Building the future, measuring the present

Addressing the energy performance gap in energy-neutral certified office buildings

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ABSTRACT

The building sector's substantial environmental impact, responsible for 40% of total energy consumption and one-third of CO2 emissions globally, emphasizes the urgency to enhance energy efficiency. While there are potentials for energy savings, there a still challenges that need to be faced. In particular, a significant 'performance gap' exists between predicted and actual energy usage in buildings. This gap, observed during the operational phase, poses challenges for realizing high-performance buildings. The focus of this thesis will be on energy-neutral certified office buildings, acknowledging their significance in sustainability efforts. A critical aspect of the performance gap is attributed to the operation and maintenance of the energy systems compared to the intended usage. The research will therefore address the critical question: *'What are the operation and maintenance related disparities between energy performance predictions and the actual usage of energy-neutral office buildings and how can these effectively be addressed?'* By conducting literature reviews and employing a mixed-method approach in future research with qualitative and quantitative methods combined, the study will utilize case studies and data from building energy management systems. Focusing on the complexities of influencing factors, specifically the operation and maintenance, the research aims to address the performance gap. Moreover, the possible relation between the energy performance gap and ownership structure, including the building its facility management, will be researched. By identifying factors contributing to disparities and proposing strategies for mitigation, actionable insights for practical solutions will be offered, fostering a more sustainable and energy-efficient built environment.

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“In theory there is no difference between theory and practice. In practice there is.”

Albert Einstein

1. INTRODUCTION

1.1 Problem statement

In the global context, the building sector stands as a significant contributor to global warming since it is responsible for 40% of total delivered energy consumption and one-third of CO_2 emissions (Yang et al., 2014; Ascione et al., 2017). At the same time, the buildings sector also offers substantial opportunities for energy savings. The Paris Proof Commitment, aiming at lowering energy usage in the built environment by two-thirds and corresponding CO_2 emissions, has now been signed by 114 market parties. This shows that stakeholders are becoming more conscious and making a commitment to reduce the ecological impact of the building industry, which is critical in the battle against climate change (DGBC, 2023). Improving energy efficiency in buildings is however challenging given that people spend considerable amounts of their time indoors and require energy for heating, cooling, and lighting to maintain a comfortable and healthy environment (Shaikh et al., 2014). Realizing the built environment its potential requires therefore a thorough understanding of influencing factors and a comparative assessment of alternative strategies in terms of their energy-saving capacities.

In order to make the building energy performance more efficient, energy modelling has become an integral part of today's design process. Nevertheless, there is a growing concern within the building industry around the 'performance gap'. Depending on the benchmark, there are two definitions of this term in current literature. In the first definition, the predicted energy consumption during the design stage is compared with the actual energy consumption of a building during the operational phase. In the second definition, the difference between actual measured consumption and the energy-efficient building standard established by authorities is what defines the gap (Zou & Alam, 2020). Since the first definition was largely accepted by previous researchers, it is used in this study. In this context, the predicted performance consists of design assumptions and energy simulation tools while the actual performance consists of management and controls, occupancy behaviour, and built quality (Menezes et al., 2011). According to previous reports, measured energy use could differ significantly, sometimes even rising to 2.5 times the amount initially predicted (de Wilde, 2014). Given the increased importance placed on addressing environmental challenges and the rising cost of energy, there is an urgent need to reduce this performance gap. Deep renovations, which combine numerous energy-saving methods, have on average a bigger energy gap compared to single renovation measures, despite achieving higher energy savings (van den Brom, et al., 2019). Moreover, it is observed that buildings with higher energy rates consume more energy than predicted, while lower energy rated buildings consume substantially less energy (Cozza, et al., 2020). These results highlight the importance of investigating the gap, since clients and the general public nowadays expect strict energy efficiency goals from renovated and newly built high-performance buildings. Problems could arise when the promised energy performance certificates are not achieved. Therefore, it is necessary to narrow the performance gap between predicted and measured performance in order to deliver high-performance buildings, such as BREEAM, net-zero-energy, and Paris Proof buildings, as well as foster change resilience. The maintenance of optimal performance over the course of a building's life and technical adaptation to changing usage conditions depend on this resilience (Fan et al., 2017). Additionally, it is required for innovative building delivery and facility management ideas such as performance-based buildings or performance contracts. These concepts envision users having a working environment with predefined comfort parameters rather than traditional hardware-based systems that may or may not provide such an environment (Fan et al., 2017).

The structure of this report comprises seven key sections. First of all, an introduction with a comprehensive literature review, including the influencing factors and unique challenges posed by office buildings will be conducted. The goal of this review is to get a better understanding of the factors around the energy performance gap and functions as an introduction to the research question. The methodology employed will be explained, outlining the comprehensive search strategy. Thereafter, the aimed research output will be discussed. The personal study targets will give an insight into the goal of the follow-up research, followed by the research plan. Finally, a reflection is provided of P1 and P2 as part of the graduation process.

1.2 Summary of literature and market research

The energy performance gap could arise from various sources related to the building life cycle phases (figure 1). During the design phase uncertainties are introduced for the practical realization due to unreliable design specifications and inaccurate simulation tools, contributing to the gap. Secondly, insufficient equipment and materials, along with inadequate building methods, make it challenging to achieve optimal energy performance throughout the construction phase. As the building proceeds toward the commissioning phase, the lack of sufficient verification for installed systems could cause a deviation from the planned operation. Finally, due to the significant influence that facility management and occupant behaviour have on the total energy consumption, difficulties with inadequately performing energy systems continue to arise in the operational phase (Kallab et al., 2017; van Dronkelaar et al., 2016). Focusing specifically on the operational phase is essential for addressing the challenges and optimize energy over the building's lifecycle since it has a long-term impact. Moreover, the operational phase often incurs the highest energy costs and influences the comfort and productivity of occupants.

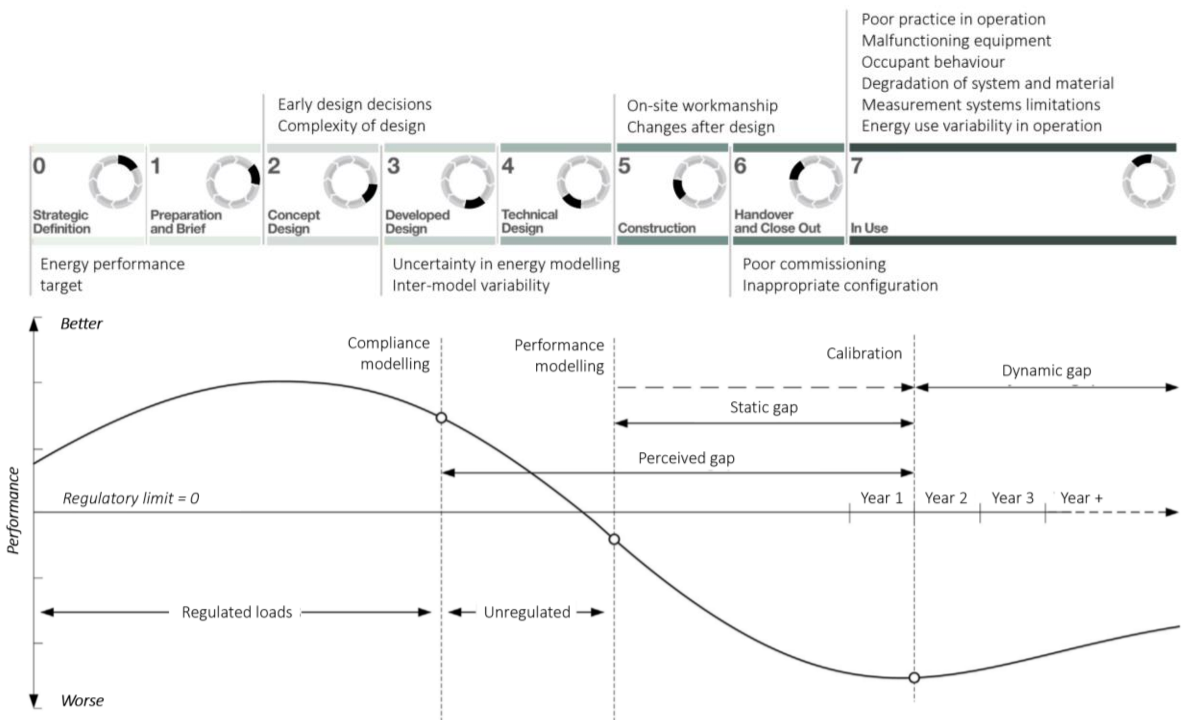

Figure 1: *Underlying causes existent in different RIBA stages and S-curve visualization of performance throughout the life cycle (adapted from van Dronkelaar et al., 2016)*

The computer-based parameters used for the energy performance predictions usually include the building orientation, number of levels, volume, total area of exposed walls, total windows area, wall ratio, floor height, indoor design temp, operating schedule, occupancies, infiltration rate, lighting level, and appliances (Ahsan et al., 2019). Parameters are often used as fixed numbers, however, external factors are dynamic. These factors include occupancy and thermal energy gains, which are important to take into account since they are interlinked and complex. Thermal energy gains include internal heat gains and solar heat gains, generated inside a space and not used as energy for heating, cooling, or hot water. Internal gains are the heat produced by occupants, lighting, and appliances inside offices. Internal gains increase the cooling load in the summer and decrease the amount of heat the HVAC system needs to provide in the winter. Solar heat gains are the thermal energy provided by solar radiation which enters a building through the windows and non-transparent walls and roofs directly and indirectly (Carlander, et al., 2020). Due to the dependence on external influences, it is important to research how this could be effectively managed during the operational phase.

One of the challenges hindering buildings from achieving substantial energy efficiency is a limited understanding of the main factors influencing the use of energy and the challenges coming with those factors (Yoshino, et al., 2017). The main factors influencing the energy consumption of buildings can broadly be categorized into the following six main elements: building equipment, building envelope, outdoor climate, operation and maintenance, occupant behaviour, and indoor environmental conditions (figure 2).

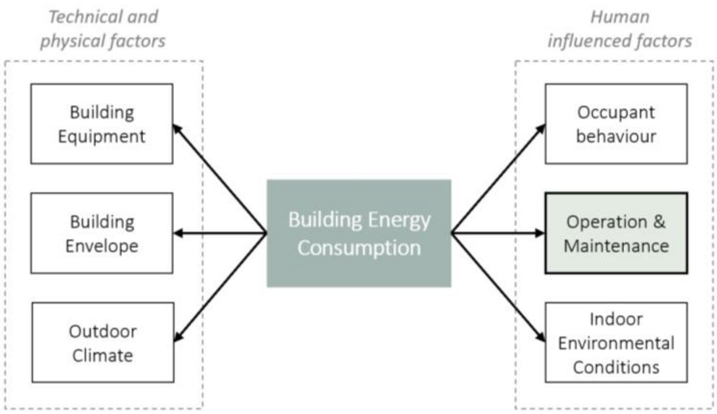

Figure 2: Six influencing factors on building energy use, adapted from Yoshino, et al. (2017).

The building equipment, part of the technical and physical factors, refers to the various systems and appliances within a building that consume energy. This includes HVAC systems, lighting, water heating, appliances, and office equipment. The integration of energy-efficient technologies, the implementation of building automation and energy management systems, and renewable energy sources play crucial roles in optimizing energy efficiency (Chen, et al., 2020). The building envelope is a influencing factor by serving as the barrier between the interior and exterior environments. It includes the walls, roof, windows, doors, and foundation of a building. The strategies related to the building envelope are considered passive strategies since they rely on natural processes and design principles to enhance the energy efficiency of a building, without the need for active mechanical systems or constant energy inputs (Sadineni, et al., 2011). The outdoor climate includes the temperature, humidity, solar radiation, and wind speed which are not influenceable, however, it directly affects the indoor building energy consumption (Chen, et al., 2020). When looking into the human influenced factors, occupant behaviour encompasses energy use related activities, interactions, and preferences in the building. A key factor is occupant awareness, which reflects the awareness of energy-efficient behaviours and how actions affect overall energy use (Ahmed, et al., 2023). The operation and maintenance involve the ongoing activities and management practices to ensure that a building or system operates optimally. This includes the usage, regular inspections, monitoring, and adjustments to enhance efficiency (Piper, 2016). Finally, the indoor environmental conditions cover the thermal comfort, visual comfort, acoustic comfort, and indoor air quality. These conditions affect human health, with research emphasizing a direct link between building design, indoor quality, and well-being (Šujanová, et al., 2019). While the three left components in the figure have received the majority of attention in previous research, more recent studies have emphasized the importance of the right three, focusing on the influence of human-influenced factors on energy consumption. This is especially important since the notable gap is often attributed more to human behaviour than to the design of the buildings (Yoshino, H, 2017).

Focusing specifically on occupant behaviour, this factor refers to the actions, preferences, and practices of people within a building that impact its energy usage. This encompasses not just standard actions such as preferred temperature, lighting usage, and appliance usage, but also how occupants interact with the building's energy systems. As shown in figure 3, occupant behaviour can be divided essentially into two categories: occupancy and occupant interactions with building systems including heating, ventilation, air conditioning (HVAC), lighting, appliances, and other energy-consuming equipment (Ahmed, 2023). The interaction with systems, such turning on the light and changing thermostats, plays a crucial role in the actual energy consumption. However, in buildings with a high energy performance that include smart and automated management building systems, the direct impact of occupant behaviour is minimized. Some systems allow users to interact with the system, however in others this is very limited and users are not even allowed to open windows. These automated systems are equipped with advanced sensors and automation that regulate energy consumption, reducing the significance of occupant behaviour and its individual actions (Naylor, et al., 2018). Centralized control mechanisms enable facility management to coordinate and fine-tune energy-consuming components. These technologies are being managed by facilities managers and react to environmental conditions without relying heavily on individual preferences.

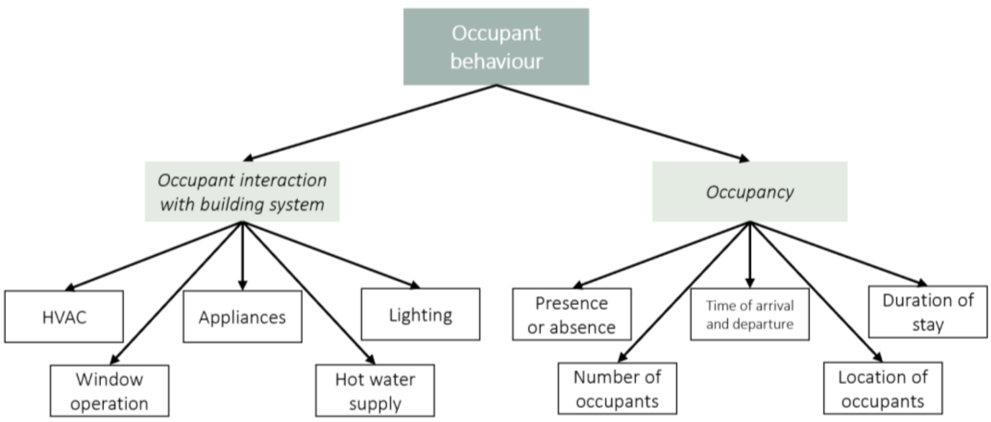

Figure 3: *The two main categories of occupant behaviour, adapted from Ahmed, et al. (2023)*

Three key factors contributing to uncertainties in energy consumption estimation within buildings are identified by van Dronkelaar, et al (2016). These factors include uncertainties in building modelling specifications accounting for 20%-60%, occupant behaviour accounting for 10%-80%, and operational practices accounting for 15-80% of estimated effects. Focussing on operation and maintenance with the highest estimated contribution, it has been shown in case studies that approximately 30% of the energy used was lost due to inadequately maintained and operated building services equipment (Granderson, et al., 2011). According to another research on the key operating parameters of 14 office buildings in Canada, the gap is greatly impacted by poor control of HVAC parameters, such as seasonal heating and cooling temperature setpoints, air handling unit start-stop times, and ventilation rates (Gunay et al., 2019). Additionally, another significant contributor to uncertainty include the influence of miscommunication among various parties or stakeholders regarding the anticipated performance of the building (Jones, et al., 2015). This is interlinked with the identified inaccurate energy regulations during hot and cold weather conditions, as well as human manual overriding of automatic control systems (Zou, et al., 2020) (figure 4). In essence, these variables collectively play a substantial role in the challenges associated with accurately predicting and managing energy use in buildings. The Energy Standard 90.1 Appendix G states: "Neither the proposed building performance nor the baseline building performance are predictions of actual energy consumption, due to variations such as occupancy, building operation and maintenance, weather, and the precision of the calculation tool." This statement emphasises the importance of the energy regulation during the operational phase. The regulation of energy usage in office buildings with advanced systems is largely influenced by its facility management. According to research, buildings overseen by facility managers with higher education levels are 13% more likely to implement temperature setbacks (Liang, et al., 2019). Moreover, it has been demonstrated that inefficient building operations across a number of parameters lead to a 49–79% increase in energy use, whereas efficient operations cut energy use by 15–29% (van Dronkelaar, et al., 2016). The operation of the building is influenced by its ownership structure. The type of owner could impact the role of financial, social and moral considerations in decision-making, as well as the influence of such issues from investors. Corporate social responsibility and sustainability goals may be more prominent factors for privately-owned buildings, while investor-owned properties may prioritize financial returns. Moreover, different owner types may have varying regulations and requirements related to energy efficiency (Kontokosta, 2016). The energy certification of green buildings relies on model-based consumption rather than performance-based consumption, which emphasizes the need for appropriate facility management to maintain the certification requirements (Liang, et al., 2019). Therefore, the interplay between the operation of facility management practices, building systems and technologies, and ownership types collectively shapes the energy efficiency and sustainability outcomes of buildings.

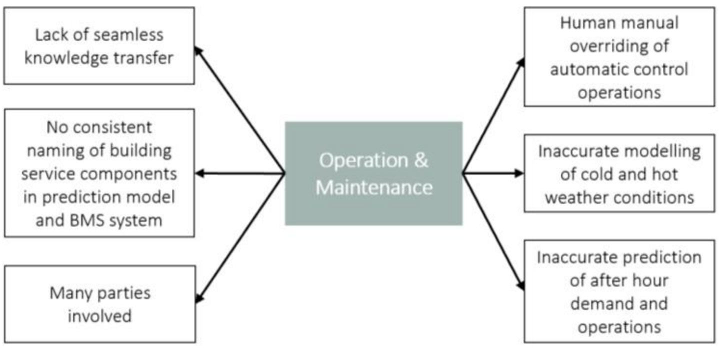

Figure 4: *Problems related building operation and maintenance, adapted from Zou, et al. (2020)*

In the field of sustainable building certifications, the BREEAM (Building Research Establishment's Environmental Assessment Method) is recognized as a standard model. This method is widely utilized to categorize both new and renovated buildings based on their environmental performance. The Dutch version of BREEAM, known as BREEAM-NL, uses a thorough evaluation and rating system to assign five star ratings to buildings, each representing a different degree of sustainability achievement: Pass (>30%), Good (>45%), Very Good (>55%), Excellent (>70%), and Outstanding (>85%). BREEAM-NL evaluates sustainability using approximately seventy parameters in nine key categories, including a building's lifecycle and its relationship to the environment. These categories, shown in figure 5, include: management, health, energy, transport, water, materials, waste, land use, and ecology and pollution (BREAAM-NL, 2023). In contrast to many certification programmes that primarily focus on energy usage, BREEAM-NL adopts a comprehensive strategy, taking into account a building's broader impact on its surroundings and the well-being of its occupants. The Dutch Green Building Council (2022) reported that BREEAM-NL has a notable impact on the Dutch real estate market with over 20 million square metres, or roughly 3,000 football fields' worth of floor area in 2021. There has been a growing recognition within the industry of the importance of sustainable building practices ever since with currently more than 1,200 utility buildings with BREEAM-NL certificates. Interestingly enough, it has been shown that buildings with higher energy ratings use more energy than predicted, whereas buildings with lower energy ratings use substantially less (Cozza et al., 2020). Therefore, high performance certified buildings are more likely to contribute to an energy performance gap, making it an important field of research. Furthermore, when sustainable certificates are awarded to buildings, it is even more crucial that these energy performances are achieved and maintained following delivery. This research will therefore focus on both BREEAM and energy-neutral certified buildings. In this context, an energy-neutral building is defined as follows: A building that, over a certain period, generates as much energy as it consumes. In other words, the building has a net energy balance of zero (Energy gov., n.d.).

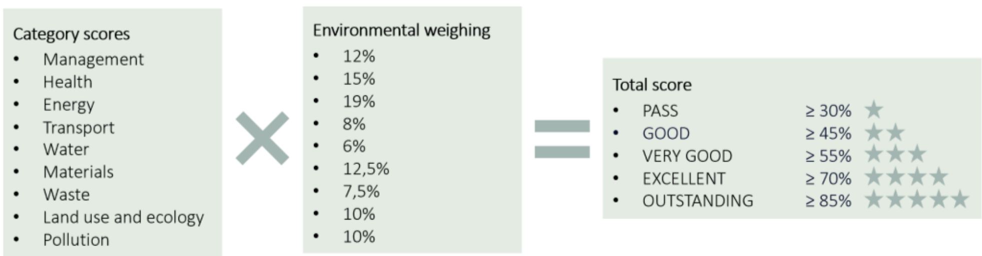

Figure 5: *BREEAM category scores, adapted from BREEAM-NL (2023)*

The energy performance gap appears in different types of buildings. Addressing this, a review of previous studies notices a significant difference between predicted and actual energy consumption, with a deviation of +34% and a standard deviation of 55% across a dataset of 62 buildings with different functions. In this dataset, 15% of the 62 buildings studied show a notable pattern in which the actual energy usage is double the amount compared to what was previously expected (van Dronkelaar, 2016). Office buildings are particularly important in the context of sustainability for a number of reasons. First, office buildings' dynamic and unpredictable occupancy patterns add to the difficulty of energy management. This includes the varying use of HVAC systems, lighting, and electrical equipment, demanding a nuanced approach to optimize energy consumption. Secondly, the technological infrastructure embedded within office buildings, including HVAC systems and other energy-intensive equipment, offers a unique potential for sustainable interventions. Finally, the behavioural dynamics in offices offer an effective way to influence sustainable business practices. Based on an analysis of 25 case studies, it is revealed that office buildings have an average deviation of +22% and a standard deviation of 50% between the predicted and actual energy consumption (van Dronkelaar, 2016). Another study, using post-occupancy evaluation, even indicates that the measured electricity use is 70% more than what was expected (Menezes et al., 2011). This emphasizes how challenging it is to predict and manage energy use in office environments, where a variety of activities lead to a performance gap that is more unpredictable.

In the quest for enhanced energy efficiency in office buildings, the improvements needed can be categorized into three core areas: building change, organizational change, and behavioural change (figure 6). Changes in the building characteristics consist the physical attributes including the design of structures and technical aspects. In terms of renovations, this aspect is focused on changing building components and technical systems since the building structure and main envelope already exists. Building components include insulation improvements and window and door replacements (Chen et al., 2020). Improvement of the technical aspects encompass the adoption of energy-efficient technologies and systems, ranging from upgraded appliances to the integration of renewable energy sources. These changes contribute to the optimization of the generation, distribution, and utilization of energy resources. Organisational changes entail reorganising practises and regulations within organisations to emphasise and promote energy efficiency. Establishing efficient energy management systems and promoting a sustainable culture collectively contribute to a more energy-conscious environment. In addition to the technological and organisational aspects, behavioural changes seek to improve sustainable energy usage (Ruparathna et al., 2016). These three core values are dynamic and interlinked with one another and to the facility management. The building characteristics have an impact on the energy label and provide direction to the overall energy. This includes technical changes which is associated with the building equipment and envelope. Building changes requires organizational support for effective implementation and both depend on behavioural, which includes operational changes, to create a culture that encourages improvements. This interdependence emphasises the value of a comprehensive strategy, recognizing that actual improvements in energy efficiency depend on organisational, behavioural, and technical changes integrated into a cohesive plan.

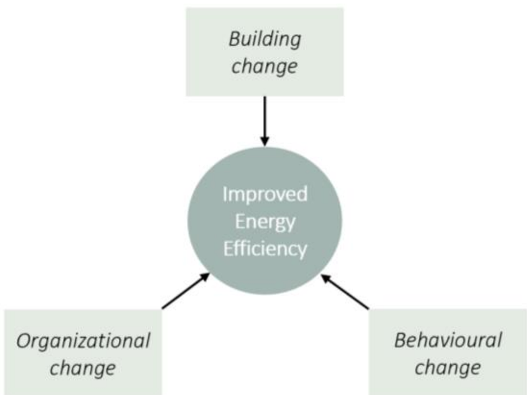

Figure 6: *Paradigms for energy performance improvement in existing buildings, adapted from Ruparathna et al. (2016)*

A greater understanding of where and how energy is used in a building, as well as which measures have the biggest effects on energy usage, can be gained by using several methods for calculating the energy performance of a building during both its design and operating phases. During the design phase, the

EPC (Energy Performance Certificate) provides information about the energy efficiency of a building. When in use, methods can locate possible energy-saving opportunities and analyse the energy efficiency and economic viability of proposed energy-saving methods. However, it is challenging to reflect actual building energy use in the real world since the built environment is complex and influenced by a wide range of independent and interconnected variables. Models are a simplification of reality, using parameters with set standards that ignore certain processes. It is crucial to quantify to what degree inaccurate the predicted calculations are before using them in the design, prediction, and decision-making processes (van Dronkelaar, 2016).

Building energy management systems can be used to monitor and control data regarding energy use, analyse consumption patterns, and optimize energy efficiency (figure 7). Given that heating, ventilation, and air conditioning (HVAC) systems, use the majority of the electricity consumed by buildings, it is crucial to include this data in the analysis of energy efficiency and identify areas of inefficiency. This involves locating weaknesses in the way the HVAC is operating and identifying timeslots with energy inefficiencies. A case study of a Houston office building demonstrates the effectiveness of data analysis and self-organizing maps in identifying potential energy savings of up to 4.6%. Energy managers can find more energy savings by using machine learning and time series analysis methods (Talei et al., 2023). Moreover, another study shows that post-occupancy evaluations in office buildings can improve the energy model's accuracy within 3% of the actual energy consumption (Menezes et al., 2011).

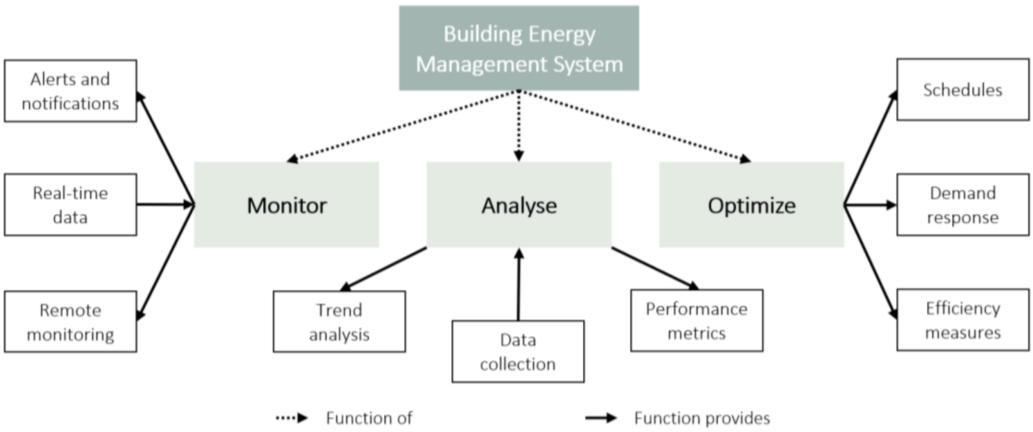

Figure 7: *Characteristics of Building Energy Management Systems*

1.3 Problem statement

When looking into previous studies, it is notable that a large amount of research has been conducted, highlighting different topics. However, upon closer examination, noticeable gaps emerge when delving into specific areas of consideration. Most studies are focused with designers, suppliers, contractors, occupants, energy managers, and owners as key players, not mentioning the role of developers. Also, when focusing on the owners, little research is done about the possible relation between the ownership type and the building its energy performance. The ownership for buildings can simply be classified into owner-occupied, tenant occupied, or a combination of both. According to research, owner-occupied buildings are more likely to install more complex, difficult-to-manage technologies, leading to the buildings' ineffective use of the systems (Liang et al., 2019). More research is needed to get a better understanding of the possible ownership and operation related factors. The literature review further underscores the global significance of the energy performance gap in office buildings, emphasizing the various challenges faced in achieving energy efficiency goals. An issue to be addressed is in terms of who is responsible and what method should be applied. There is a challenge faced in making more precise predictions and enhancing energy related operations. In addition, the findings indicate that the gap results from various underlying factors, necessitating appropriate usage of buildings and their service systems and collaboration and a comprehensive understanding among all stakeholders engaged (Zou & Alam, 2020). The identified complexity of this gap is reflected in the operational phase, with the influence of inadequate operation and maintenance emerging as a critical factor. The need for customized strategies developed to the specific challenges faced by office buildings is highlighted, considering factors such as changing occupancy patterns, dynamics in usage, and technological infrastructure. Furthermore, the literature emphasizes the potential contribution advanced control and monitoring systems, such as building energy management systems, in addressing the gap. These technologies offer accurate output data analysis, identification of inefficiencies, and energy model improvement, thereby contributing to new insights. Post-occupancy analyses are recognized as valuable tools for enhancing predictions and aligning them with actual usage. In purposing future research directions, there is a specific need for a focused understanding in the complexities of the parameters used for the predictions and the incorrect usage of the energy systems. The proposed research seeks to delve into the operation and maintenance-related disparities in energy-neutral certified office buildings, given the importance of the accuracy of the energy usage. Moreover, the research will focus on possible links between the building's ownership structure in relation to the managed energy usage. The final aim is to offer detailed insights and practical strategies for closing the performance gap, ultimately enhancing sustainability and reliability in their energy performance.

1.4 Societal and scientific relevance

The study will take into account societal and scientific reliability and applicability and their complex interactions. From a social point of view, the study recognizes that human influenced factors within the built environment, including operation and maintenance, are varied and dynamic and that facility management can have substantial impact on energy usage. Developing sustainable solutions that meet the occupant's expectations and societal guidelines requires an awareness of this. In terms of science, the study explores the complexity of energy performance predictions within office buildings. It emphasizes the integration of advanced methods, such as data analysis using building management systems and smart meters, to bridge the gap between predicted and actual energy use. By addressing both societal and scientific dimensions, the research aims to provide a comprehensive understanding of the challenges and opportunities in building energy efficiency, fostering solutions that are both technically robust and socially relevant.

2. RESEARCH QUESTIONS

Researching the performance gap within the context of both existing and newly built office building, holds particular significance for several reasons. It is essential for achieving energy efficiency, sustainability, cost savings, occupant well-being, regulatory compliance, and technological innovation. Addressing both existing and newly built office buildings provides a more complete picture of the challenges and opportunities in the built environment. It allows for a nuanced understanding of the factors influencing building performance and facilitates the development of effective strategies for a more sustainable and resilient built environment. Office buildings present unique challenges and opportunities since they frequently have diverse usage and ownership patterns. To specify the field of research, the scope will be focused on energy-neutral certified office buildings. The high promised energy performance linked to the certification make the accuracy of these energy specifications even more important. Due to the challenge of balancing sustainability with economic constraints and navigating a competitive real estate market, researching minimal investment strategies is essential for mitigating financial risks during an economic downturn and ensuring the attractiveness of sustainable buildings. To tackle the mentioned challenges, this research aims to systematically identify and address the energy performance gap of energy-neutral certified office buildings with the goal to enhance sustainability and performance reliability (figure 8). Therefore, the main question is stated as:

- *How can operation and maintenance-related energy performance gap in renovated office buildings be effectively addressed to meet the Paris Proof commitment targets?*

This research explores various aspects through a set of sub-questions (SRQ). These aim to uncover factors influencing the performance gap, explore the influence of ownership structures, and examine the human influencing factor of operation and maintenance in specific. With the overarching goal to address the EPG, the following sub-questions will be discussed:

1. *What are the main factors influencing the energy performance gap in buildings?*
2. *What are the key operational and maintenance challenges that contribute to disparities in energy performance from predictions?*
3. *What responsibilities do various stakeholders have in relation to the energy performance of a building and what agreements and information exchanges are in place for this purpose?*
4. *What operational and maintenance practices should be implemented to realise Paris Proof redeveloped office buildings?*

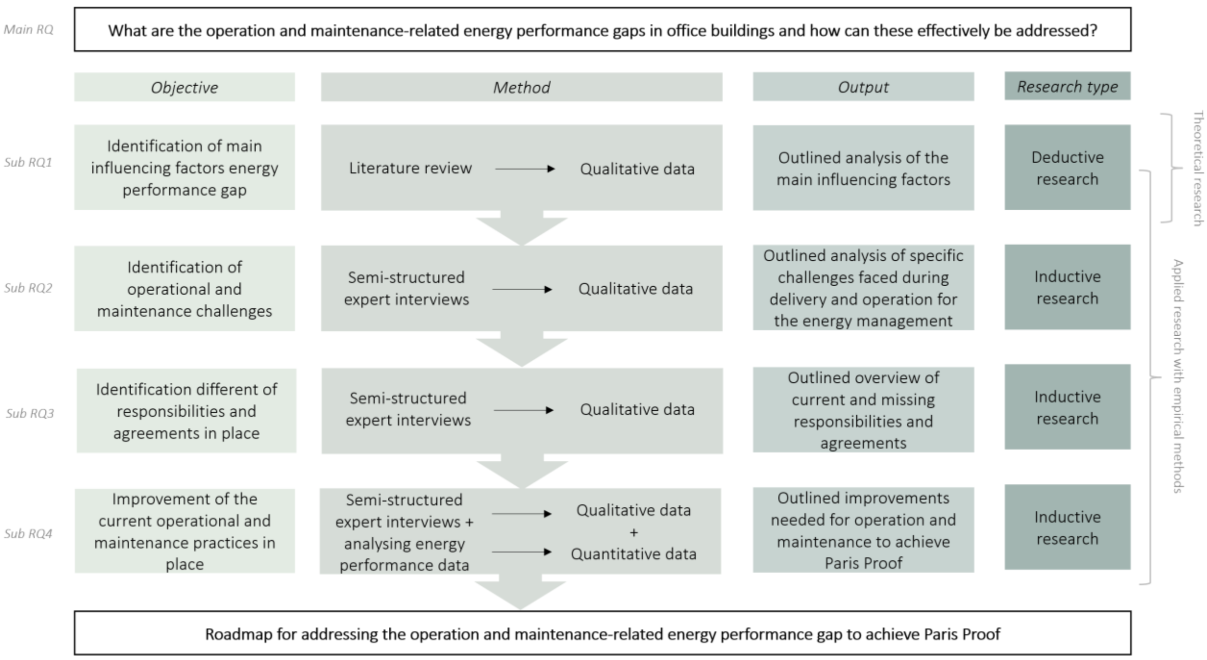

Figure 8: *Conceptual framework (own illustration)*

3. RESEARCH METHOD

3.1 Type of Study

The research methodology that will be used in this study is an explanatory mixed-methods research study, combining both qualitative and quantitative methods to fully address the energy performance gap (figure 8 and 9). The explanatory nature aims to go beyond describing the identified phenomenon and seeks to explain the underlying causes and relationships contributing to the gap. Given the complexity of this gap, the research attempts to provide an in-depth understanding of the problems and possible solutions by connecting quantitative data with qualitative insights. After conducting theoretical research, applied research will be done to address the challenges faced and to develop practical strategies. This will be done by using empirical methods which involves data collection from energy management systems and in-depth interviews.

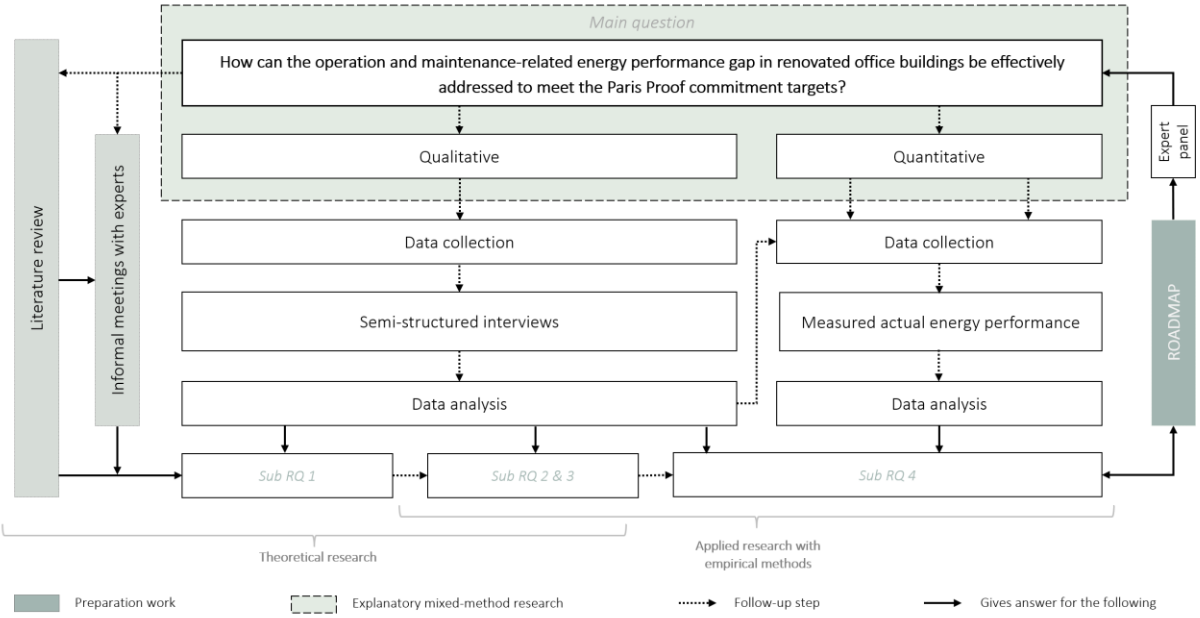

Figure 9: *Explanatory mixed-methods research*

3.2 Methods and Techniques

This study will be based on case studies of newly-built and renovated energy-neutral certified office buildings, using data on energy consumption that has been collected for a minimum of one year. The method starts with a thorough review of the literature, delving into the collection of information already existing to develop an in-depth understanding of the variety of factors influencing the performance gap. Subsequently, quantitative data collection will focus on key parameters, including data about energy consumption, building performance, and cost and efficiency. To collect this data, advanced technologies such as smart meters and building energy management systems will be used. Based on the outcomes, a qualitative in-depth interview will be constructed, using ATLAS.TI and Excel for the analysing.

3.3 Data Collection

A crucial step is collecting quantitative data, which captures important aspects of the building its energy performance. Based on the knowledge obtained during literature reviews and informal meetings with experts in different professions in this field, this process involves collecting information related to energy consumption, building performance indicators, and cost-efficiency measures. The approach applied is deductive, starting with a theoretical understanding of the gap, followed by a hypothesis formulation and the collection and analysis of data for confirmation. The data needed to get insights into the energy predictions consist of the EPC-calculations (Energy Performance Certificate). The data that will be analysed includes the energy consumption of the heating, ventilation, and air conditioning (HVAC) systems, lighting, pumps, and tap water. The minimum one-year measurement period of the data will guarantee a thorough examination of long-term trends and patterns. The quantitative data will be gathered from projects of the development company Edge. To get a comprehensive understanding, three different case studies projects will be used, all with different characteristics. The selected projects are the newly built Triodos and the renovation projects Edge Olympic and Edge West. All projects are BREEAM Outstanding or BREEAM Excellent certified buildings. BREEAM, standing for Building Research Establishment's Environmental Assessment Method, is the world's leading method for assessing the sustainability of projects in the built environment and sets the standard for best practice in sustainable design (BRE Group, 2023). Moreover, the energy-neutral certificate emphasis the importance of complying with the predictions. Triodos is owner-occupied while Edge West is rented with an intermediary party regulating the facility management. Edge Olympic is a hybrid version since the own developed building is being rented, however, the facility management is taken care of inhouse (Edge, 2023). Based on the results of the quantitative data, further qualitative data will be gathered, using in-depth interviews in order to gain additional insights into a building its energy management and how it affects the performance gap. The approach for the qualitative data is mostly inductive since it starts with a question, followed by observations using interviews, a tentative hypothesis, and finally a theory.

3.4 Data Analysis

Prior to the data analysis, information will be gathered from literature reviews and informal meetings with a climate system expert, building operator and developers. The knowledge obtained will provide a basis for the follow-up steps. The data analysis is characterized by a dual focus on first the quantitative data after which the qualitative dimensions will be developed. In the context of quantitative data, building performance, energy consumption, and cost and efficiency data analysis will be done based on minimal one year monitored data of three energy-neutral certified office buildings. The collection of quantitative data for three distinct case studies offers a comprehensive and diverse analysis of building energy performance since it includes newly constructed and renovated buildings, varying ownership and management models, and different systems and equipment. The minimum one-year measurement period ensures a thorough examination of long-term trends, while the inclusion of the ownership structure provides insights into the cost-efficiency measures. Furthermore, qualitative data of the case studies will be gathered and examined for trends and deeper insights concerning the challenges faced. Qualitative case studies involves an empirical inquiry that investigates a project within its real-life context. The case study methodology allows for flexibility in selecting data collection methods to suit the research purpose, emphasizing the significance of conducting a thorough, unbiased investigation over a sustained period (Priya, 2021). In-depth interviews will be done with people involved in the selected projects and with experts in the field of energy efficiency and the energy performance gap in the built environment. The interview transcripts are primary data and will be analysed using ATLAS.ti and Excel as tools. The goal of this thorough study is to find the gaps and patterns that are critical for understanding and addressing the issues presented by the performance gap in office buildings. The integration of different perspectives will provide nuanced insights into possible causes and facilitates the formulation of effective strategies to bridge the identified performance gap.

3.5 Data Plan

A data plan is needed to outline the comprehensive strategy and for handling and disseminating research data during and after the thesis in adherence to the FAIR guiding principles, which stands for Findable, Accessible, Interoperable, Reusable (Wilkinson, et al., 2016). The initial step encompasses literature reviews and informal meetings with project stakeholders and experts in energy efficiency and building performance, forming the basis and direction for further research. These experts are business partners and colleagues of Edge, facilitating the contact and exchange of knowledge. Further research will be based on the quantitative data from three distinct case studies. Following the data collection phase, the analysis process will begin with a focus on quantitative dimensions. This includes analyses of the building performance, efficiency, and energy consumption obtained from the monitored data. All the necessary data and other documents will also be provided by Edge since all the projects have been developed by the company. The data will be examined for trends and patterns, allowing for a comprehensive understanding of the long-term dynamics. Simultaneously, the qualitative data gathered through in-depth interviews will be subjected to empirical inquiry, emphasizing the importance of conducting a thorough, unbiased investigation of data gathered over an extended period of time. The integration of both quantitative and qualitative perspectives aims to identify critical patterns and gaps. The comparative analysis will facilitate the formulation of effective strategies to address the operation and maintenance-related performance gap. Throughout these steps, the data will be carefully managed and organized to ensure accuracy and reliability. Analyses will be carried out on quantitative data to draw meaningful insights, while qualitative data will be subject to thematic analysis and coding to identify key themes and challenges. The results of this data analysis will form the basis for recommendations and strategies to address the identified performance gap in office buildings. In accordance with the FAIR guiding principles, this research proposal outlines a methodological approach that aligns with principles of findability and accessibility. The research begins with a thorough examination of case studies, providing a clear starting point. In an effort to improve accessibility, the finalised thesis will be published in the TU Delft repository, ensuring its availability and longevity to the broader academic community affiliated with the Technical University of Delft. Standard research procedures are implied by the emphasis on careful data management, the use of standard formats, and clear references. The commitment to analyse both quantitative and qualitative data suggests the potential reusability of findings for future research projects. Furthermore, ethical considerations, data sharing agreements, and potential access restrictions will be addressed to enhance the overall FAIR compliance of this research.

3.6 Ethical Considerations

This thesis involves a research, employing a two-phase approach incorporating quantitative and qualitative data collection. The ethical considerations are guided by principles aimed at safeguarding the rights and well-being of all involved parties. Prior to data collection, clear informed consent processes will be implemented, ensuring participants understand the research's purpose, potential impacts, and their right to withdraw. Moreover, steps will be taken to safeguard privacy, including anonymizing and aggregating data to prevent the identification of individuals. Maintaining the integrity of the research requires a strong commitment to accurate and high-quality data. A key component will be transparent reporting that addresses any constraints or uncertainties related to the data. Comprehensive efforts will be made to mitigate potential biases in both quantitative and qualitative data throughout analysis and interpretation, once they are acknowledged. An essential component of this research's ethical approach is transparent reporting. The procedure of integrating quantitative and qualitative data will be carefully explained, enhancing the credibility and reproducibility of the results. Findings will be communicated back to the people involved, fostering a collaborative relationship that extends beyond the research framework.

4. RESEARCH OUTPUT

4.1 Goals and objectives

This explanatory mixed-methods research aims to comprehensively address the disparities between computer-based energy performance predictions during the (re)development phase and the actual usage in the operational phase of office buildings. The scope is on energy-neutral certified office buildings given the problems that could arise when the promised performance is not in alignment with the predictions. In order to achieve this goal, the research evolves with numerous interconnected goals and objectives. Addressing the disparities caused in the operational phase is the initial objective. This involves identifying the gaps that currently exist. To do so, a thorough literature review is conducted as part of the research. This literature review will provide the foundation for comprehending the current state of the performance gap. Moving forward, the research aims to analyse the main factors that contribute to the observed performance disparity. This entails a thorough analysis and classification of the many factors impacting the disparities, including the possible influence of the building's ownership structure and incorrect energy management. The analysis will specifically be focused on the operation and maintenance since it is impactful for the energy efficiency. Certifications, including BREEAM-NL and energy-neutral, and energy labels will be used as a benchmark. As a standardized indicator prominently displayed on buildings, these labels communicate expected energy performance to various stakeholders. They serve as a translation between theoretical energy models and real-world outcomes and foster transparency.

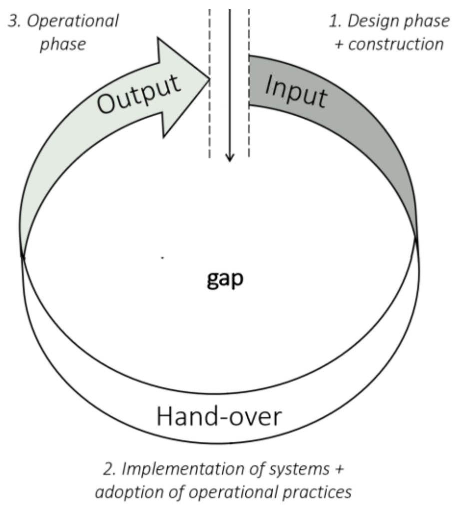

Figure 10: *Input vs output energy loop (own illustration)*

The whole process of comparing the energy predictions to the actual outcomes can be seen as a loop. In addressing the operation and maintenance-related energy gap, the scope will be focused on three main points in the process loop, as shown in figure 10. The input consists of the parameters and computer-based data used for the energy predictions, functioning as the starting point. The second aspect focuses on the information transfer and implementation of services and installations provided during delivery, recognizing their substantial impact on efficiency in energy management. The third and last focus is on the output, exploring the operation and maintenance of the energy systems in usage. Through close examination of these core points, the research aims to understand the impact of implemented parameters, identifying any factors that are presently missing in the output, and thus are essential to include in the input or output. In the end, strategies will be developed to address the gap in terms of the appropriate usage in the operation and maintenance.

4.2 Deliverables

The data analysis will be done using building energy management systems that offer monitoring, analysing, and improvement. When analysing the data, the focus will be on heating, cooling, and electricity usage with the parameters used for the energy prediction calculations as a starting point. These parameters, derived from a comprehensive investigation into real energy usage patterns, play a crucial role in predicting energy performance and its credibility. Importantly, this analysis helps identify any missing or unpredictable parameters and provides insights into possible errors in the way the energy systems are being managed. By addressing these gaps in knowledge, the research aims to provide a more holistic and accurate framework for developing strategies to address the existing performance gap in office buildings. Depended on the research outcome, this strategy could be a 'green menu' for the facility manager with different energy performance outcomes linked to different energy efficiency scores. This strategy anticipates on the unpredictable energy usage and emphasises that energy efficiency is related to different energy certificate achievements. Another possibility is the development of an energy performance agreement, manual or method for post-occupancy building monitoring and tuning. The proposed strategy will be focused on the possible linkage between the energy performance gap and the ownership structure of the building. This is directly linked to the financial considerations and the facility management. This approach not only contributes to the reduction of disparities but also strengthens the overall reliability of the computer-based predictions and real-world usage, facilitating more effective and sustainable (re)developments for office buildings.

4.3 Dissemination and audiences

Finally, the research concludes by providing recommendations for diverse stakeholders, aiming to facilitate the effective implementation of strategies and the practical addressing of identified disparities in energy performance, specifically strategies related to the operation and maintenance. These recommendations are aimed at key players in the building industry, including developers for addressing the energy performance gap in their projects and facility managers, building owners and renters who benefit from improved energy efficiency. Moreover, the strategy is focused on improving the usage of management energy systems due to an improved facility management. The research output, in terms of deliverables, is a comprehensive document that captures the breadth and depth of the research findings. These include a thorough review of the literature, an analysis of the contributing factors supported by relevant datasets, and the practical strategies outlined. As the research is a thesis affiliated with the Technical University of Delft, the findings will be published in the TU Delft repository.

5. PERSONAL STUDY TARGETS

For this thesis, the personal study targets embrace a multidimensional approach aimed at achieving a comprehensive insight in understanding and addressing the identified disparities in energy performance of office buildings from a development point of view. These targets emerged from an interest in sustainable practices in the built environment. As a graduating student, the main goal during P1 and P2 is to develop a strong foundation of knowledge through a review of existing literature and creating a research plan for the follow-up steps. Developing an insightful analytical perspective to examine and classify the factors that contribute to the observed performance disparities is an essential aspect of the personal study goals. The classified factors will be further examined separately through which the collection of information will be arranged and filtered. Depending on the causes, influencing factors, and possible solutions, a focus will be placed on specific areas. A key element of the personal study targets is acquiring expertise to evaluate the viability of proposed strategies. The overall goal of this research is to make a contribution to academic understanding and real-world building energy performance solutions. In order to improve sustainable building practices, it is important to develop more knowledge in the field and gain the ability to successfully explain and apply the study findings.

6. RESEARCH PLAN

6.1 Main tasks

The research plan involves several key tasks aimed at comprehensively addressing the energy performance gap in energy-neutral certified office buildings (figure 11). Initially, a literature review is done to understand the global significance of the gap and its challenges. Subsequently, a focused research question is formulated based on the literature review and informal meetings to investigate disparities in energy performance predictions versus the actual usage in the operational phase, with a specific emphasis on operation and maintenance-related factors. The main tasks include the implementation of a mixed-method research methodology, incorporating both qualitative and quantitative approaches. This involves case studies of Triodos, Edge Olympic, and Edge West, all three energy-neutral certified office building with distinct characteristics. The associated tasks include gathering data of each case study, processing it systematically, analysing it, and determining whether the outcomes are related to the ownership structure. Advanced technologies, including smart meters and building energy management systems, will be used to collect the building performance, energy consumption, and cost and efficiency data and interviews will be conducted. As part of the empirical research, in-depth interviews with people involved in the projects are essential to get a deeper understanding of the results. By combining the two approaches, the aim is to identify critical trends and understand gaps. Careful data management and organization is an important task to ensure accuracy and reliability. Insightful findings from the analysis of both quantitative and qualitative data will serve as the foundation for recommendations and strategies to address the identified performance gap. While conducting the research, ethical considerations need to be taken into account with a commitment to clear informed consent processes, participant privacy, and transparent reporting. The final task it to finalise the research output, captured in the final document with the goal to provide practical strategies for closing the performance gap.

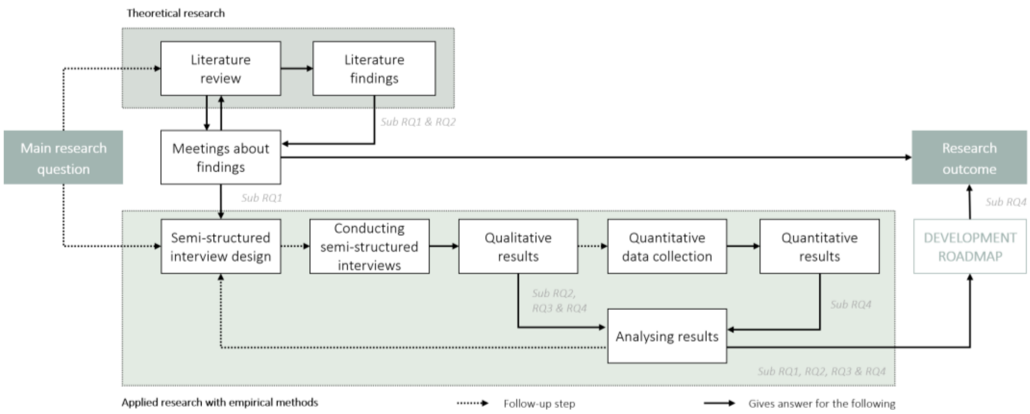

Figure 11: *Research process from the research question to the research outcome (own illustration)*

6.2 Main milestones

The whole process is structured through five phases, divided into 5 P's, to systematically develop the research. The first phase, which starts with P1, entails a thorough literature analysis to identify the research gap and understand the global relevance of the energy performance gap. The literature review emphasises the challenges during the operational phase, with a particular focus on challenges related to operation and maintenance. Moving on to P2, a crucial milestone is reached with the formulation of research questions focusing on disparities between energy performance predictions and actual usage in energy-neutral office buildings. Sub-questions delve into influencing factors, ownership structures, and operation and maintenance-related disparities. In addition, a key component of P2 is the research methodology, which uses a mixed-method approach to combine quantitative and qualitative techniques. In this phase the energy-neutral certified office buildings are selected as case studies. Based on the available data of these case studies, the data collection and analysis will be developed. As shown in figure 12, the actual research starts after P2 since the preparatory work has been done. The P3 phase is dedicated to progress evaluation, ensuring that the working method aligns with the requirements for the subsequent P4 phase. A data plan describes the FAIR-compliant handling and distribution strategy for research data. Ethical considerations include informed consent, privacy safeguards, and transparent reporting to ensure the integrity and protect the rights and well-being of all parties involved. The use of a mixed-method approach in the research methodology represents a significant milestone, incorporating qualitative and quantitative methods. The case studies, using advanced technologies serve as an important source for the data collection. The analysis in this phase entails a thorough investigation of both the quantitative and qualitative aspects. To understand the energy performance gap, factors including the energy building performance will be examined closely. An important milestone to be reached is the completion of the study output, which includes thorough findings from the literature review, an analysis of contributing factors, and development of practical strategies. Transitioning to P4, the research is finalized into a document with the P5 including the final presentation. The research plan, clarified in the conceptual framework and data loop, is strategically designed across the 5 P's to deliver valuable insights and practical strategies for effectively addressing the energy performance gap in energy-neutral certified office buildings.

Figure 12: *Research schedule (own illustration)*

6.3 Interdependencies between tasks and milestones

The research plan is carried out in five phases that are divided into multiple tasks and milestones that are logically linked together by interdependencies. The initial literature analysis (P1) sets the foundation for the field of research, shaping subsequent tasks such as formulating research questions and developing a mixed-method research methodology (P2). This methodology, in turn, influences case study selection and data collection in P2 and P3. The gathered information forms the basis of the analysis (P3), a crucial step that results in the finalisation of the study's output whereby specific tasks are needed to achieve the main milestones. Progress evaluation in P3 ensures alignment with future requirements. The final document (P4) and presentation (P5) are closely linked to insights and strategies obtained from thoroughly exploring the energy performance gap, reflecting the careful management of interdependencies in the research plan.

7. REFLECTION: Experiences AR3MBE100

The journey through AR3MBE100 has been both challenging and rewarding, serving as a crucial preparation for the upcoming graduation course AR4R010. My decision to focus on energy transition lab has shaped the process of my exploration, leading through the process of brainstorming, discussions with peers and professors, and literature reviews. While working towards my P1, the importance of thorough preparation was emphasized. This process involved extensive literature and market research, as well as coming into contact with an external company. These interactions provided interesting new insights for refining my research directions and facilitated the identification of potential gaps in existing studies. Moreover, it led me to a graduation internship at the development company Edge. I started my internship in November, which gave me a head start in learning about the company's insights while exploring the available data, helping future research. This hands-on experience allowed the integration of theoretical knowledge with practical insights, strengthening the relevance and feasibility of my proposed research. My progress has been significantly contributed by the collaborative bi-weeks lab meetings together with other students, all with diverse research directions. These interactions of thoughts and perspectives provided interesting discussions, knowledge exchange, and helpful feedback.

The P1 assessment marked a decisive moment, where I presented a draft version of my P2 report, demonstrating the progress. The feedback received during the P1 assessment served as a valuable guide for further refining the research proposal. This process went along with ups and downs in the process. I noticed that I sometimes had to take a step back to be able to go a step further. Moreover, the regular meetings with my mentors and colleagues have been of great added value due to their input which made me thinking and gave me new insights. As I transition towards P2, I recognized the helpfulness of the comprehensive understanding of the research subject through an extensive literature review, the formulation of substantiated research questions and feasible goals. Moreover, it gave support for the development of a research plan that aligns with both deliverables and learning objectives. The time between P1 and P2 became crucial requiring thorough decisions to ensure both reliability and adaptability for the upcoming AR4R010.

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