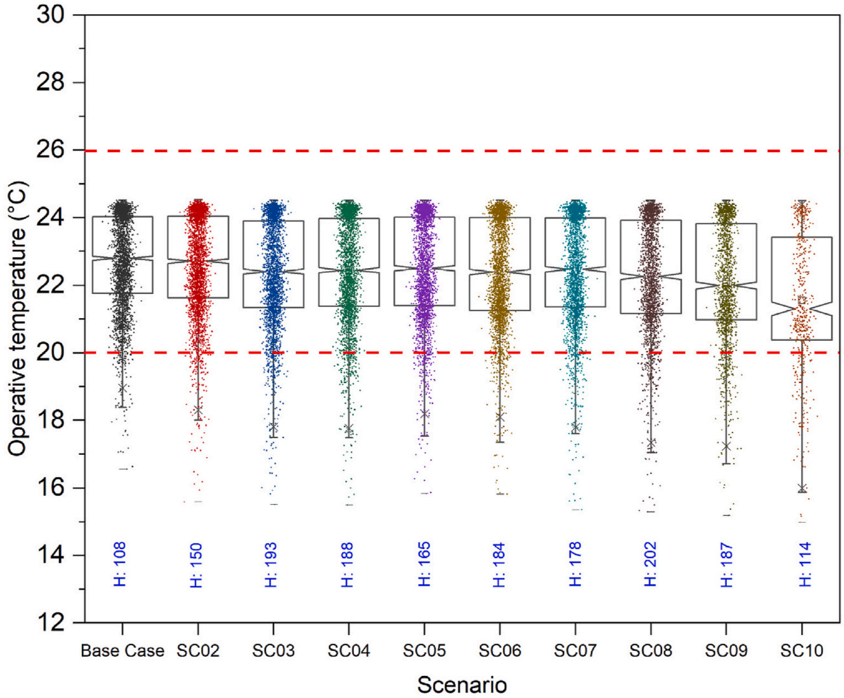

Fig. 10. The hourly operative temperature of Office Room 1 during occupied hours in a year for each scenario.

temperatures above 20 °C during occupied hours. This is an interesting finding, as the ASHRAE standard is often assumed to represent optimal conditions for comfort and energy use. As the other finding of the simulation, the scenarios exhibiting the highest number of hours below the comfort threshold were SC03 with 193 h, and SC08 with 202 h, implying that these specific arrangements may not align well with the heating schedule or building thermal characteristics.

Based on the box and whisker plot in Fig. 10, the lowest mean value for operative temperature was recorded in scenario SC10 with

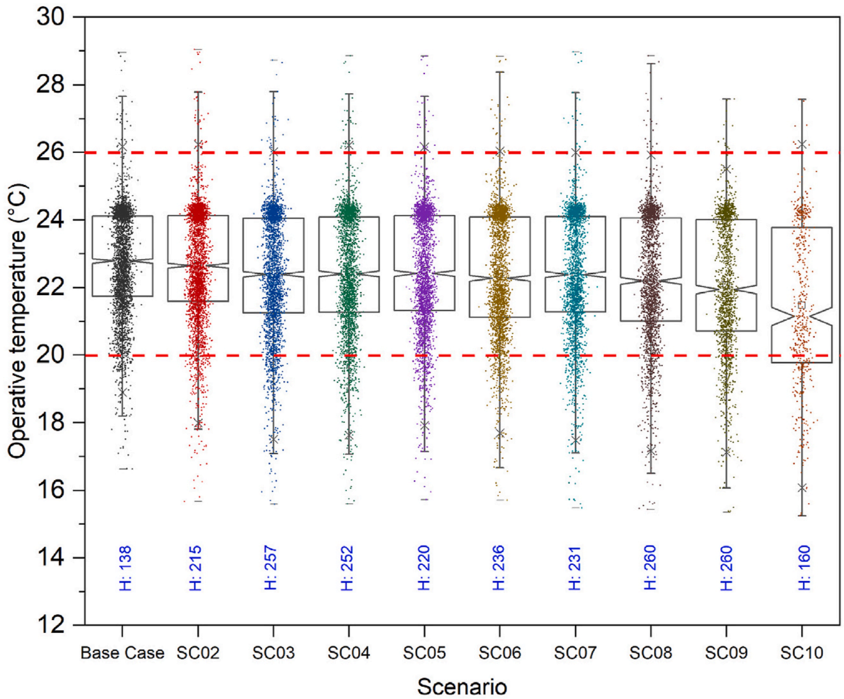

Fig. 11. The hourly operative temperature of Office Room 2 during occupied hours in a year for each scenario.

the value of 21.5 °C, which represented a 4.5 % temperature reduction compared with the other scenarios. The correspondence value for all 5-day scenarios and SC07, SC09, SC02, and SC08, the mean operative temperature was 22.1 °C.

Fig. 11 outlines the operative temperature distributions during occupied hours within Office Room 2 across various scenarios throughout the year. The temperature dropped below the acceptable level for 138 h in the Base case scenario which was the lowest uncomfortable hours among all scenarios. When contrasting the SC02 demonstrated a marginal rise, as 215 h were accumulated below the comfort threshold. According to the results, the duration of sub-threshold temperature conditions during occupied hours is not significantly reduced by the implementation of ASHRAE standards. Scenarios incorporating remote work patterns, such as SC08 and SC09 matched 260 h each below the comfort limit, representing the highest thermally uncomfortable hours.

As the box and whisker plot showed, the mean temperature varied between 21.4 °C and 23.3 °C. The lowest mean indoor operative temperature was related to the SC10 scenario with a value of 21.4 °C. However, except for the base case with 22.7 °C, which was the highest, other scenarios indoor operative temperatures fluctuated between 22.0 °C and 22.5 °C. It is worth mentioning that scenario SC10 with the least occupied hours observed as the most thermally uncomfortable scenario.

Comparing the results of operative temperature, the lower overheating hours in office room 1 than in office room 2 could be raised from differences in operational and physical characteristics. As office room 2 had a higher glazed area (WWR = 52 %) and also higher internal loads associated with the higher number of occupants and equipment compared to office room 1, it would receive more solar radiation into the room and result in higher indoor temperature specifically during summer months.

3.2.2. IOhD and IOcD

The IOhD and IOcD were calculated based on the excess of the indoor temperature over the upper and lower comfort threshold (26 °C and 20 °C) during occupied hours, as per equation (1) given by Hamdy et al. [99]. For the calculation of these metrics, the whole building (all zones) was considered. Fig. 12 illustrates the variation in indoor thermal performance using IOhD and IOcD metrics across scenarios evaluated based on standards for Category II buildings. It is worth noting that the building's comfort level will be higher if the IOhD and IOcD are lower.

The base case (SC01) demonstrates the most favorable energy performance with the lowest IOcD and IOhD at 1.051 °C and 0.046 °C, respectively. This indicates a well-balanced operation of the building's heating and cooling systems with the occupancy schedule. Conversely, SC10 showed significant energy inefficiencies, recording the highest IOcD and IOhD values of 2.087 °C and 0.251 °C, indicating that the existing HVAC controls are not adequately adapted to such flexible occupancy patterns, leading to excessive energy consumption due to overcooling and overheating when the building is unoccupied.

The scenarios encompassing various workweek configurations (SC03 to SC06) indicated a moderate deviation in IOcD (ranging from 1.355 °C to 1.450 °C) and relatively low IOhD values (ranging from 0.110 °C to 0.127 °C) and from the base case. The results indicate that shifts in the starting time of work hours improve the building's thermal performance by decreasing the IOcD from 1.45 °C in SC03 to 1.35 °C in SC05. Similarly, IOhD was decreased from 0.127 °C (SC03) to 0.109 °C (SC05). Notably, the scenarios incorporating remote work strategies (SC07, SC08, and SC09) highlighted a clear trend of increasing inefficiencies in energy consumption, with the IOcD and IOhD values rising with the decrease in on-site workdays.

According to the results, the base case scenario showed higher comfort compared to other scenarios. The main reason behind the

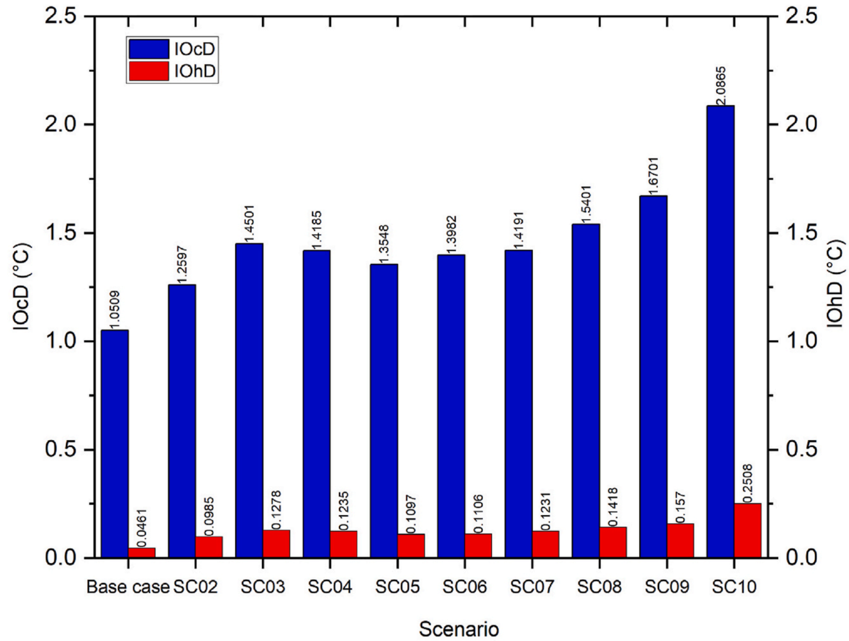

Fig. 12. IOcD and IOhD among each scenario considering the whole building.

higher comfort stems from the considered set points of heating and cooling systems during unoccupied hours. The HVAC and ventilation systems were set to work during nighttime and weekends. Therefore, the building was preheated for the working hours and most of the time met the requirements for comfort temperature. On the other hand, in remote scenarios (SC07, SC08, SC09, and SC10) the building was not occupied for some days, and the outdoor temperature when working hours started the energy systems required more time to reach the set points and hardly could meet to the comfortable temperature. As a result, the IOcD for SC07, SC08, SC09, and SC10 were increased by the value of 35.1 %, 46.5 %, 59 %, and 98 % compared to the base case scenario, respectively. Consequently, it is evident that if a building does not have an adequate active heating system, the discomfort caused by excessive cooling would surpass the discomfort caused by overheating, particularly in remote scenarios in cold climates such as Norway.

4. Discussion

The investigation conducted in this study regarding the relationship between office building occupancy patterns and energy consumption provides significant contributions to the understanding of energy efficiency and sustainability strategies in buildings. The findings shed light on how different occupancy scenarios, ranging from standard workweeks to various forms of remote work arrangements, significantly impact energy use, particularly in terms of heating, lighting, equipment, also thermal comfort of building users. These insights are pivotal for policymakers, building designers, and facility managers aiming to optimize energy use while maintaining a comfortable and productive work environment. This study underscores the complexity and interdependence of building systems and occupancy patterns. The variations in energy consumption observed across different scenarios highlight the need for a holistic approach to building design and operation, one that considers the dynamic nature of how buildings are used. The move towards more flexible work arrangements, accelerated by global trends such as the rise of remote work, poses both challenges and opportunities for energy management in office buildings.

Based on these findings, the following sections of this discussion will provide a more detailed analysis of the specific effects of different occupancy patterns on energy usage, the difficulties in ensuring thermal comfort as occupancy changes, and the broader implications for sustainable building management and design.

4.1. Findings and recommendations

This study conducted a thorough analysis of energy use and the level of comfort in office buildings under different occupancy scenarios, considering both traditional and flexible work schedules. The key findings emphasize the considerable opportunity for saving energy by implementing optimized occupancy scheduling and adopting energy-efficient practices. Significantly, introducing remote work arrangements and compliance with standards such as ASHRAE 90.1 [90] and NSPEK 3031 [94] resulted in significant decreases in energy use.

The comprehensive analysis of annual delivered energy in various occupancy scenarios offers significant insights into energy efficiency in office buildings. Results of energy analysis revealed that the base case scenario (SC01) had the highest energy use at 55401 kWh. Implementing the ASHRAE 90.1 (SC02) resulted in a reduction to 50461 kWh. Further reductions were observed in scenarios involving changes to the workweek schedule, with the 4-day remote working scenario (SC10) showing the most significant decrease in energy use, down to 30083 kWh. The findings are in agreement with the studies of [42,51,100] which mention that offices consumed more energy, even when they were unoccupied, unless occupancy-based technologies were implemented to reduce energy use.

The highest portion of delivered energy was related to heating, contrary to what was expected in remote working scenarios. For example, the SC10 saw an increase in electric heating consumption by 1.6 %, reaching 19904 kWh, compared to the baseline scenario (SC01). This increase indicates that the decrease in occupancy did not result in a proportional decrease in the demand for electric heating. When the occupancy level of a building decreases, such as only one day in a week, the heat gain of the building decreases as well. As a result, a greater amount of energy for heating the building is required to reach the set point temperature. Findings are in agreement with the study of [51,100] where the authors conclude that the energy use related to heating remained constant during the lockdown, despite decreased occupancy, and explore scenarios to enhance heating efficiency, emphasizing possible energy savings and adaptable methods for future disruptions.

Despite the increase in electric heating, district heating in the SC10 showed a substantial decrease of 72 %–260.7 kWh. This indicates a more effective adjustment of the district heating system to the reduced occupancy. Alternatively, this could indicate inefficiencies in the building's heating system control, which may not have been adequately responsive to changes in occupancy levels. Several factors might explain these results. A possible explanation for the lack of substantial energy savings in the remote working scenario would be that the case study building was a high-performance building with extremely low energy consumption. The climate condition in Norway could be mentioned as another factor. Since the set point temperature for heating in Norway is 15 °C, the heating system operates even when the building is unoccupied. These results are in line with the findings of [41,101,102]. They mentioned that energy saving and space saving could be achieved when teleworking and remote working are implemented properly. More precisely, it is suggested that to maximize the potential of energy and cost savings associated with remote working, the office space should be designed as an open-plan layout, where employees do not have assigned desks and instead use a hoteling system. The office should consistently be operating at near-full capacity every day. The lighting, HVAC, as well as office equipment, are all managed in a detailed and precise manner based on the occupancy of the space, both in terms of location and time. Similarly [103,104], found that the HVAC and lighting systems of office buildings are relatively roughly controlled. Therefore, the building systems are required to maintain comfortable temperatures and ventilation in anticipation of occupancy, regardless of the presence of an individual occupant.

The study found that implementing practices such as remote working and compressed working weeks, which result in reduced physical occupancy, leads to a decrease in the EUI of buildings. The scenario of a 4-day compressed working week (SC07) was found to be particularly effective in reducing EUI, indicating significant energy conservation advantages. In SC09, the EUI was reduced by 22 % compared to the base case EUI.

By implementing some of the strategies discussed in this paper, such as encouraging telecommuting and implementing flexible work schedules, building owners and managers can reduce energy use and save money on energy costs. The results demonstrate a distinct pattern in which an increase in non-occupancy days corresponds to a decrease in energy consumption. This emphasizes the potential of such strategies to contribute to the goals of energy conservation and sustainability in the built environment. The results of this study are in line with the findings of [41] which mentioned that teleworking decreases energy use however there are some exceptions. Although there is theoretical potential to decrease energy use in offices, the implementation of teleworking in a normal office setting, where individuals possess designated workspaces, may not yield such reductions. To reach the highest potential of energy saving in offices there is a need that most employees to opt for teleworking [101,105].

In addition, the analysis of thermal comfort showed that different occupancy patterns have a significant impact on indoor operative temperatures. Flexible work arrangements present challenges in maintaining thermal comfort because there are differences between how the HVAC system operates and how the building is used. The results indicate that in scenarios involving a standard five-day occupancy pattern, temperatures are maintained in closer proximity to the comfort standard. Conversely, in scenarios involving a greater number of remote workdays, temperatures exceed the comfort range for a greater number of hours. This highlights the significance of the adaptability of HVAC systems to changes in occupancy patterns, indicating a potential requirement for more advanced control systems to guarantee both comfort and energy efficiency in consideration of flexible work arrangements. The results of this paper demonstrated that the IOcD for remote scenarios such as SC07, SC08, SC09, and SC10 increased by 35.1 %, 46.5 %, 59 %, and 98 %, respectively, in comparison to the base case scenario. The results of [50] align with our findings on the energy performance and thermal satisfaction of office buildings, particularly in the context of flexible workspaces. Although this paper reports cooling electricity savings of up to 22 % and a 15.7 % increase in comfort probability through space match strategies, our research emphasizes the overall energy reductions from remote work and flexible occupancy schedules, particularly in terms of heating demands. As a result, it is clear that in remote scenarios in cold climates like Norway, the discomfort caused by excessive cooling overcomes the discomfort caused by overheating if a building lacks an adequate active heating system. Therefore, to implement remote working scenarios in office buildings, it is highly recommended that the climate conditions should be considered for reaching the thermally comfortable spaces.

The study's findings regarding energy use and thermal comfort in office buildings during flexible occupancy scenarios inform several recommendations that aim to enhance energy efficiency and facilitate flexible work patterns. Firstly, it is crucial to optimize HVAC control systems to be more adaptive to changes in building use rather than relying on predefined schedules. It is recommended to utilize advanced control technologies like smart thermostats and AI-driven systems to optimize heating, ventilation, and air conditioning. These technologies can dynamically adapt the temperature settings based on real-time occupancy data. Secondly, it is recommended to make improvements to the building's thermal insulation and heating systems to offset the higher energy demands for heating during periods of low occupancy. Enhancing the building envelope and incorporating more effective heating systems can reduce the increased energy consumption during times of low occupancy in the building. Thirdly, performing regular energy audits can help identify inefficiencies and offer data-driven insights to optimize energy consumption, particularly in buildings that operate with teleworking and flexible schedules. This is particularly relevant in scenarios like the SC10, where unexpected increases in heating demand suggest potential for optimization. Another recommendation is that integrating criteria for flexible and remote working environments into building energy standards, such as ASHRAE 90.1 and ISO 18523, will guarantee that energy benchmarks are practical and attainable. Additionally, it is highly recommended to promote interdisciplinary research and establish training initiatives for building managers that specifically target energy management and indoor environmental quality in office spaces that are subject to frequent changes in usage. These measures will not only optimize energy efficiency but also enhance occupant comfort and productivity, in line with current work trends and sustainability goals.

4.2. Strengths and limitations

It is possible to identify a number of strengths within this study. The first strength of this paper was that the authors utilized a real case study office building, which was a calibrated and high-performance office building located in Norway. Occupant behavior is one of the most influential variables influencing energy use in high-performance buildings [106–108]. The second strength was the implementation of various occupancy schedules, which included remote working. This was a novel approach, and the effects of these schedules on energy use in office buildings have rarely been investigated. This research provides new insights into the correlation between work arrangements and energy efficiency in office buildings by focusing on the overlooked aspect of teleworking within the Annex 79 framework. By integrating an interdisciplinary approach that spans architecture, environmental science, and organizational behavior, this study offers a nuanced understanding of how space utilization and work arrangements can significantly influence energy performance. The results of flexible work arrangements, specifically implementing a 4-day compressed working weeks (SC07), have been incorporated into the labor laws of several countries, including Belgium, New Zealand, and Iceland. The relevance of this research is further amplified by the current global trend towards more flexible work environments, propelled by advancements in technology and shifts in work culture.

The authors acknowledged that this research might have limitations. However, the authors tried to consider different scenarios and possibilities in real work environments. The generalizability of the findings may be limited due to the complexity introduced by the variation in teleworking practices among different organizations. Furthermore, the dynamic and evolving character of remote working, which may vary substantially over time and between used cases, is not adequately accounted for by the assumption of static work patterns. These limitations highlight the necessity for more research to investigate these elements thoroughly, examining the wider consequences of flexible working arrangements on organizational sustainability and energy efficiency in the built environment.

4.3. Implication on practice and future research

This research has numerous potential implications that extend across various domains. Architects and urban planners can use the acquired insights to design office spaces that are energy-efficient and suitable for the changing nature of work. In comparison to occupancy-based energy management strategies, installation-based strategies may be more effective at reducing energy consumption in office buildings [109]. One reason for this is that although spaces are often not fully utilized, energy is often still being consumed. Using timers on HVAC systems is an illustration of an installation-based approach. By determining the durations and times of peak and off-peak utilization of a given space, it is feasible to program the air conditioning system to activate just before the scheduled use of the space and deactivate it just before it is vacated [61]. This may result in significant energy savings, specifically for teleworking scenarios.

The energy and comfort implications of various space allocation and usage scenarios can be evaluated through simulation. This capability can assist building owners and designers in making more informed decisions. Implementing energy-efficient design during the construction of a new building is frequently simpler and less expensive than retrofitting an existing structure. Significant energy savings can be achieved through modifications in space type and spatial allocation without compromising occupant comfort or productivity [110]. Energy managers and sustainability experts can use these findings to develop more efficient energy management strategies specifically designed for flexible work arrangements. Furthermore, policymakers can utilize this research as a foundation for formulating guidelines and standards that facilitate energy conservation in constructed spaces, fostering a transition towards more environmentally sustainable methods. As the worldwide labor force increasingly adopts flexibility, the findings of this research could have a substantial influence on the future of work, sustainability, and urban development.

Further studies are needed to conduct an in-depth examination of occupancy patterns by using direct measurements obtained from advanced sensors and Internet of Things devices. This approach would not only enhance our knowledge of the intricacies of energy use but also enable the development of predictive models customized for varying occupancy situations. Furthermore, exploring the incorporation of sustainable energy solutions in flexible offices is a valuable area of research. By examining the possible synergies among teleworking, flexible scheduling, and the utilization of renewable energy, future studies might develop novel approaches to enhance sustainability in office buildings.

While this study reveals significant office energy consumption reductions due to remote work, it is necessary to consider that remote working could result in increased energy use in buildings. Teleworkers might use more heating or cooling energy, especially during winter and summer seasons, depending on the energy efficiency of their homes [111]. Therefore, the net energy savings from remote work need to account for the potential rise in home energy use. While this study focuses on office energy consumption, future work could assess the overall energy balance, including home energy use, to provide a more holistic view of the impact caused by remote working on total energy use.

The thermal comfort findings advocate for the implementation of intelligent building systems capable of adapting to both the cyclical patterns of standard occupancy and the less predictable schedules of flexible work arrangements. By harnessing data-driven HVAC operation, there exists a substantial opportunity to reduce energy consumption while enhancing thermal comfort. A dual objective that aligns with the sustainability goals of modern building management. Future research should explore the efficacy of adaptive control systems in real-world settings, furthering the pursuit of optimized indoor environmental quality in the era of flexible work arrangements.

5. Conclusions

This study provides an in-depth exploration of the impact of space utilization on the energy performance of an office building under different occupancy scenarios. The high-performance building (ZEB Flexible Lab) in Trondheim, Norway, was considered as a case study for this research. Simulations were conducted utilizing the advanced simulation tool IDA ICE 5.0. By exploring various occupancy scenarios, from standard workweeks to extensive remote work configurations, the research provides valuable insights into optimizing energy efficiency and sustainability in office buildings. The simulation data related to energy use and indoor air temperature were calibrated with measured data.

Our findings reveal that implementing flexible work schedules, including remote working and compressed working weeks, significantly impacts energy performance, offering potential energy savings of up to 45.70 % in scenarios with increased remote working. For instance, the electric heating demand in the SC06 decreased by approximately 23 % compared to the base case scenario, reflecting enhanced efficiency in heating operations. Furthermore, the study found that different occupancy scenarios could substantially influence both district heating and electric heating demands. For example, the introduction of remote working in the SC09 not only reduced the overall energy consumption but also led to a more balanced use of heating resources, suggesting a shift towards more sustainable energy consumption patterns in office buildings. On the other hand, the results showed that when the remote scenarios were considered, the thermal comfort was decreased. For example, the IOcD for SC09 (2-day remote working), and SC10 (4-day remote working) increased by 59 %, and 98 %, respectively compared to the base case. It shows that climate conditions are a fundamental parameter for implementing remote works that need to be considered.

Moreover, our research underscores the importance of integrating energy-efficient practices and building design adjustments to accommodate new work patterns. Utilizing occupancy-based technologies and advanced simulation tools proved crucial in predicting and enhancing the building's energy performance under varied occupancy scenarios. These technologies not only help achieve energy efficiency but also ensure that comfort levels within the building are maintained, thereby supporting sustainable building operations.

Our findings contribute to the ongoing discourse on sustainable architecture by providing actionable insights for architects, building managers, and policymakers. By understanding the dynamic interplay between space utilization and energy efficiency, stakeholders are equipped to make informed decisions that promote environmental sustainability and operational effectiveness in office buildings.

CRediT authorship contribution statement

Alireza Norouziasas: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Conceptualization. **Shady Attia:** Writing – review & editing, Project administration, Methodology, Conceptualization. **Mohamed Hamdy:** Writing – review & editing, Supervision, Project administration, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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