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An innovative approach to implementing advanced energy projects in urban areas: From comprehensive simulation to actual implementation☆

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ABSTRACT

The recent energy crisis has once again confirmed that energy and resource efficiency, combined with the use of renewable-energy sources, must be the backbone of future sustainable development across all sectors. It is also clear that achieving climate neutrality by 2050, or sooner, will require new approaches. At the implementation level, the social, technical and financial realities of local energy projects demand solutions that appeal to a variety of stakeholders, including utilities, energy service companies, banks, and end users, who must collaborate to bring projects from the idea to a practical implementation. Presented here is a methodical approach to establishing advanced energy communities in complex urban environments and implementing advanced projects with a common energy infrastructure. The outcomes of the first use case clearly indicate that investing in an energy community is beneficial from multiple perspectives. Detailed simulations enabled an accurate assessment of additional renewable-energy potential, revealing that the company in question has the capacity to install another 11,000 kW_p of PV in Ljubljana and other locations across Slovenia. This would increase the share of renewable energy in its total electricity consumption to 31 %, which is in line with the national target for 2030. In the second use case, a significant potential for utilizing excess heat from a data room was identified. An economic analysis showed that the excess-heat utilization project has a payback period of 2.5 years, a net present value of over EUR 47,000 and an internal rate of return of 40 %.

1. Introduction

Renewable-energy communities have a major role to play in the current energy policy of the European Union (EU). The first step in this process was the Clean Energy for All Europeans Package [1], which was adopted in 2019. It was to encourage the decentralization of energy production, moving it away from large, centralized power plants to smaller, local renewable-energy sources like solar, wind and biomass. The next legislative push came with the adoption of the revised Renewable Energy Directive (EU/2023/2413) [2], the recast Energy Efficiency Directive (EU/2023/1791) [3] and the recast of the Directive on Common Rules for the Internal Electricity Market (EU/2019/944) [4]. The research presented by Olabi et al. [5] confirmed that renewable-energy resources contribute positively to achieving the Sustainable Development Goals (SDGs), with SDG-7 “Affordable and Clean Energy” being the most impacted, followed by SDG-13 “Climate Action”, SDG-15 “Life on Land”, and SDG-8 “Decent Work and Economic Growth”. Furthermore, according to [6], there is a growing emphasis on developing software tools that can analyse the environmental impact of renewable-energy systems and support sustainability goals. However, the research of Dioba [7] revealed that regulatory complexity is the primary barrier that hinders the establishment and subsequent development of energy communities in the countries of the EU.

The systematic planning of a sustainable-energy infrastructure is essential for the effective and widespread implementation of energy-community projects. According to [8], pragmatic policies, economic benefits, and the optimised management of human and physical resources are essential for establishing stable energy communities.

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Wilberforce et al. [9] confirmed that modelling the renewable-energy potential within urban areas faces several challenges, including a lack of data, the complexity of the urban energy system, scalability, the need for interdisciplinary collaboration, and the refinement of adopted policies regarding energy-infrastructure investments and urban planning. Stegen et al. [10] proposed a cooperative approach aimed at sizing the distributed energy resources in a renewable-energy community and concluded that such communities can boost the energy transition in two ways: by increasing the maximum profitable capacity and by improving profitability in the use of distributed energy resources. Košnjek et al. [11] proposed the concept of the reference architecture for an energy-community model that enables both systematic and sustainable local planning. Kerscher et al. [12] evaluated six different energy-community planning approaches that considered regulatory and social perspectives, and demonstrated that grid-friendly, energy-community planning enables the high penetration of photovoltaic (PV) systems, while only minimally affecting the community benefits. The research presented by Marino et al. [13] revealed that the further development of grid connected systems will involve PV systems equipped with a smart supply management for multiple users, who are interconnected and linked to the grid in a way that allows them to share any surplus PV production before exporting it to the grid. This setup enables the exchange of excess solar generation within the community, maximizing local consumption. According to [14], in future smart grids, energy-storage technologies have the potential to address the challenges posed by the intermittent and unpredictable nature of renewable-energy sources, facilitating an overall energy balance and efficient scheduling. The research of Berg et al. [15] revealed that the ratio between the commercial and residential load profiles in a mixed-load configuration significantly impacts on the feasibility of energy-community projects. In general, a high ratio of commercial loads results in a higher self-consumption rate and a lower maximum import, but it does not necessarily reduce the costs. This is also in line with the research presented by Velkovski et al. [16], which confirmed that substantial consideration should be given to designing tariff structures that incentivize energy sharing in renewable-energy communities. Additionally, Miky et al. [17] presented an interesting hybrid system concept based on a solar PV/battery combination for direct-current (DC) power supply in commercial buildings. They concluded that integrating local generation and storage with DC power could improve the energy efficiency by avoiding conversion losses, which occur when alternating current (AC) is converted to DC for storage and then back to AC for end use [17].

According to [18], current energy-demand forecasts indicate that heating needs are expected to decrease (due to better-insulated buildings and milder winters), while cooling requirements are projected to increase (as a result of hotter summers and urban heat-island effects). In this context, the application of advanced, PV-based energy communities in urban areas has the potential to support the grid during the peak summer months. Coupling PV with heating-and-cooling applications is achieved by using heat pumps [19]. The research presented by Zhang et al. [20] revealed that data centres consume large amounts of electricity, and as a result, a lot of excess heat is usually discharged to the external environment through electric cooling. This heat is not effectively utilized for heating or, at the very least, for the generation of sanitary hot water, and simply adds to the problem of urban heat islands. Yang et al. [21] introduced the concept of the prosumer data-centre system and proposed a rule-based optimization strategy to adjust the optimization variables based on renewable-energy generation. In the system-optimization process, the selection of the heating temperature of the surrounding buildings according to renewable-energy generation is one of the envisioned steps [21]. The research presented by Jouhara et al. [22] suggests that, to achieve optimal efficiency through excess heat recovery, each specific process should be thoroughly examined and analysed before assigning the most suitable recovery method. This implies that there is no universal solution that is applicable to all processes. Each process should be carefully evaluated and simulated to identify potential opportunities for improvement.

The research described in this paper was inspired by the recommendations of Olabi et al. [5] and Wilberforce et al. [9], which suggest that future research should focus on enhancing distributed photovoltaic systems, developing innovative data-collection methods, encouraging interdisciplinary collaboration, and creating strategies to boost both self-consumption and energy efficiency in urban locales. Additionally, this paper evaluates the economic effectiveness of selected projects in two different contexts: a large business entity and a complex of buildings for educational and research purposes. In the case of the large business entity, the key parameter determining the project's overall performance is the price of electricity offered to leaseholders in the selected buildings. This price is partly driven by the self-consumption rate and must remain competitive while ensuring a positive cash flow for participants in the energy-community project. In contrast, for public buildings used for educational and research purposes, the key parameter is the amount of saved energy and the reduction in CO_2 emissions. According to [23], energy-community projects also represent a promising solution to the challenges faced by buyers and sellers of carbon credits in the voluntary market, particularly when there are credibility concerns. The selection of PV systems as the primary renewable-energy source (RES) in the presented research was based on a combination of site-specific factors, including available roof surfaces, ease of integration with the existing infrastructure, favourable economics, and alignment with the typical daytime load profiles of the buildings. The case studies are located in Central Europe, where long, low-sunlight winters limit the year-round effectiveness of solar thermal systems, particularly when the buildings are already connected to local district-heating systems. Additionally, wind energy was not considered viable at these specific urban sites due to an insufficient wind potential and the regulatory constraints related to urban planning. However, the proposed approach is intentionally modular and technology-neutral, and it can be adapted to include other RES technologies such as a solar-combi system for indoor space heating [24], hybrid PV-wind systems with micro-compressed air energy storage [25], or even geothermal and biomass solutions where local conditions are more suitable. The methodological framework supports such configurations by design, and its flexibility allows for an optimization based on the specific energy demands, climate characteristics, and policy context of each location.

2. Methodology

The methodology of the proposed innovative approach evolved from the traditional management structure, the plan-do-check-act (PCDA) model, which has been upgraded with modern tools for modelling complex energy systems, predicting future energy consumption, and calculating the feasibility of selected projects. Due to the extent and complexity of the relationships between various business entities and the variety of their professional and social backgrounds, designing a common energy infrastructure is a very complex task. During the definition of the methodology, special attention was given to the selection of appropriate buildings. Fig. 1 schematically presents the identified, essential steps in the process of creating an advanced energy community or implementing advanced projects with a common energy infrastructure. The concept is similar to the research methodology proposed by Venhovens et al. [26], which includes the following steps: stakeholder analysis, identifying effects, quantifying effects, defining financial indicators, defining scenarios, and a sensitivity analysis. Also, it follows on from the recommendations for future work proposed by Vergerio et al. [27], and includes a wider list of key performance indicators to support large-scale energy-retrofit actions. However, the proposed approach includes comprehensive modelling and simulations, which can be considered an important upgrade.

The core element of the model is the energy cost centre (ECC). The concept of energy-consumption modelling based on a network of ECCs was introduced by Morvay and Gvozdenac [28], and it starts with the

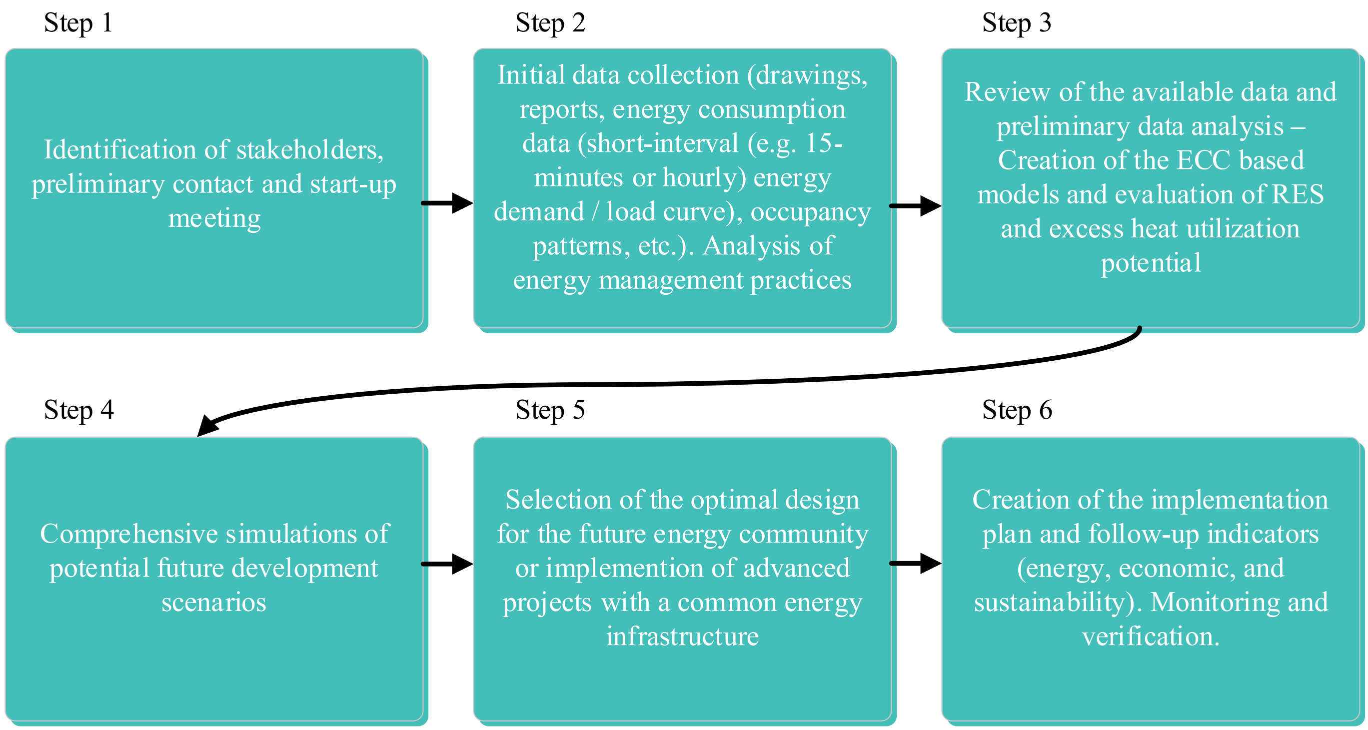

Fig. 1. Essential steps in the process of creating an advanced energy community or implementing advanced projects with a common energy infrastructure.

integration of energy within the activity flow charts. In the case of the addressed business entity, an ECC can be any building, department, or machine that uses a significant amount of energy or creates significant environmental impacts [28]. However, the guiding principle for the modelling setup is to follow the activity at a specific location, and then try to define the ECCs so that they coincide with the existing boundaries. Also, in each ECC, loads are called energy-cost units and are classified into controllable and uncontrollable loads. Uncontrollable loads are those that cannot be part of the peak-load management actions. The amount of data needed to optimize the energy performance of a selected building is directly connected to the activities that take place in that building. The presented modelling concept provides a framework for performance monitoring and targeting at each designated responsibility centre and directly connects people with tasks in each ECC. The identified activities and actors that must be involved in the implementation of an advanced energy-community project in a complex environment or in implementing advanced projects with a common energy infrastructure are presented in Table 1. However, the selection of simulation tools should be guided by the specific requirements of each specific use-case-scenario simulation as well as the technical system optimization relevant to advanced energy projects in urban environments. For example, in the addressed research the PV-generation simulations were developed using Matlab, with a time resolution of 15 min. The input parameters included the historical irradiance data, roof orientation, and load profiles from already-installed meters. The load simulations were built on ECC segmentation, using real electricity-consumption data from 2022 as a baseline. All the models were validated against existing measurements, and each ECC was categorized by the load controllability and operational pattern. For simulations involving excess-heat recovery, boundary conditions were defined using temperature distributions, airflow rates, and equipment power densities derived from Computational Fluid Dynamics (CFD) calculations.

Table 1
Activities and actors involved in the creation of an advanced energy community or implementing advanced projects with a common energy infrastructure.

Activity	Actors involved
Self-assessment of the energy needs and environmental impacts related to the energy use at the selected location	Energy manager Facility manager Environmental manager
Setting a baseline for the performance monitoring	Energy manager with the support of external expert organization
Technical evaluation of possibilities for the creation of advanced energy community or implementing advanced projects with a common energy infrastructure	Independent external expert organization supported by the energy manager
Evaluation of existing electricity or district-heating grid capacity at the supply/connection point	Utility
Analysis of the existing electricity and heating demand and impacts of local electricity generation or excess heat utilisation (simulations and calculation of the feasibility for all addressed alternatives)	Independent external expert organization supported by the data from the utility, local energy-management system and expert support from energy manager
Creation of realistic implementation plan and follow-up indicators	Energy manager supported by the external expert organization
Formal approval of the selected advanced energy-community project or advanced projects with a common energy infrastructure	Management board, owners and leaseholders
Implementation of the selected advanced energy-community project or advanced project with a common energy infrastructure	Company specialized in envisioned worksEnergy and facility managers (monitoring and supervising)
Verification of performance improvements based on the real-time utility data and energy-management system	Energy manager supported by the data from the utility and local energy-management system

2.1. *Use case 1: Large business entity from Ljubljana, Slovenia*

The addressed business entity is situated in the eastern part of Ljubljana, the capital of Slovenia. With nearly 225,000 m^2 of business premises and 21 million visits per year, it is one of Europe's largest business, shopping, recreation, entertainment, cultural, and innovation centres. In terms of energy use and environmental impacts, the addressed business entity is among the most advanced large enterprises in Slovenia. The company has committed to actively support the introduction and promotion of the most modern and cleanest technologies that enable environmental protection at the highest achievable level. In the process of a sustainable transformation, the company has already established and certified its quality-management system according to the ISO 9001 standard, its environmental management system according to the ISO 14001 standard, its energy-management system according to the ISO 50001 standard, and the asset-management system according to the ISO 55001 standard (the first in Slovenia). Altogether, this forms a uniform, integrated management system, which represents a unique feature in corporate management and a novel approach in the retail and service sector.

The addressed business entity consumes approximately 34,000 MWh of electricity and 17,000 MWh of district heat annually. It also successfully generates renewable electricity through solar plants. The pilot at the addressed location includes the following infrastructure: 12 transformer stations, 8 km of district-heating network, 12 km of water-supply network, a large battery, 5 emergency diesel generators, 2 PV plants (with two more built during the CREATORS research project – CREATing cOmmunity eneRgy Systems), and more than 60 electric-vehicle (EV) charging points.

The large business entity provided a real testing environment for the validation of the proposed concept. According to [29], this represents an opportunity with unusual levels of research access.

2.2. Use case 2: Complex of buildings for educational and research purposes in Slovenia

At the time of writing, the described concept is being tested at an educational and research building complex in Slovenia. The aim of this use case is to examine how excess heat from a data room at the selected site can be utilized to heat a nearby building. The location provides a real-world testing environment, with full support from the management and maintenance staff, as well as open access to all the requested data needed to validate the proposed concept. In line with Eisenhardt and Graebner [29], this represents an opportunity for unusually comprehensive research access.

The selected Slovenian site consists of seven large buildings dedicated to research and education, covering a total useful floor area of 10,500 m^2, plus two auxiliary buildings with a total useful floor area of 300 m^2. Within these nine buildings, there are four research departments and eight centres providing specialized services, staffed by approximately 120 employees, and receiving about 10,000 annual visitors (pupils, students, teachers, etc.). The data room operates continuously, 24 h a day, seven days a week, with an average load of about 50 kW.

3. Results and discussion

3.1. Large business entity

The first activity prior to the creation of an energy community was a SWOT analysis, which was the result of comprehensive sets of discussions among the representatives of the addressed business entity and the technical support organisation, as well as representatives from different stakeholder groups, such as energy utilities, final users and leaseholders, consulting companies, representatives of energy service companies (ESCOs), and individual energy experts. Additionally, the SWOT analysis was crucial for a better understanding of the needs and expectations of the local community at the addressed location, and it should be considered as the first step in the future implementation of the development strategies within a complex urban environment. The initial SWOT factors related to the implementation environment for energy-community-related projects are detailed in Table 2. This analysis also provided deeper insights into the community characteristics that are essential for energy-community planning and implementation.

Table 2
Initial SWOT analysis of the implementation environment for energy-community-related projects in the addressed large business entity.

Strengths	Weaknesses
• High level of technical and energy-efficiency culture, openness to new technologies, ability to innovate • Strong sensitivity towards sustainability – trendsetters in city of Ljubljana	• Some roofs should be reinforced before installation of PV plants, which makes projects more expensive • Lack of engagement among leaseholders and residents of neighbouring buildings regarding the benefits of energy-community projects
• Pioneers in implementation of innovative energy projects including the first energy community and excess heat-utilisation project	• Concerns about the visual impact of RES installations • Integrating new energy solutions with existing urban infrastructure can be challenging
• Positive experience with implementation of RES-based projects and utilisation of energy flexibility • Located in the urban environment with possibility to connect with owners of neighbouring buildings and exploiting local environment as one big energy system	• Possible fluctuations in the economic activity in the urban area could have a negative impact on funding and investment in energy-community projects
Opportunities	Threats
• Enhancing local energy independence and security and enhancing urban resilience to energy-supply disruptions and climate-change impacts.	• Complex regulations regarding the establishment of local energy communities, which makes the process of obtaining necessary permits very complex and time-consuming
• Creating new jobs in installation, maintenance, and management of community energy systems	• Weak support from the state for the implementation of energy-community projects and the green transition of urban areas
• Fostering a sense of community and collective action towards sustainability goals	• Fear that natural disasters or extreme weather events could damage infrastructure and disrupt energy supply (consequence of the severe 2023 flooding in Slovenia)
• Increasing public awareness and demand for local sustainable projects with the focus on RES and e-mobility • Greening the image of all participating stakeholders, reducing carbon footprints and contributing to cleaner, healthier urban environments	• Fear that rapid technological advances could render current systems obsolete or less efficient • High volatility of energy prices could threaten the economic feasibility of future projects • Fear that geopolitical instability and climate-related disruptions (e.g., extreme weather, supply-chain breakdowns) could affect technology deployment and reliability and delay project timelines and increase costs

In the case of the addressed business entity, the structure of the model is defined by the collection of signals in the selected buildings. This approach is suitable for commercial applications and is commonly used to facilitate control, record current operating conditions, and direct an analysis along a logical path, starting from energy-conversion systems, through the distribution network, on to the final users. A performance improvement starts with energy benchmarking, which is used to compare the performance of individual ECCs with the most energy-efficient ECCs.

Fig. 2 presents a schematic of the ECC model for the addressed pilot site. From the business perspective, it was vitally important to simulate different future-development scenarios and be capable of objectively evaluating the economic feasibility of the two main groups of future projects: renewable-energy utilisation and peak-load management. Technological assemblies (battery-storage systems) that have not yet been installed on site are shown in glow. Elements that are installed or were utilised during the CREATORS research project are marked with the CREATORS logo (two PV plants and an emergency diesel generator for one of the buildings).

The initial aim was to investigate the economic performance of

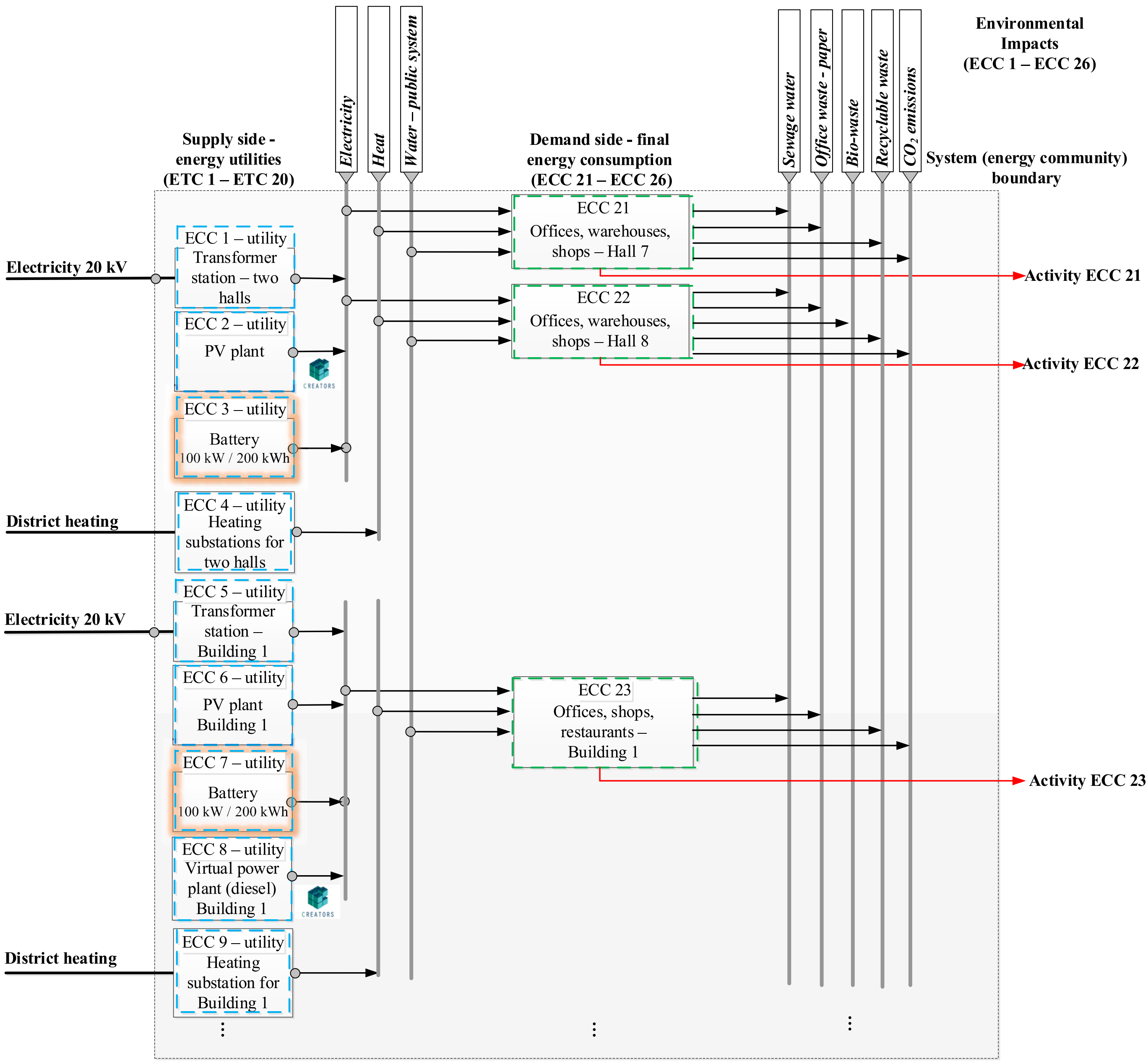

Fig. 2. Energy-cost-centre-based modelling – schematic of one part of the addressed pilot site.

small-scale PV installations on the roofs of two buildings. To achieve this, models were developed and enriched with historical data, as well as data from newly installed meters, which facilitated the modelling, identification, and evaluation of new local RES capacities (rooftop PV systems) and the potential for utilizing flexible assets to provide auxiliary services. Data from 2022 were selected as the reference dataset for all future scenarios.

The first analysis enabled a more accurate assessment of the RES potential and revealed that the examined business entity could install an additional 11,000 kW_p of PV capacity, thus increasing its level of self-consumption and raising the share of RESs in the total electricity consumption to 31 %. The total PV potential of 11,000 kW_p refers to installations not only at the main business entity in Ljubljana but also across other properties owned by the same company throughout Slovenia. The simulation considered all the available roof areas in this wider portfolio to estimate the maximum technically feasible PV capacity. The current energy-system design prioritizes the direct, real-time consumption of all the electricity generated on-site, ensuring that renewable energy is immediately utilized without the need for intermediate storage. This setup is economically optimal under current conditions, where the PV capacity remains below 7 MW_p, and where the generation of electricity closely aligns with the demand patterns. As such, the integration of battery-storage technologies has so far been limited to simulation and feasibility studies, which indicated only marginal economic benefits at the present scale.

Initial PV system models, capable of calculating electricity generation in 15-minute intervals, were created in MATLAB. In the next step, models developed for the PC platform were transferred to a dedicated computer platform. These models empowered the energy manager to conduct comprehensive analyses of potential future-development scenarios. Fig. 3 illustrates the results for 2026, for which it was assumed that 4 MW_p of PV capacity could be installed. The simulation for 2026 assumes a projected, installed PV capacity of 4 MW_p as part of a phased rollout plan. This includes initial smaller-scale installations, such as the

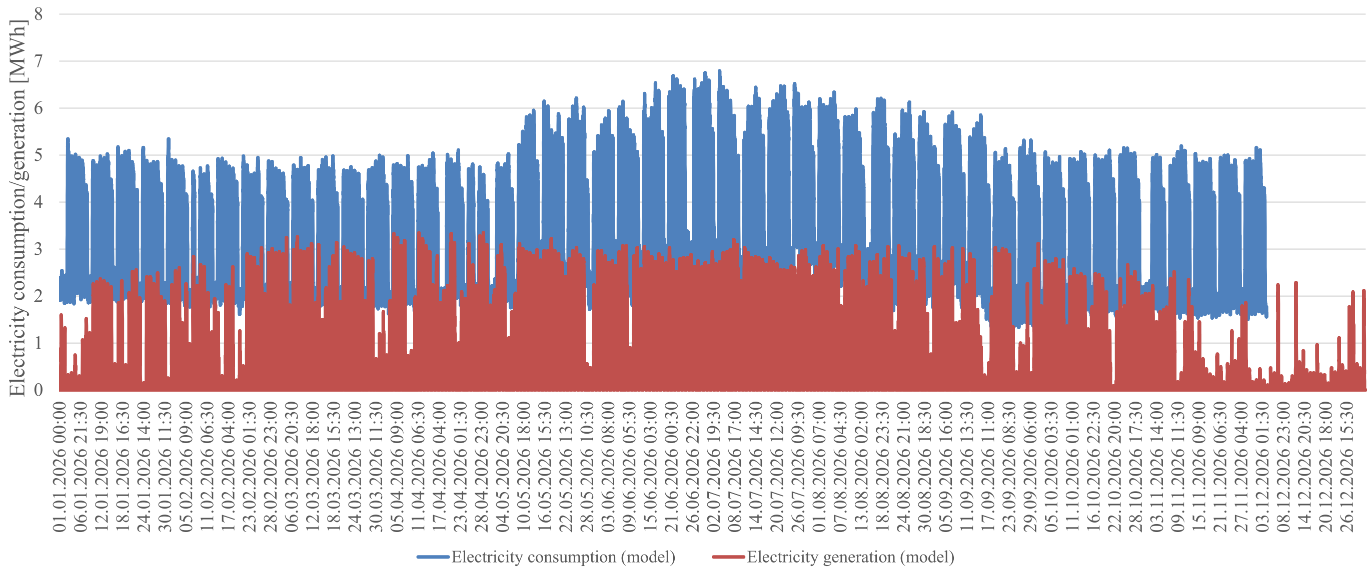

Fig. 3. Modelled electricity consumption and generation in 2026 (estimated installation of 4 MW_p PV).

200 kW_p pilot project illustrated in Fig. 2 (marked with CREATORS logo), and progresses towards a medium-term target of 4 MW_p at the main business site. The longer-term technical potential across all the company-owned locations is approximately 11 MW_p. These figures illustrate the different planning horizons, from the pilot scale (200 kW_p), medium-term expansion (4 MW_p), and full technical potential (11 MW_p).

The developed model also allows the energy manager to evaluate the electricity generation from the PV system on the selected rooftop and compare it to the actual consumption in the corresponding building. Fig. 4 illustrates the situation for ECC 21 (Hall 7), where the modelled PV generation significantly exceeds the on-site electricity consumption. This imbalance, visible in orange, prompted the energy manager to explore the potential for establishing a local energy community, by connecting the surplus generation in ECC 21 with the nearby ECC 22 (Hall 8), which shares the same transformer station. Although only ECC 21 is shown in the figure, the analysis considers both cost centres as part of a broader optimization strategy aimed at maximizing the self-consumption and reducing the grid dependency through local energy sharing. This, in turn, led to a further investigation of the economic performance of a small PV system installed on the roof of ECC 21 and the creation of an energy community. Following the creation of a local energy community through the connection of the two ECCs, the entire quantity of PV-generated electricity is utilized on-site, without any exporting to the public grid. The results of the economic analysis are presented in Table 3.

A complex simulation of the use of a battery-storage system for local balancing, peak-load management and providing auxiliary services (secondary frequency control) was also performed. Due to higher investment costs and relatively low gains from the peak-load management, the economic performance of this project was negative. The results of the economic analysis are given in Table 4.

On the other hand, an economic analysis of the potential for utilising the flexibility of the existing emergency diesel generator for providing

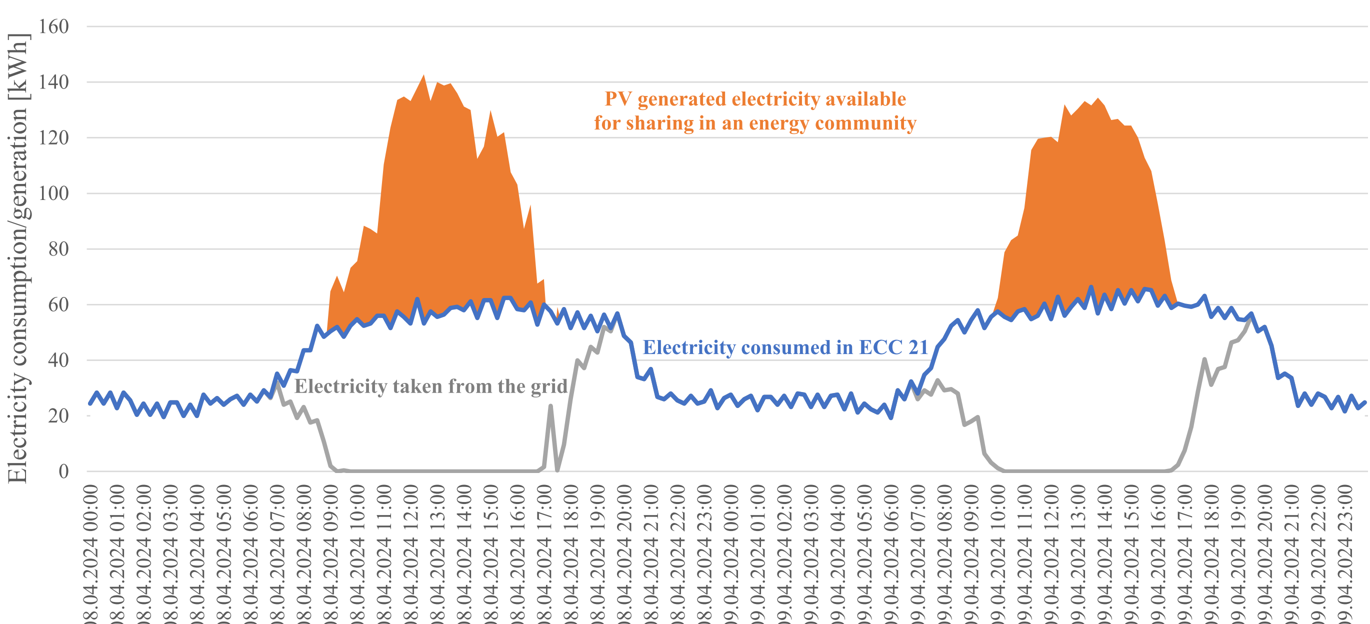

Fig. 4. Visualisation of the electricity consumption and generation in ECC 21.

Table 3
Results of the economic analysis of a small PV-based energy community.

	Units	Value
Installed power	kW	200
Estimated electricity price (including energy and grid fee)	EUR/MWh	140
Investment	EUR/kW	900
Economic lifetime	years	15
Required return on equity	%	5.0
Fixed annual maintenance costs	EUR/kW	8
Fixed annual insurance costs	EUR/kW	8
Design, connection and commissioning	EUR	21,000
Total costs of the PV system (investment)	EUR	201,000
Expected electricity generation	MWh/year	207
Value of the generated electricity	EUR/year	28,980
Operation, maintenance and insurance costs	EUR/year	3,200
Total savings	EUR/year	25,780
Simple payback period	years	7.8
Internal rate of return	%	9.6
Net present value	EUR	66,588

Table 4
Results of the economic analysis of a small battery-system installation for local balancing, peak-load management, and provision of auxiliary services.

	Units	Value
Installed battery power (C = 0.5)	kW	100
Installed battery capacity	kWh	200
Investment	EUR	95,000
Economic lifetime	years	10
Required return on equity	%	5.0
Fixed annual maintenance costs	EUR	1,000
Expected annual savings	EUR/year	10,500
Simple payback period	years	9.0
Internal rate of return	%	1.9
Net present value	EUR	−13,922

tertiary frequency regulation showed excellent economic performance, see Table 5. With very small modifications, the existing emergency diesel generator was made capable of providing essential backup power and supporting grid stability by operating synchronously with the grid during emergencies or peak demand times.

The results showed that there is a need for a clear guideline, including the applications and service packages to support the initiators and local service providers in initiating, planning, implementing and operating an energy-community project. In this context, an addressed business entity represented an ideal sandbox for testing innovative approaches for creating smart energy communities.

From the energy manager's perspective, various simulations of potential future-development scenarios should enable informed decision-making based on detailed financial assessments, including costs, expected savings, payback period, and the net present value for each option being analysed. The results also suggest that utility companies should take a more active role in the creation of local energy communities and support their establishment in multiple locations to serve as system reinforcements. This underscores the significance of data availability, reliability, and relevance for the successful simulation of energy consumption in the addressed areas and participating buildings. Also, in order to additionally support the energy manager a sensitivity analysis for a small PV-based energy community and a small battery-system installation for local balancing was conducted, assessing the impact of ± 20 % variation in electricity prices and investment costs. The results in Table 6 confirm that the PV community project remains economically viable in all cases, while battery systems became feasible only in cases when the investment costs are 20 % less than initially estimated or monetary savings are 20 % higher than initially estimated. This is mainly because of the relatively high investment costs for battery systems.

At the end, it is important to emphasise that two out of three modelled projects with positive economic indicators, such as the small PV-based energy community and the diesel generator utilization for tertiary frequency regulation, have already been implemented. Initial operational results indicate even better performance than originally estimated in the feasibility analyses, confirming the robustness of the simulation approach. This is vitally important for all future projects since demonstrating tangible benefits in the initial phases builds trust among management and stakeholders, strengthens institutional support, and accelerates commitment towards future phases of decarbonization and community-based energy initiatives.

Table 5
Results of the economic analysis for the utilisation of the emergency diesel generator to provide tertiary frequency regulation.

	Units	Value
Installed capacity of the emergency diesel generator	kW	700
Investment	EUR	19,000
Economic lifetime	years	10
Required return on equity	%	5.0
Expected annual savings	EUR/year	10,170
Simple payback period	years	1.9
Internal rate of return	%	53.4
Net present value	EUR	86,561

3.2. Complex of buildings for educational and research purposes

The first energy-efficiency project that was implemented in the addressed data room was the implementation of the modern energy-management tool for energy performance monitoring [30]. The availability of data for the performance evaluation was a precondition for the exploration of possibilities for any future update and eventual utilisation of the excess heat. The first activity in the possible future exploitation of the excess heat was a self-assessment of the energy needs and environmental impacts related to the energy use of the data room. This was also

Table 6
Results of the sensitivity analysis: a small PV-based energy community and a small battery-system installation for local balancing.

Project	A small PV-based energy community				
	−20 %	−10 %	0 %	+10 %	+20 %
Investment costs [EUR]	160,800	180,900	201,000	221,100	241,200
Simple payback period [years]	6.2	7.0	7.8	8.6	9.4
Internal rate of return [%]	13.7	11.4	9.6	8.0	6.6
	−20 %	−10 %	0 %	+10 %	+20 %
Electricity price [EUR/MWh]	112	126	140	154	168
Expected annual savings [EUR]	19,984	22,882	25,780	28,678	31,576
Simple payback period [years]	10.1	8.8	7.8	7.0	6.4
Internal rate of return [%]	5.5	7.6	9.6	11.5	13.3
Project	A small battery system installation for local balancing				
	−20 %	−10 %	0 %	+10 %	+20 %
Investment costs [EUR]	76,000	85,500	95,000	104,500	114,000
Simple payback period [years]	7.2	8.1	9.0	10.0	10.9
Internal rate of return [%]	6.4	3.9	1.9	0.1	−1.5
	−20 %	−10 %	0 %	+10 %	+20 %
Expected annual savings [EUR]	8,400	9,450	10,500	11,550	12,600
Simple payback period [years]	11.3	10.1	9.0	8.2	7.5
Internal rate of return [%]	−2.2	−0.1	1.9	3.7	5.5

in line with recommendations of Singh et al. [31], who proposed that the assessment should include an evaluation of thermal management including CFD simulations and field data collection, including IT load, air temperature, and humidity. CFD has been increasingly recognized as a valuable tool for analysing the thermal behaviour in data-intensive environments and optimizing heating, ventilation and air-conditioning (HVAC) systems in complex building configurations. It is particularly effective in identifying hotspots, validating cooling strategies, and supporting decisions related to excess heat recovery. CFD enables detailed spatial simulations of the airflow, heat transfer, and thermal interactions that are not easily measurable with physical monitoring alone. Stavrakakis et al. [32] outlined the fundamental principles and common computational tools used in building-energy and urban-microclimate simulations, highlighting CFD's role in accurate, high-resolution thermal modelling. In the context of the presented use case, the CFD analysis enables spatially detailed, predictive modelling that complements real-time monitoring and supports the strategic implementation of an excess-heat-utilization system. For this purpose, the CFD model of the data-room configuration was created, see Fig. 5. The main components include server racks (centre), cold aisle containment (front), hot aisle (rear), air inlets and extraction vents.

The next step involved the creation of the ECCs model for the entire location to identify potential heat sinks. The main idea is to enable the creation of an efficient heat-exchanger network that will enable reliable simulations and support the installation of additional sensors and meters that will be used in the future verification of the achieved energy savings. Fig. 6 shows the activities and energy flows through all the ECCs at the selected location, with inputs, outputs, and interactions involving the environment. It is important to emphasise that the selected location represents one of the most advanced public-research campuses in the country in terms of energy management and technical infrastructure. Several energy-efficiency projects have already been successfully implemented, including the integration of a high-efficiency, combined-heat-and-power (CHP) unit in a local central heating system, as well as excess-heat recovery from one of the laboratories, which is used to heat adjacent office spaces. In addition, the emergency diesel generator is already operational and actively used for tertiary frequency regulation, demonstrating the site's engagement in demand-side flexibility and grid services. Against this advanced baseline, the remaining challenge addressed in this research was to design and verify the utilization of excess heat from a more complex setup and to transfer low-grade waste heat from the data room (operating continuously) to a set of research laboratories with varying thermal demand profiles. In the case of the data room, data about the average aggregated IT load on the addressed cluster computers and total electricity consumption were used as input data for the estimation of excess-heat-recovery potential. The extracted excess heat will be transferred to laboratories that need heating. To ensure efficient system operation, advanced control will be necessary, allowing adjustments according to the current heat demand and the availability of excess heat.

Even the simulation-and-planning phase revealed that implementing an excess-heat-utilization project, where heat from a data room will be used to heat laboratories operated by a different department, can be challenging because each department often operates with its own budget, goals, and decision-making authority. Coordinating a cross-departmental initiative requires substantial negotiation and the alignment of priorities. Each department had its own mission-critical projects, making it difficult to secure time and resources for cross-departmental initiatives. Also, it was recognised that the addressed facilities (laboratories and data room) are subject to different codes (e.g., lab safety, hazardous materials, or specialized research requirements), making a unified approach to heat transfer more complex. In the addressed use case, the IT manager was concerned that excess heat would negatively impact the reliability of the existing heat-evacuation system, which could compromise server performance or availability. On the other hand, the operators of the laboratories were concerned that their heat demand might not perfectly align with the data room's excess-heat supply even though it operates 24/7. By addressing these technical, financial, and organizational barriers proactively, and with the support of independent, external expert organizations like those outlined in the proposed methodology, institutions can successfully implement excess-heat-recovery projects that enhance sustainability and energy efficiency while respecting departmental boundaries and priorities.

The simplified technical diagram of the envisioned system for the excess-heat utilisation is given in Fig. 7. Since the direct use of excess heat was not possible, the selected system with a heat pump offered an optimal trade-off between simplicity, efficiency, and adaptability for the existing infrastructure. Nevertheless, alternative heat-recovery methods were also considered but deemed less appropriate due to higher complexity and costs.

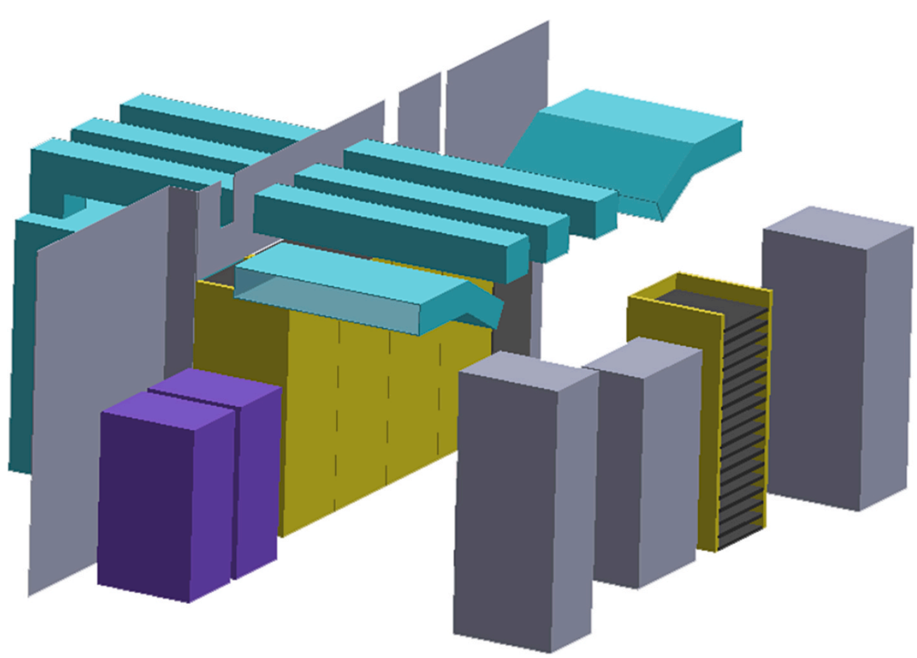

Fig. 5. Three-dimensional CFD geometry of the addressed data room for simulation of thermal air flows.

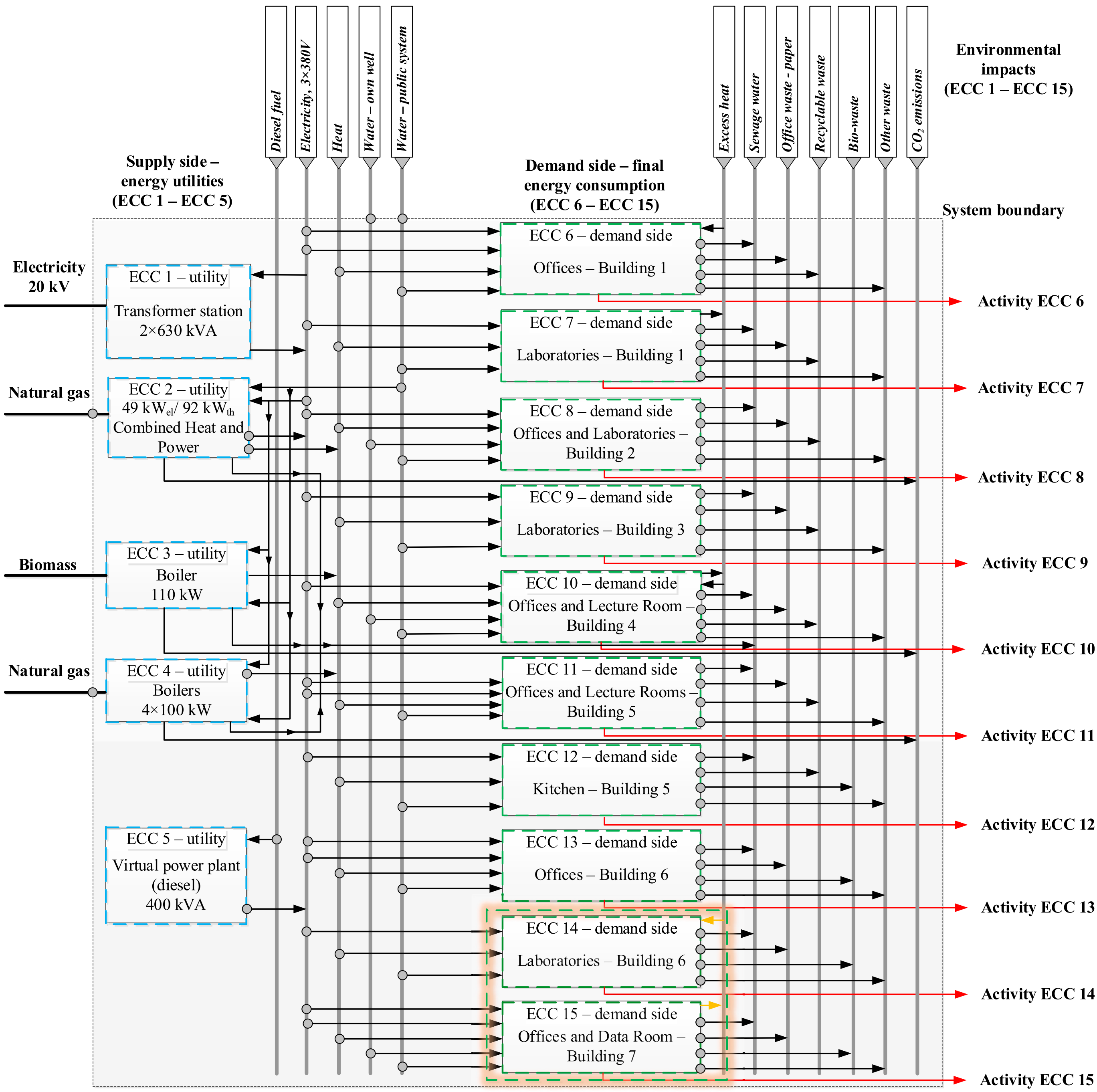

Fig. 6. Energy-cost-centre-based modelling – schematic of the addressed complex of buildings for educational and research purposes.

A simulation of the excess-heat-utilization system was carried out to evaluate its technical feasibility and economic impact. This involved assessing temperature requirements, infrastructure compatibility, and operational constraints. Due to the relatively moderate investment costs and substantial energy savings, the project demonstrated a very good economic performance. The results of the economic analysis are presented in Table 7.

The described excess-heat-utilization project has been implemented, and early operational data confirms that energy savings are in line with the initial estimates. Since a modern energy-management system is already installed at the addressed location, the validation of the concept is being tested in real-world conditions with installed sensors and metering infrastructure.

3.3. Discussion

The presented research confirmed that, due to the complexity of relationships among various stakeholders and their diverse professional and social backgrounds, designing a common energy infrastructure is always a challenging task. One of the most frequent mistakes when evaluating complex projects, such as establishing an energy community in an urban setting or implementing advanced initiatives with a shared energy infrastructure, is adopting an overly narrow perspective or failing to recognize key factors that influence the project's performance during the planning phase. Often, attention is devoted solely to specific technical solutions without adequately accounting for external and internal time-varying factors that may affect a project's economic viability. For instance, in electricity generation from PV, simulations are

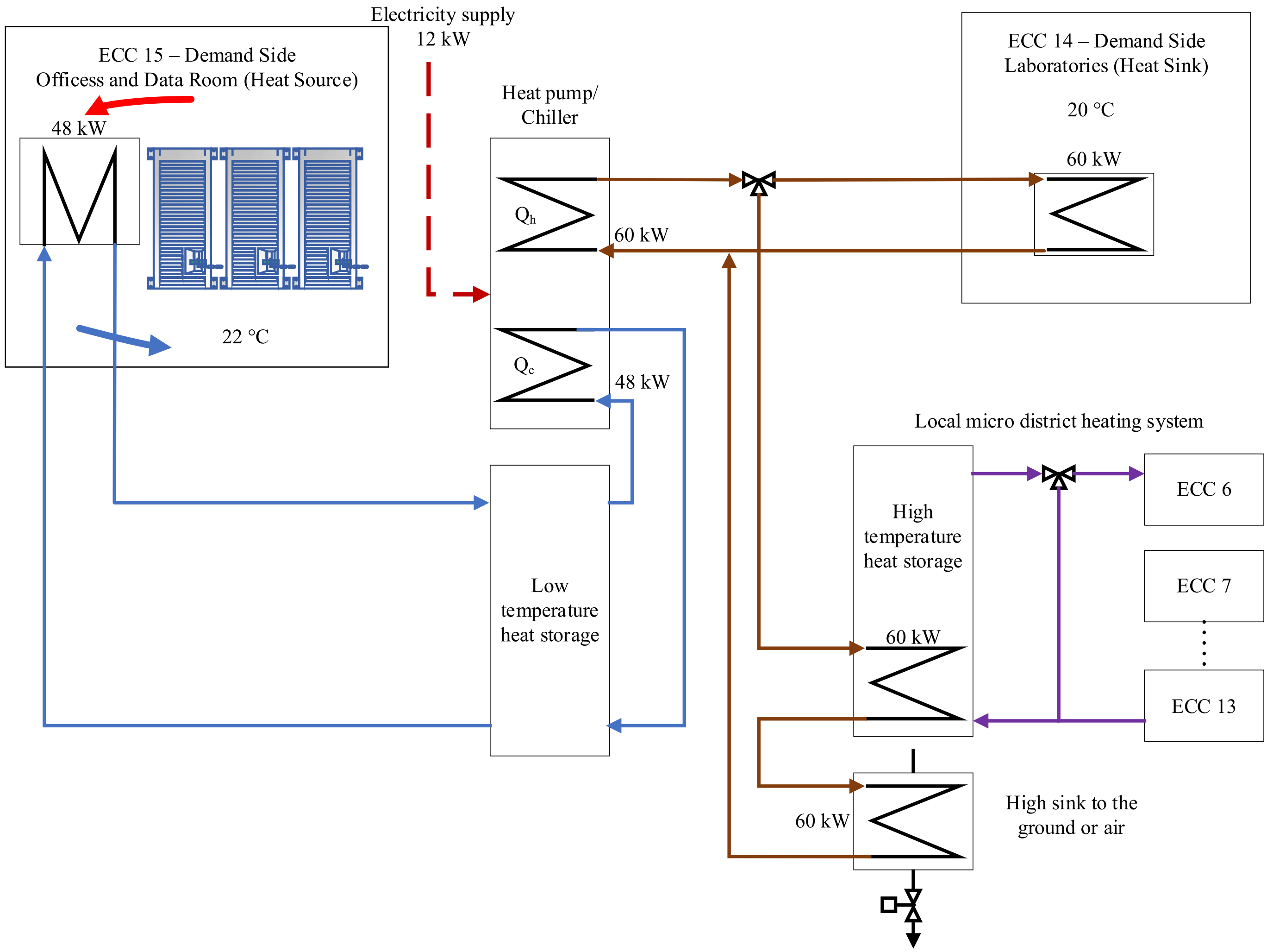

Fig. 7. Technical diagram of the envisioned system for excess-heat utilisation.

Table 7
Results of the economic analysis of the excess heat-utilisation project.

	Units	Value
Reduction of energy consumption	kWh	110,000
Investment	EUR	15,000
Economic lifetime	years	15
Required return on equity	%	5.0
Fixed annual maintenance costs	EUR	500
Expected annual savings	EUR/year	6,000
Reduction of CO_2 emission	kg/year	20,500
Simple payback period	years	2.5
Internal rate of return	%	40
Net present value	EUR	47,278

often performed on a daily or even monthly basis, which is insufficient for robust decision-making as it overlooks the influence of existing tariff systems and billing rules. A similar issue arises with excess-heat utilization from data rooms, where the building's heat demand may not fully align with the data room's excess heat supply, necessitating additional storage or a backup system.

During the described research, it became evident that both use cases, the energy community in a complex urban area and the data room's excess-heat utilization project, are characterized by dynamic variables that significantly affect energy flows and, consequently, the overall economic feasibility. In the case of the large business entity, fluctuations in occupancy rates and the varied energy demands of leaseholders lead to changes in energy consumption. Also, in the data-room setting, variable server loads produce different amounts of excess heat at different times. These transient conditions can yield unexpected energy behaviours, potentially impacting system efficiency and the reliability of heating or cooling networks. To accurately quantify and analyse these fluctuations, real-time monitoring and measurement were crucial. In both use cases, having such data available proved highly beneficial. This confirms the findings of Wilberforce et al. [9], who identified limited data availability as one of the primary obstacles to effectively modelling the renewable-energy potential in urban areas.

The proposed implementation approach, which involves comprehensive simulations of possible future-development scenarios, introduced an additional feedback loop necessary for identifying optimal solutions. This aligns with Jouhara et al. [22], who suggested that to achieve maximum efficiency through excess-heat recovery, the specific process in question must be thoroughly examined and analysed before finalizing any solution. In this new loop, it is vital to propose an efficient method for verifying energy savings by correlating recovered heat or shared energy resources with ongoing demand patterns. In both the examined use cases, existing energy-management tools were deployed for this purpose, enabling practical fine-tuning of the proposed solutions.

A review of the relevant literature revealed a lack of real-world case studies demonstrating how the interplay between digitalization, policy-driven market mechanisms, and local stakeholder engagement can lead to the development of community-centric, circular-energy economies.

The presented approach was designed to be modular and adaptable. While it was applied in Slovenia, its core structure, particularly the ECC-based modelling and stakeholder-engagement processes, can be customized to other urban contexts. These include regions with different regulatory environments, economic constraints, or infrastructure-maturity levels. However, future work should be aimed at testing the approach in varied urban settings across Europe.

When it comes to the replicability, it has to be admitted that in cases where the regulatory and economic conditions are not favourable, many complex projects in urban areas will not be implemented. This is considered as a major obstacle to implementation in countries with a non-supportive legislative framework. Selected advanced projects with a common energy infrastructure must adapt to evolving regulatory frameworks, which can involve revising operational practices, updating compliance measures, and seizing new opportunities created by supportive legislation. In previous years, economic conditions, including energy prices, the availability of subsidies, and financial incentives, were fluctuating in many EU Member States. These changes impact the economic viability of various energy projects within the community. To enable broader deployment, regulatory simplification and dedicated support schemes are essential. These may include the creation of dedicated permitting teams within utility companies for energy communities, subsidies for shared infrastructure, and clearer legal frameworks for multi-stakeholder projects. Also, future iterations of the proposed approach will be necessary to explore interoperability with district heating, electric-vehicle charging networks, and future smart-grid systems. The presented research once again confirmed that continuous financial assessment and strategic planning are necessary to optimize investments, manage costs, and ensure long-term sustainability.

It was also recognized that extracting relevant information from historical data required substantial effort, expertise and time in both use cases. Before selecting any future site for establishing an energy community or implementing any other advanced project reliant on a shared energy infrastructure, a thorough analysis of stakeholder needs is essential. This is also in line with the recommendations from Vergerio et al. [27]. Moreover, before replicating the proposed approach at another facility, having an energy audit is beneficial, as it clarifies current consumption patterns and management practices while identifying measures for improvement. A key outcome of such an audit is the establishment of a reliable baseline for ongoing performance monitoring. In the context of this research, the audit provided critical insights for modelling potential future-development scenarios. Vergerio et al. [27] also recognize energy audits as a valuable source of information.

Another limitation of the proposed methodology is the high level of expertise required during the planning and simulation phases. In this research work, multiple iterative development loops were conducted to ensure that the models aligned with end-user needs, allowing for user-driven refinements as the system evolved. Unfortunately, additional support from high-profile experts can significantly increase the cost of the proposed solution and extend the payback period.

While the proposed approach relies heavily on detailed simulations, technical evaluations, and the availability of high-quality operational data, it is important to emphasize that technical accuracy alone is insufficient for a successful project implementation in real-world settings. Also, it has to be admitted that a major barrier in both use cases was stakeholder hesitancy, particularly in multi-actor environments. Leaseholders, in the case of the large business entity, and department heads, in the case of the educational buildings, expressed concerns over control, maintenance, complexity, and perceived risks related with future costs. Recent research has shown that the active inclusion of community members and end users at every stage of the design process, from problem definition to system co-design and operational feedback, is a critical success factor in energy-community projects [33]. Future implementation should include awareness campaigns, incentives, and inclusive governance models to address these challenges.

The implementation of an advanced project with a common energy infrastructure represents the introduction of change within the complex operational and organizational environment of multi-use buildings, where the relationships between the property owner and multiple leaseholders must be carefully navigated. In such settings, the key parameter determining the overall performance and attractiveness of the advanced project with a common energy infrastructure is the price of the energy (both electricity and heat) that can be offered to the leaseholders or any other final users. This price must remain competitive while enabling a sustainable positive cash flow for all participants, including the property owner.

To ensure economic feasibility and technical efficiency, it is crucial that the advanced project with a common energy infrastructure is designed to maximize on-site self-consumption by carefully aligning local energy generation with actual consumption patterns. By doing so, the system can minimize the need for costly energy-storage technologies and avoid exporting surplus energy to the grid under less favourable conditions. This is especially important in urban environments where available space for PV and other energy infrastructure is often limited, and regulatory complexity may discourage excessive investment in underutilized capacity.

In order to fully unlock the potential of local renewable-energy sources and efficient heat recovery within complex buildings, a comprehensive simulation of potential, future energy-generation and demand scenarios must be carried out. These simulations should model both the electrical and thermal loads and evaluate the potential for matching generation and consumption in real time. The results provide the foundation for selecting the optimal configuration of a common energy infrastructure, ensuring that the majority of the produced energy is consumed locally and utilized effectively.

Based on the insights from the presented research and implementation experience the following replication roadmap to support the wider deployment of advanced projects in similar complex urban settings is given in Fig. 8. A visual representation of the proposed replication roadmap illustrates the planning steps, and key activities required for the successful implementation.

The proposed roadmap has the potential to serve as a practical guide for replicating and scaling advanced projects with a common energy infrastructure in other urban developments, particularly where energy consumption is distributed across multiple users and where energy pricing and self-consumption optimization are central to the project's success.

4. Conclusion

The results achieved clearly indicate that investing in an energy community or an advanced project with a common energy infrastructure is meaningful from multiple perspectives. Moreover, it can serve as a benchmark for how energy and facility managers in complex urban business parks can collaborate with end users or leaseholders, as well as how energy managers can coordinate with IT managers and laboratory operators to enhance sustainability and energy efficiency while respecting departmental boundaries and priorities. This underscores the importance of data availability, reliability, and relevance for successful energy-consumption simulations in the areas and buildings under consideration. In this context, close collaboration among property owners, leaseholders, energy managers, facility managers, IT managers, and electricity utility companies was crucial to the overall success of the two presented use cases. Furthermore, it was essential to support the decision makers in these initiatives with simulations of various potential, future-development scenarios, which represents the greatest added value of the proposed approach.

It is also important to highlight the need for governments to establish appropriate regulations and offer incentive measures. In the case of energy communities, such support is vital for encouraging private investors and leaseholders to collaborate with property owners and assist them in upgrading their energy infrastructure. With appropriate

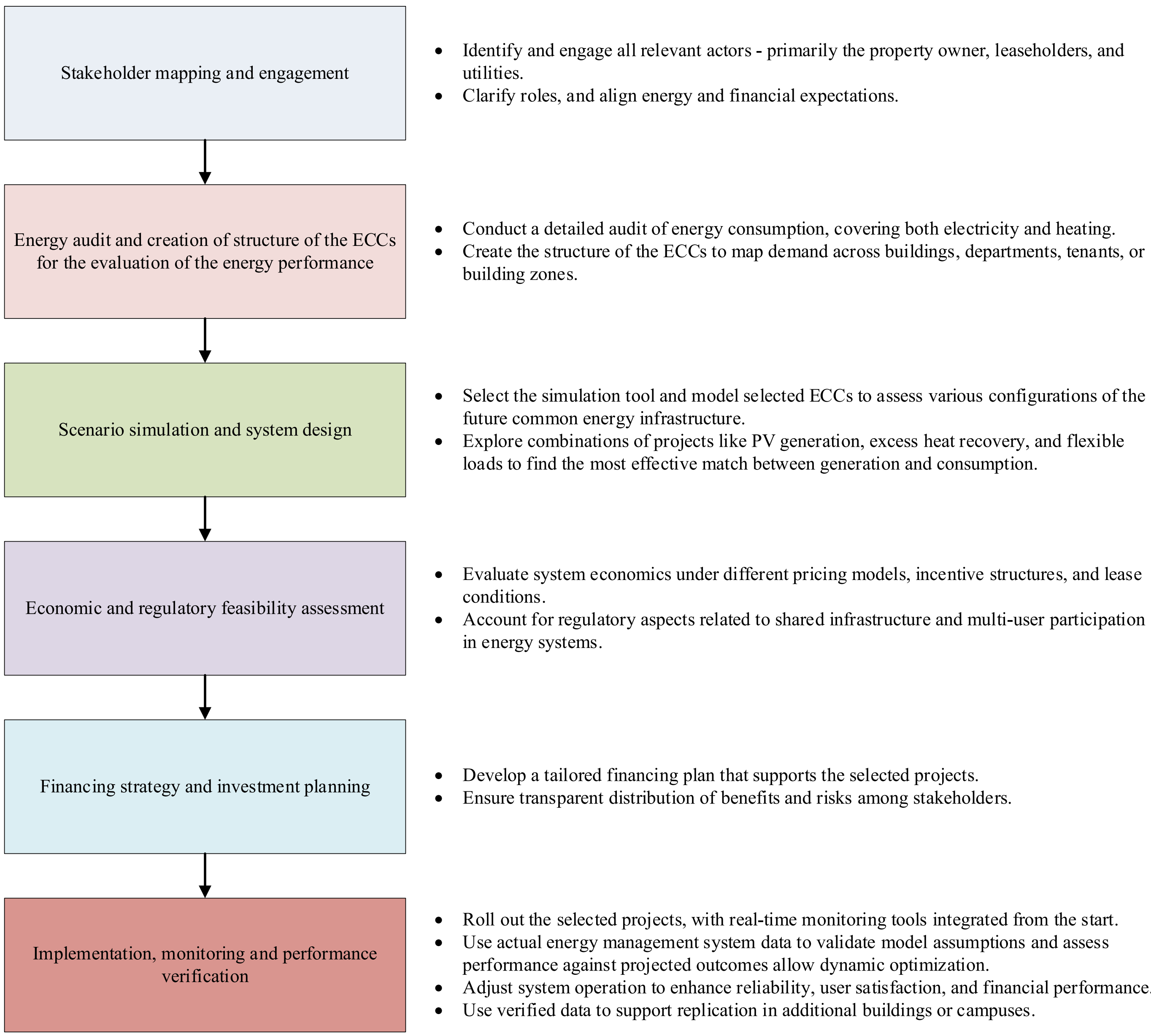

Fig. 8. Proposal of the replication roadmap to support the wider deployment of advanced projects in similar complex urban settings.

governmental support and an efficient system for obtaining permits in a reasonable timeframe, energy-community projects can realize their full potential, contributing to the sustainable transformation of urban areas. Moreover, future renewable energy-support schemes should prioritize energy-community projects, given that most of the electricity generated is consumed locally without overburdening the grid. Such projects also foster community engagement and collective action towards sustainability goals. Solar PV installations in tertiary-sector buildings in densely populated urban areas can be exemplary models of sustainable practices, motivating neighbouring buildings and communities to adopt similar green initiatives.

When it comes to implementing advanced energy projects that rely on a shared infrastructure, such as excess-heat utilization, it is important to recognize that these projects also involve multiple stakeholders and require supportive policies to overcome technical and financial barriers. Governments should provide clear guidelines to encourage and streamline the use of excess heat, ensuring that projects meet health, safety, and environmental requirements without becoming prohibitively expensive for the end users. In this context, adapting existing renewable and efficiency incentive frameworks, such as feed-in tariffs, to encompass excess-heat recovery would be highly beneficial. It is promising that Slovenia has already included excess-heat recovery in its strategic documents, such as its national energy and climate plan [34], aligning funding and policy mechanisms. The next phase should capitalize on completed projects to develop innovative, collaborative models in which public entities (such as big research and educational institutions or municipalities) partner with energy utilities and private companies to share the costs and benefits of joint advanced projects in complex urban environments.

All these efforts ultimately contribute to the most significant outcome of the sustainable transformation of large urban business areas, i.e., the continuous improvement of quality of life, which directly influences the attractiveness of the city and subsequently drives economic growth for both the city and the wider region. By implementing advanced, sustainable projects, such as smart-energy communities and excess-heat utilization, it is possible to provide an optimal business and living environment that meets the evolving needs of citizens.

While the presented research primarily focuses on economic feasibility, the evaluated projects also contribute to environmental sustainability. Future work will include full lifecycle assessments (LCAs) to evaluate the long-term environmental benefits, resource savings, and carbon-footprint reductions.

CRediT authorship contribution statement

Boris Sučić: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Conceptualization. **Edvard Košnjek:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **Marko Đorić:** Writing – review & editing, Writing – original draft, Visualization, Formal analysis, Conceptualization. **Fouad Al-Mansour:** Writing – review & editing, Conceptualization. **Marko Matkovič:** Writing – review & editing, Conceptualization. **Tomaž Damjan:** Writing – review & editing.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT in order to improve language and readability. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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.

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Data availability

Data will be made available on request.

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