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Towards Positive Energy Districts: Multi-criteria framework and Quality Assurance

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Abstract. This research develops a multi-criteria framework and Quality Assurance checklist (QA) for Positive-Energy-Districts (PEDs). PEDs have a large potential to contribute to reach urban climate goals but require also changes of planning, development, and transformation processes of neighborhoods. Our understanding of PEDs has been broadened to include aspects of circularity and economic viability, ensuring that PED concepts not only contribute to environmental sustainability but are also economically feasible. In this enhanced perspective, Digital Twins serving as essential carriers of information and facilitators of communication, effectively bridging the gap between different dimensions of sustainable development and practical implementation and monitoring. This study is part of an ongoing European project, *Digital Twin for PEDs (DT4PEDs)*, with Living Labs in three countries: Austria, Sweden, and Turkey. The presented study addresses the central research question, "In what phases can specific requirements be linked to the process to ensure PED development throughout the entire process using a Digital Twin?" within the context of the *DT4PEDs* project. Based on a participatory workshop with stakeholders from partner countries and a parallel literature review, the study encompasses three key areas. First, it seeks to consolidate property development practices across Austria, Sweden, and Turkey, including both new construction and retrofitting, into a unified framework. Second, it formulates a PED multi-criteria framework, complemented by a Quality Assurance (QA) checklist. Finally, the recommendations for digital twin are proposed to support energy related information flows and stakeholder dialogue.

1. Introduction

In recent years, the concept of Positive Energy Districts (PEDs) has garnered significant attention in the fields of urban planning, sustainable development, and energy management. PEDs represent a visionary approach to urban design, aiming to not only reduce energy consumption but also generate a surplus of energy through the integration of renewable sources and energy efficient technologies. Central to the success of PEDs are three fundamental pillars: Energy Efficiency, Renewable Energy Sources, and Energy Flexibility [1]. These pillars have been extensively explored in the literature as key drivers of PED development [1-3]. They serve as the foundation for achieving energy neutrality within urban areas. While these pillars provide a robust framework for PED development, there is a growing recognition of the need for extensions to the PED framework. This study is part of the European project "Digital Twin for PEDs" (DT4PEDs) [4], which involves three Urban Living Labs (ULL) from Austria, Sweden, and Turkey. The overarching goal of DT4PEDs is to develop a QA method for PEDs by integrating Digital

Twin models from the early design phases onwards. Each partner plays a pivotal role in contributing to the co-development and testing of the QA process and digital twin energy model within their respective ULLs. This approach will ensure that planned energy performance is realized throughout the operation phase of urban districts. In this study, a PED is interpreted in line with the JPI definition [5]: "Positive energy districts are energy-efficient and energy-flexible groups of connected buildings which produce net zero greenhouse gas emissions and actively manage an annual local or regional surplus production of renewable energy. … require integration of different systems and infrastructures and interaction between buildings, the users and the regional energy, mobility and ICT systems, while securing the energy supply and a good life for all in line with social, economic and environmental sustainability." Our focus is primarily on buildings, encompassing both retrofit and new developments. The Austrian ULL is mostly focusing on the new development, the Turkish ULL is mostly considering the retrofitting buildings and the Swedish side include both.

In our study, we introduce two essential extensions to the PED framework: Circularity and Business Models, which are crucial for all partners withing DT4PEDs project. Circularity extends the PED concept by emphasizing the importance of resource efficiency, waste reduction, and the promotion of a circular economy within districts [6,7]. Business Models, on the other hand, emerge as pivotal drivers of PED development, as they determine the financial viability and attractiveness of urban projects from economic sustainability dimension [6,8].

As Positive PEDs gain importance, there's a clear need for effective Quality Assurance (QA) processes. This is especially crucial for harmonizing strategies across the three national ULLs, ensuring that PEDs meet their energy, environmental, social, and economic targets. To address this need, our study embarks on the development of QA process. This process begins with aligning the Building Life Span phases withing different national and international standards and classifications. The QA checklist serves as a critical tool for upholding the fidelity of energy efficiency, climate impact, and stakeholder engagement, all of which are crucial factors contributing to the success of PEDs [6,9].

This study places a considered emphasis on the energy intensity during the use phase of building lifecycles, recognizing the potential for operational efficiencies via thoughtful design and the application of contemporary technologies. This focus is informed by an understanding of the prominent role that energy consumption plays during occupancy and utilization within urban infrastructures, thereby situating use phase energy considerations as a pivotal entry point for advancing environmental and possibly economic sustainability within Positive Energy Districts (PEDs). Furthermore, this work modestly proposes an expansion of the traditional PED concept to embrace a life cycle approach, which thoughtfully considers all stages of urban development from inception through to decommissioning. The ambition to integrate Life Cycle Assessment (LCA)-based methodologies throughout the stages of project development, planning, and construction is acknowledged, yet the study is forthright about the inherent complexities and emerging challenges of such integration. These challenges entail establishing clear and universally acceptable definitions, developing specific target values, and aligning multifaceted processes across diverse stakeholder groups and project phases. Recognizing these hurdles, the study does not claim to offer a definitive reflection of LCA methodologies within its current framework but instead identifies them as areas warranting further scholarly attention and exploration to aid in the maturation of sustainable urban planning practices.

Furthermore, our study bridges the topic of PEDs to the realm of DTs, which offers a unique framework for connecting the product and process aspects of building development and operation. The integration of Digital Twin concepts into the PED framework holds immense potential for enhancing the precision and efficacy of energy- and climate-related data management, thereby fortifying stakeholder communication and engagement across all phases of the building development [10]. In an era where the product and operation phases of urban infrastructure development often remain disconnected, the synergy between PEDs and its DTs emerges as a promising avenue for more holistic and sustainable urban development.

2. Research objectives and overall methodology

2.1 Research objectives

In addressing the central research question, "*In what phases can specific requirements be linked to the process to ensure PED development throughout the entire process*?", the study posits the following research objectives within the ambit of the DT4PEDs. Firstly, the study proposes to consolidate the property development process, seeking commonalities through property development practices across Austria, Sweden, and Turkey. This endeavor aims to assimilate both the construction of new buildings and the retrofitting and transformation of existing structures within a singular, coherent framework. Secondly, the formulation of a PED multi-criteria Framework, complemented by QA checklist, emerges as a practical objective. This framework incorporates a spectrum of criteria, aligned with the different phases of the Building Life Span. The integration of QA checklists strives to uphold and monitor the fidelity of energy efficiency, sustainability, and stakeholder engagement. Lastly, the identification of measurable parameters suitable for DT integration constitutes a final objective. This task is directed towards the specification of quantifiable metrics that are prior to the management and performance monitoring of PEDs. By embedding these parameters within a DT conceptual model, the study aims to enhance the precision and efficacy of energy-related data management, thereby fortifying stakeholder communication and engagement across all phases of PED development.

The research question guides the establishment of research objectives within the scope of the DT4PEDs project. This study seeks to explore and identify common practices within the property development processes of Austria, Sweden, and Turkey. The aim is to integrate these practices, encompassing both new constructions and retrofitting projects, into a unified framework that respectfully acknowledges the diverse methodologies employed by each country.

2.2 Overall methodology

The methodology for this study involves a multifaceted approach that encompasses a participatory workshop conducted in a physical setting with delegates from participating countries—Austria, Sweden, and Turkey and a parallel literature review of scientific publications and EU reports related to the PED topic. The data generated during the participatory workshop were analyzed for commonalities and variations among partner countries and urban case districts. The workshop's methodology unfolds in three stages: participants first reflect on the PED process within national groups, then collectively define PED QA requirements, and finally, determine the parameters for PED Digital Twins. Throughout, participants use post-its for idea capture, with each stage allowing time for small group work and larger discussions to integrate perspectives. This structured approach facilitates a cohesive strategy for implementing Positive Energy-Districts across varied urban contexts. The workshop methodology draws upon established participatory and systems thinking approaches aligning with contemporary strategies that emphasize stakeholder engagement and iterative development [11]. The workshop's insights were aligned with the comprehensive body of knowledge sourced from the literature, ensuring a robust and informed foundation for the development of the study's outcomes. The literature review in this study presents a comprehensive overview of Positive Energy Districts (PEDs) and related concepts, as evidenced by the number of entries in the Scopus database. It delves into several key areas, including Zero Energy Buildings (ZEB) [12], Net Zero Energy Buildings (NZEB) [13], Life Cycle Zero Energy Buildings (LC-ZEB) [14] and Positive Energy Neighborhoods (PEN) [15], with PEDs themselves receiving significant attention [10]. In addition to theoretical frameworks, the review also considers practical implementations of PED concepts in various projects, such as PEDRERA and Syn.ikia, among others [16,17]. The literature and projects are analyzed for aspects like performance assessment, design processes, quality assurance, and the integration of digital twins, providing a multifaceted view of how PEDs are conceptualized and operationalized in real-world settings [18]. Building upon these insights, an improved PED multi criteria framework and QA checklist were developed to ensure a positive energy balance throughout the PED development phases. Simultaneously, recommendations were formulated for the seamless integration of the identified measurable parameters into the DT conceptual model to facilitate energy-related information flows and support stakeholders' dialogue. Throughout this methodology, close coordination and collaboration with urban planners, property owners, and other stakeholders were maintained, ensuring that the developed QA process and measurable parameters aligned with their specific needs and objectives. The overall methodology of the study, which includes the income methods and outcome results is presented in Figure 1.

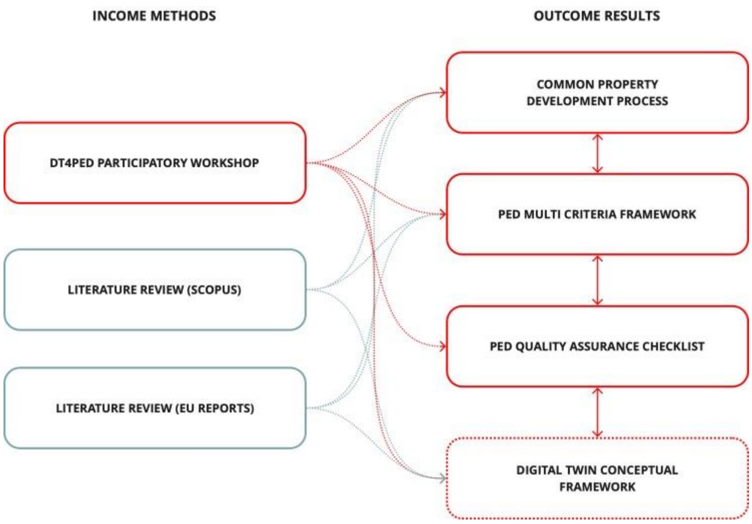

Fig. 1. Overall methodology of the study

The DT4PED participatory workshop formed an integral component of the research methodology, engaging 20 stakeholders from Austria, Sweden, and Turkey in a collaborative exploration of Positive Energy Districts (PEDs). The half-day workshop was structured into three distinct brainstorming sessions designed to facilitate in-depth discussions and knowledge sharing. The workshop participants represented different backgrounds such as architects, researchers, energy consultants, digital twin consultants, municipality, housing developer, and housing manager.

Initially, participants mapped the property development or renovation processes specific to their national contexts with post-its on a templated poster (Figure 2). After this, the second session invited participants to outline PED-related criteria relevant to each phase of their respective development or renovation processes, with a particular emphasis on the applicability to their individual PED projects. The third session concentrated on the articulation of quantifiable parameters for the previously identified PED criteria, utilizing a pre-established template to ensure the consistency and clarity of the data collected. The sequential sessions culminated in a comprehensive group dialogue, enabling participants to reflect upon and assimilate the breadth of information gathered. To facilitate ongoing analysis and iterative refinement, the workshop facilitator meticulously transcribed the collective inputs onto a MIRO board, which was made available to all participants for subsequent review.

After the collaborative workshop, the research methodology was supplemented with a parallel review of extant literature, encompassing both scholarly articles and grey literature. This deliberate and expansive literature review was instrumental in augmenting the PED criteria, integrating vital elements that were not initially surfaced during the workshop discussions. The process of literature review acted as a methodological counterpoint, ensuring that the research captured a comprehensive array of PED-related criteria beyond the empirical insights provided by the participatory sessions. In the development of the final PED multi-criteria framework, the data acquired from both the participatory workshops and the comprehensive literature review were systematically coded using a color-coding scheme within the MIRO collaborative digital platform. This visually organized data was subjected to review and commentary by the members of the DT4PED consortium, ensuring a collaborative evaluation of the synthesized information.

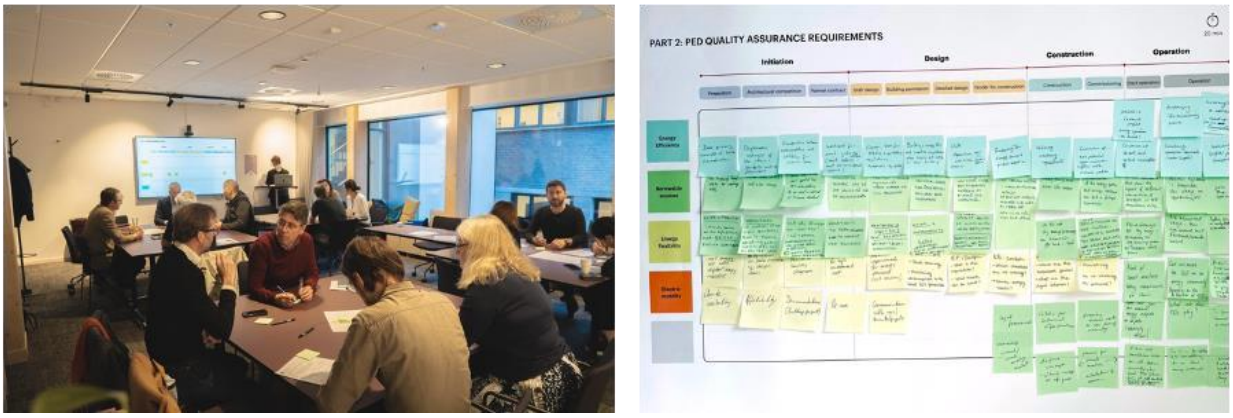

Fig. 2. Participatory workshop process. Participants from Austria, Sweden, and Turkey brainstorm in groups (left) and results are collectively mapped on a templated poster (right).

3. Results

3.1 Common property development and renovation process

The building development process for both new builds and retrofits are delineated into distinct main phases: Preparation, Design, Construction, Operation, and End-of-Life [19]. Each phase is pivotal in shaping the trajectory of the development or retrofit project, infused with insights from Swedish, Austrian, and Turkish building practices.

− *Preparation Phase:* For new builds, the Preparation phase commences with strategic definition, pivoting around feasibility studies that set the project's direction, as informed by the multi-faceted European housing market dynamics [20]. For retrofits, this phase requires a strategic re-definition, focusing on existing conditions analysis, a critical aspect given the complexity of integrating modern standards into existing structures, especially within Austria's historically rich built environment.

- *Design Phase:* The Design phase in new construction involves draft design and securing building permissions, while for retrofits, it is centered on retrofit design development, both demanding meticulous planning and an understanding of stringent local regulations, akin to the detailed planning processes [21]. The tender for construction marks the culmination of the design phase, reflecting a confluence of innovation and regulatory compliance.

- *Construction Phase:* The Construction phase follows, where new builds move from preconstruction activities to commissioning, aligning with Building Commissioning process [22]. In retrofit projects, a phased renovation approach is adopted, allowing for the continuation of building occupancy and operations. The commissioning in retrofitting specifically targets the upgraded systems, ensuring they integrate seamlessly with the existing infrastructure.

- *Operation Phase:* During the Operation phase, the focus shifts to the building in use, with post-occupancy evaluation (POE) and continuous improvement being critical for assessing performance against sustainability benchmarks and stakeholder expectations. This phase is designed to monitor and enhance building performance and user satisfaction.

– *End-of-Life Phase:* Finally, the End-of-Life phase is characterized by deconstruction planning, a phase that underscores the importance of sustainable dismantling practices and material recovery, resonant with the principles of circular economy. This phase is essential for planning the building's disassembly, prioritizing the reuse and recycling of materials, and minimizing the environmental impact of demolition.

3.2 PED multi-criteria framework

In the context of the participatory workshop, the study centered on three foundational pillars of PEDs for the templated discussions: energy efficiency (EE), renewable energy sources including local sources (RES), and energy flexibility (EF). These pillars were chosen as they are recurrently highlighted across various studies as critical components in the development of PEDs [1,4,5]. Notably, while decarbonized mobility is often considered a significant element in PED frameworks, this topic was deliberately omitted from the current framework. The rationale for its exclusion rests on its relatively lower prioritization within the scope of the three PED projects under consideration by the partner countries. Furthermore, the study allowed for an additional component space within the workshop template, providing an opportunity for stakeholders to propose extensions to the overall PED framework. This space for extension was employed to explore the integration of circularity, which carries the potential to progress PEDs towards Climate Neutral Districts [23], underscoring a commitment to broader environmental sustainability [4]. Additionally, the inclusion of a business model as a fundamental pillar was proposed, recognizing its importance in ensuring the economic viability and longevity of PEDs [6]. Each criterion is mapped to a corresponding phase in the development process, ensuring that the PED objectives are integrated from the initial planning to the eventual decommissioning of the building. The PED criteria are summarized in the framework presented in Figure 3

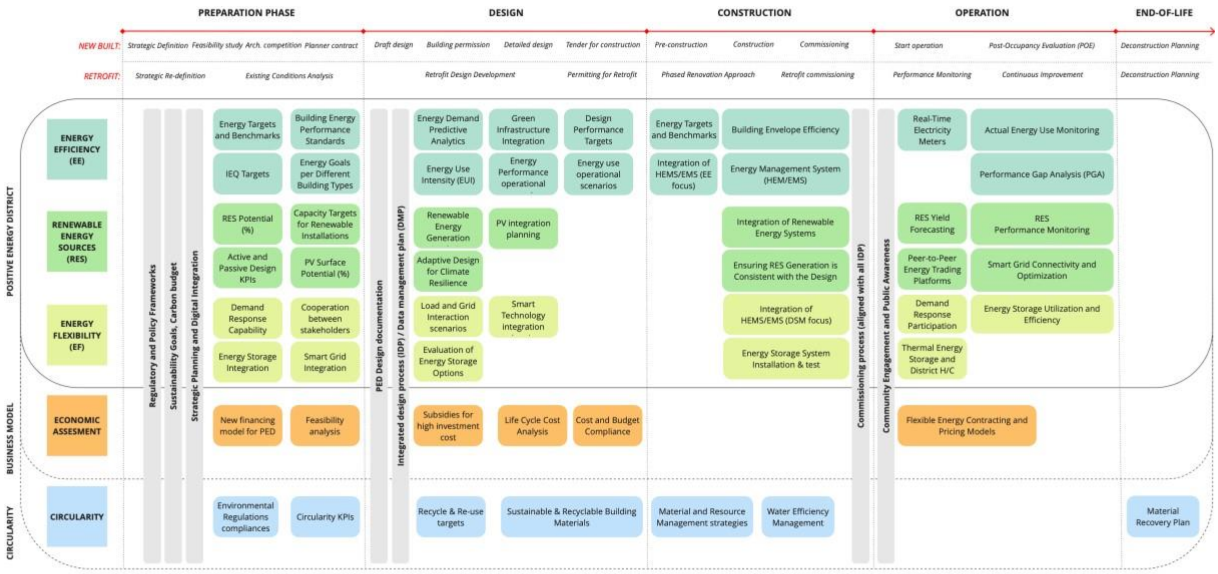

Fig. 3. PED multi-criteria framework based on participatory workshop and literature study.

Preparation Phase:

The preparation phase criteria within the PED framework emphasize a sustainable and adaptable approach to both new builds and retrofits, grouped into the three foundational pillars of energy performance. The EE criteria are designed to catalyze the development of high-performance buildings by establishing energy targets and benchmarks that go beyond minimum performance standards. These benchmarks are envisioned not as mere thresholds but as indicators of what is achievable, encouraging innovation and striving towards optimal energy efficiency in both new constructions and retrofits. By setting these aspirational targets, the criteria aim to guide and motivate stakeholders towards realizing the full potential of energy-efficient design and operation. These targets are tailored to the specific building types to ensure customized efficiency strategies. Indoor Environmental Quality (IEQ) targets complement these measures by focusing on the health and comfort of occupants, a critical aspect of sustainable living spaces. RES criteria are designed to harness the potential of on-site and nearby renewable energy resources. This includes not only the quantification of RES potential as a percentage contribution to the buildings and districts energy profile but also the establishment of capacity targets for renewable installations, ensuring that the infrastructure is in place to meet or exceed these goals. The criteria also incorporate considerations for the integration of photovoltaic (PV) systems, measured by the PV surface potential, which reflects the capacity for solar energy generation.

EF criteria address the dynamic nature of energy demand and supply, emphasizing the importance of demand response capabilities and energy storage integration. This flexibility allows buildings to adapt to varying energy needs and supply conditions, ensuring stability and resilience within the PED. The overarching criteria reflect a commitment to not just individual energy related aspects, but also to the holistic integration of these systems within the broader context of smart, sustainable urban development. The Business Model and Circularity criteria at this stage underscore the importance of integrating economic and environmental sustainability into the core operational strategy of PEDs. Within the Business Model criterion, developing new financing models tailored for PEDs is essential to ensure projects are economically viable and attractive to investors. This involves creating mechanisms that can support the upfront costs of implementing sustainable technologies and practices. A comprehensive feasibility analysis is equally crucial, serving to evaluate the potential returns on investment and long-term economic benefits of PED initiatives, which often have higher initial costs but promise reduced operational expenses. In terms of Circularity, the criteria focus on embedding the principles of the circular economy into the PEDs from the outset.

Compliance with environmental regulations ensures that the development and operational processes meet current standards for sustainability and can adapt to evolving legal requirements. Meanwhile, establishing clear Circular KPIs allows for the monitoring and evaluation of circular practices, such as the extent of material reuse, waste reduction, and the lifecycle impacts of the built environment. These indicators help track progress toward minimizing the ecological footprint of PEDs and enhancing their resource efficiency, thus contributing to the broader goals of sustainable urban development.

Design Phase:
During the design phase, the integration of PED-specific criteria is crucial to achieving an integration of PED related technology during the early stage of the design process. Under the EE pillar, the design phase focuses on the incorporation of Energy Demand Predictive Analytics to anticipate future energy needs and to tailor the design accordingly. Energy Use Intensity (EUI) targets are set to specify energy performance benchmarks that the design must achieve. Alongside this, the incorporation of Green Infrastructure aims to seamlessly integrate natural and built environments, enhancing both energy efficiency and the quality of living spaces. The RES pillar emphasizes the importance of simulating Renewable Energy Generation to gauge the potential contribution of on-site and nearby renewable resources. PV integration planning is critical in maximizing solar energy capture, and Adaptive Design for Climate Resilience ensures that the building's design remains robust in the face of changing climate patterns. For EF, the criteria include devising scenarios for Load and Grid Interaction to manage energy demand and supply dynamically. The evaluation of Energy Storage Options is essential to provide the system with the ability to respond to fluctuations in energy generation and consumption. In the broader context of the design phase, the Business Model category addresses the economic viability of PEDs, with an emphasis on Subsidies for high investment costs, Life Cycle Cost Analysis to understand the long-term financial implications and ensuring Cost and Budget Compliance to keep the project within financial constraints. Lastly, the Circularity category is integrated into the design phase to ensure sustainable

material cycles. This involves setting Recycle and Re-use targets to minimize waste and selecting Sustainable & Recyclable Building Materials that can be cycled back into use at the end of their life, reducing the ecological footprint of the development.

Construction phase:
During the construction phase within the PED framework, the criteria are intricately designed to guide the transition from design to physical realization, ensuring that both new builds and retrofits adhere to the sustainability and efficiency goals. EE criteria during construction focus on the building envelope's efficiency, energy systems' and building services' efficiencies and verification of intended design performance, which is crucial for minimizing energy loss. The integration of Home Energy Management Systems (HEMS) or Energy Management Systems (EMS) with an EE focus ensures that energy consumption is monitored and controlled effectively. These systems are tested and validated during commissioning to confirm their efficiency. RES criteria involve the physical integration of renewable energy systems into the construction, such as solar panels or geothermal systems. It is vital to ensure that the RES generation is consistent with the initial design intent, providing a reliable and sustainable energy supply. For EF, the construction phase includes integrating HEMS/EMS with a Demand Side Management (DSM) focus, which allows for the dynamic adaptation to energy supply and demand changes. Additionally, the installation and testing of energy storage systems are pivotal, ensuring that surplus energy can be stored and used when needed, enhancing the overall resilience and flexibility of the energy supply. The Business Model criterion at this stage may involve an economic assessment to ensure that the implemented sustainability measures align with financial objectives and constraints, potentially affecting the selection of materials and technologies based on their cost-effectiveness. Circularity criteria are essential during construction, with a focus on construction waste management, ensuring that waste is minimized, and materials are managed sustainably. Material and resource management strategies are implemented to promote the use of sustainable, recyclable, or reclaimed materials, while water efficiency management ensures the conservation of this critical resource during the construction process.

Operation phase:
During the operation phase of a PED, the focus shifts to the management, monitoring, and continuous improvement of building performance. This phase is vital for ensuring that the building's operation aligns with the initial sustainability goals set during the design and construction phases. EE is maintained using real-time electricity meters, actual energy use monitoring, heat meters and operation energy system parameters. These tools provide immediate feedback on the building's energy performance, allowing for quick adjustments to improve efficiency. RES are managed through yield forecasting and performance monitoring, ensuring that the generation of renewable energy is optimized and aligns with consumption patterns. This can include solar, wind, or geothermal energy sources integrated into the local energy system. EF is achieved through demand response participation, where the building's energy consumption is adjusted in response to supply conditions, and through the utilization and efficiency of energy storage systems. The integration of thermal energy storage and district heating and cooling (H/C) systems further enhances the building's ability to adapt to energy demands and supply fluctuations. The Business Model aspect of the operation phase involves flexible energy contracting and pricing models, which can provide financial incentives for energy efficiency and the use of renewable energy sources. This economic assessment ensures that the building remains cost-effective to operate. Circularity is an ongoing consideration during the operation phase, with strategies aimed at minimizing waste and maximizing the reuse and recycling of materials. This sustainable approach to resource management contributes to the building's overall environmental performance. The operation phase is characterized by effective communication and collaboration between stakeholders including local authorities, operators, service providers, building owners and occupants, raising awareness about the building's energy features and sustainability initiatives. This engagement fosters a culture of conservation and promotes the broader adoption of sustainable practices within the community.

3.3 PED Quality Assurance checklist

The PED Quality Assurance (QA) checklist is a comprehensive tool designed to align with the PED multi-criteria framework, ensuring that each phase of building development adheres to established sustainable practices. The checklist encompasses critical considerations across energy efficiency, renewable energy sources, energy flexibility, economic assessment, and circularity. For energy efficiency, the checklist ensures that energy targets and benchmarks are met, indoor environmental quality is considered, and building envelope performance is up to standard. In terms of renewable energy, it verifies the integration and potential of renewable systems, ensuring consistency with design specifications and energy yield forecasting, monitoring the intended design performance and standards related to minimum performance requirements. Energy flexibility is guaranteed through the validation of demand response strategies and the effective integration and testing of energy storage systems.

The economic assessment ensures financial viability through the exploration of new financing models, life cycle cost analysis, and compliance with budgeting protocols. Circularity is emphasized by confirming compliance with environmental regulations, the inclusion of circularity objectives from the outset, and the strategic sourcing of sustainable materials. Additionally, the checklist includes the monitoring of real-time energy consumption, implementation of flexible energy contracting, and the validation of operational circularity practices such as greywater systems or material take-back schemes. At the end of the building's lifecycle, the checklist confirms that deconstruction plans are in place to maximize material recovery and recycling, reflecting a commitment to a sustainable, circular economy. The PED QA checklist can be instrumental in the development of a Digital Twin for a PED in the DT4PED project by serving as a guide to ensure that all aspects of energy efficiency, renewable energy sources, energy flexibility, economic assessment, and circularity are incorporated into the Digital Twin model from the outset.

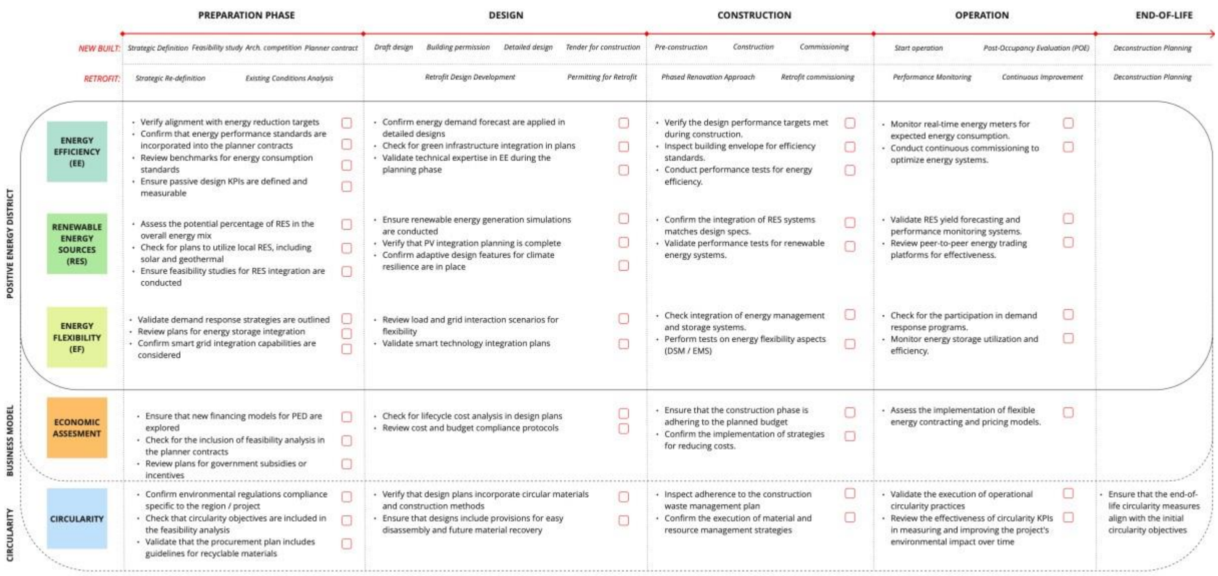

Fig. 4. PED Quality Assurance checklist

3.4 Digital Twin concept for PED

Digital Twins (DTs) offer a multi-layered, complex representation of physical entities through digital models, serving various applications across multiple lifecycle phases [24]. The DT levels start from basic information modelling, scaling up to incorporate Building Information Modelling (BIM), simulations, sensors, and ultimately, artificial intelligence, providing a comprehensive digital mirror of the physical world [25]. The overall solution architecture of a DT includes a hierarchical structure from components to systems and multi-systems, enabling detailed analysis and operational control. In terms of data architecture, it involves the flow from raw data through analytics to user interfaces, which supports decision-making processes and stakeholder communication. The models used in DTs range from simple 2D and 3D visualizations to sophisticated simulations that allow for scenario planning and operational management [26]. These models can predict system behaviour, simulate asset performance, ensure asset interoperability, and facilitate maintenance planning [27,28]. Visualization techniques in DTs not only illustrate current states but also simulate future conditions, providing an immersive experience of the urban environment. Reflecting on urban-scale and district DT applications, they encompass system prediction, simulation, asset interoperability, maintenance, system visualization, and product simulation. Utilizing the insights from various DT approaches can significantly enhance the planning, construction, operation, and maintenance of PEDs [8]. The integration of DTs in PEDs could enable real-time energy management, predictive maintenance for energy systems, and participatory urban planning and district transformation, leading to efficient and resilient energy-positive communities. Such knowledge and technology, when applied to PEDs, can drive the optimization of energy consumption, facilitate the use of renewable energy sources, and support achieving overarching goals of energy positivity and sustainability in urban districts. DT for a PED key recommendations from the DT4PED project team and parallel literature review are:

- *Model-Oriented Integrated Approach:* The PED DT development should leverage a model-oriented approach. This means integrating various data sources and models (like energy consumption, renewable energy production, and building performance) into a cohesive digital representation. The integration should cover all aspects of the PED, from individual buildings to district-level infrastructure.
- *Data Quality Assurance Process:* Implementing a robust quality assurance process for all data and models that feed into the DT is crucial. This ensures the reliability and accuracy of the DT, making it a dependable tool for decision-making and performance monitoring.
- *Model-Based Interface for Feedback and Modifications:* The DT should include a user-friendly interface that allows stakeholders to provide feedback and suggest modifications. This could be especially useful in the planning and development phases of the PED, where stakeholder input can significantly influence the outcome.
- *Continuous Follow-Up with Real-Time Data:* The DT should be capable of providing real-time updates and analysis. This involves continuously monitoring various parameters such as energy consumption, renewable energy generation, and environmental impacts. Such real-time tracking allows for immediate adjustments and proactive management of the PED.

- *Automated Checks for Requirement Fulfilment:* Automating the process of checking if the PED meets certain requirements (like energy efficiency standards, carbon emission targets, etc.) can significantly enhance the efficiency of managing the district. The DT can be programmed to alert managers when certain thresholds are crossed or when performance deviates from the set targets.

By applying these principles to a PED, the DT becomes a pivotal tool in this transformation, enabling a more sustainable, efficient, and responsive urban environment. This DT would not only aid in the efficient management and operation of the PED but also serve as a dynamic platform for continuous improvement and stakeholder interaction.

4. Discussion and conclusion

Based on a participatory workshop and a literature review, this study developed a Quality Assurance (QA) process for Positive Energy Districts (PEDs) comprising a multi-criteria framework with a related checklist and a Digital Twin concept to support the implementation of PEDs. Besides this framework development and the identification of key measurable parameters, results also signify a critical step in aligning this study with the ongoing DT4PED project in three countries. By synthesizing the insights gained from stakeholders representing diverse urban case districts in Austria, Sweden, and Turkey, the derived QA process and measurable parameters will be harmonized with best practices and experiences from other EU initiatives focusing on sustainable urban development and energy efficiency. In the future, the broader landscape of similar European Union (EU) projects could apply to the proposed QA checklist. This alignment will foster cross-project knowledge sharing, allowing for the integration of complementary strategies and methodologies and, ultimately, contributing to a more unified approach towards achieving the ambitious urban climate goals set by the EU. Additionally, the findings from the participatory workshop integrated into the ongoing literature review enriches the academic discourse on PEDs, QA processes, and the role of DT technology in enhancing energy performance and climate impact reduction in urban areas. This holistic approach ensures that the outcomes of this study are not isolated but rather positioned to drive synergy across EU initiatives and the wider academic community, fostering a collective effort towards sustainable urban development.

This study's exploration into the PED framework reveals its potential for urban sustainability, particularly in energy neutrality. However, there's an evident need for extension and adaptation to address specific urban challenges [29,30]. For instance, integrating concepts of circularity and innovative business models, as proposed in our study, could significantly enhance the framework's applicability and effectiveness.

The transition from defining PED criteria to developing a QA checklist represents a critical step in ensuring project success. A QA process is crucial for aligning PED projects with established sustainability and efficiency goals [31]. Our checklist, derived from comprehensive criteria, serves as a foundational tool for maintaining and evaluating project standards. This approach mirrors similar strategies in related fields, where QA checklists have proven effective in maintaining project integrity [32].

The PED multi-criteria framework and Quality Assurance (QA) checklist provide a structured approach to advancing sustainability in urban neighborhoods through several practical ways. By setting stringent energy targets and benchmarks that exceed basic compliance, the EE criteria ensure that new buildings are designed to reduce energy consumption and carbon emissions. This leads to long-term operational savings and contributes to the mitigation of climate change impacts. The framework encourages the use of renewable energy by assessing the potential percentage of RES in the overall energy mix, promoting a shift from fossil fuels to cleaner energy sources. This helps urban neighborhoods reduce their carbon footprint and move towards energy self-sufficiency. Validating demand response strategies and energy storage plans enables neighborhoods to adapt to energy availability and demand, thus optimizing energy consumption patterns and reducing strain on the grid during peak times. Confirming compliance with environmental regulations and focusing on circularity KPIs, the framework embeds the principles of circular economy into urban development, emphasizing waste reduction, resource efficiency, and the reuse and recycling of materials. Through the QA checklist, ongoing performance monitoring, including real-time energy metering and continuous commissioning, is mandated, ensuring that buildings operate as intended and that any performance gaps are promptly addressed. The inclusion of deconstruction planning in the framework ensures that the sustainable use of resources is considered throughout the entire lifecycle of the building, thus contributing to a reduced environmental impact. In addition, by including new financing models and feasibility analyses, the framework ensures that the economic viability of PED projects is considered from the outset, aligning financial and environmental sustainability.

The application of Digital Twin technology in our study illustrates its potential in bridging the product and use phases of the building stock. Digital Twins offer enhanced data analytics, decision-making support, and real-time monitoring, which are vital for the operational efficiency of PEDs. Their implementation aligns with findings from [33], who demonstrated the significant benefits of Digital Twins in urban development scenarios. Our study, while being comprehensive, has limitations. The scope of our case studies may not capture the full diversity of urban environments where PEDs could be implemented. Furthermore, the participatory workshop approach, while valuable, could introduce biases in stakeholder feedback. These limitations highlight the need for cautious interpretation of our findings and their broader applicability. However, this study sets the stage for several critical future research directions. Testing the QA checklist in participatory serious game workshops with all partners will provide practical insights and allow for refinement. Additionally, selecting and implementing key PED criteria in the DT models for each pilot neighborhoods will be crucial. The development and testing of these models within a defined timeframe will offer empirical data to assess their effectiveness. Comparatively analyzing results from different pilot neighborhoods will further enhance our understanding of PED implementations in diverse urban contexts.

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