Fostering Sustainable Urban Energy Transitions: Backcasting for Positive Energy Districts and Digital Twin strategies in a European Context

Fostering Sustainable Urban Energy Transitions: Backcasting for Positive Energy Districts and Digital Twin strategies in a European Context

Elena Malakhatka, elenamal@chalmers.se
Chalmers University of Technology, Department of Architecture and Civil Engineering, Sweden

Holger Wallbaum, holger.wallbaum@chalmers.se
Chalmers University of Technology, Department of Architecture and Civil Engineering, Sweden

Sara Abouebeid, saraabo@chalmers.se
Chalmers University of Technology, Department of Architecture and Civil Engineering, Sweden

Gerhard Hofer, gerhard.hofer@e-sieben.at
E-Sieben, Austria

Parham Pooyanfar, parham.pooyanfar@ekodenge.com
Ekodenge, Türkiye

İlker Dursun, ilkerdursun@subu.edu.tr
Sakarya University of Applied Sciences, Department of Electrical and Electronics Engineering, Türkiye

Gundula M Weber, gundula.weber@ait.ac.at
Austrian Institute of Technology AIT, Austria

Hüseyin Serdar Gecer, serdargecer@subu.edu.tr
Sakarya University of Applied Sciences, Department of Electrical and Electronics Engineering, Türkiye

Liane Thuvander, liane.thuvander@chalmers.se
Chalmers University of Technology, Department of Architecture and Civil Engineering, Sweden

Abstract
Positive Energy Districts (PEDs) have emerged as a key innovation to accelerate the transition toward climate neutrality and sustainability in cities. This study integrates backcasting methodologies and Digital Twin (DT) strategies to advance PED developments using a two-step approach: participatory backcasting workshops to co-create long-term visions and actionable strategies, and DT applications tailored to three Urban Living Labs: Vienna/Austria, Gothenburg/Sweden, and Sakarya/Türkiye. The backcasting process identified pathways to energy efficiency, renewable energy integration, and decarbonization, creating a roadmap for PED development. DT functionalities—including Digitize, Visualize, Simulate, Predict, and Orchestrate—translated the plans into operational tools, enabling real-time monitoring, predictive modeling, and energy management. Results underscore the critical role of stakeholder collaboration to align local priorities with sustainability goals and demonstrate the capacity of DT frameworks and PEDs in diverse urban contexts. Still, challenges such as scalability, resource intensity, and sustaining long-term engagement persist. The study highlights the potential of integrating participatory planning with digital tools to bridge the gap between visionary energy goals and practical implementation, offering a replicable framework for urban energy transitions.

Keywords
Backcasting, Digital Twin, Positive Energy District

1 Background

The development of Positive Energy Districts (PEDs) represents a transformative shift in urban sustainability, requiring integrated approaches that consider not only technological advancements but also governance structures, stakeholder participation, and adaptive energy management strategies. PEDs are defined as urban districts that produce more renewable energy than they consume on an annual basis while integrating efficiency measures, smart grids, and energy-sharing mechanisms (JPI Urban Europe, 2020). PEDs align with global climate neutrality goals and represent a systemic innovation in urban energy transitions (Sassenou et al. 2024). The concept builds upon earlier research on energy-efficient buildings and smart grids but extends to district-scale energy management, requiring new governance models and interdisciplinary collaboration (Krangsås et al. 2021; Sareen et al. 2022). Recent studies highlight that PEDs face technical, regulatory, and social challenges, particularly regarding stakeholder engagement and the integration of renewable energy systems (Albert-Seifried et al. 2022). Scholars emphasize the need for participatory approaches that allow urban planners, policymakers, and local communities to co-design PED solutions tailored to specific socio-economic and climatic conditions (Baer et al. 2021). This aligns with the concept of Urban Living Labs (ULLs)—real-world experimental environments where PED strategies can be tested, refined, and scaled up (Derkenbaeva et al. 2023). However, ensuring that these ambitious visions translate into structured, actionable steps remains a challenge, particularly given the long-term nature of PED development and the uncertainty of future urban energy systems. To address these challenges, there is a growing interest in future studies methodologies that integrate visioning, scenario planning, and participatory foresight approaches (Geels et al. 2019; Loorbach et al. 2010). These approaches facilitate the exploration of multiple pathways toward sustainable urban futures while fostering collaborative decision-making. In this paper, we adopt backcasting as a participatory tool for envisioning and structuring long-term PED planning and Digital Twins as a technological tool for continuously aligning these visions with real-time data-driven decision-making. By integrating these methodologies, we aim to bridge the gap between long-term aspirations and short-term, actionable strategies in PED development. Backcasting is a normative strategic planning approach that starts by defining a desired future state and then works backward to determine the necessary steps to achieve it (Dreborg et al. 1996). Unlike forecasting, which relies on current trends and incremental projections, backcasting is particularly suited to sustainability challenges that require transformative system change (Robinson et al. 2011). It enables stakeholders to co-develop visions of preferred futures and systematically outline the policies, technologies, and governance structures needed to realize those futures (Pereverza et al. 2019). However, while backcasting provides a high-level roadmap, challenges remain in translating these visionary goals into real-time, adaptive implementation frameworks (Geels et al. 2019). This is where Digital Twin technology can play a crucial role in bridging the vision-reality gap. Digital Twin (DT) technology offers a powerful data-driven approach to managing urban energy systems by providing real-time simulation, visualization, and predictive analytics (Madni et al. 2019). A Digital Twin is a virtual replica of a physical entity, continuously synchronizing with real-world data to enable dynamic scenario modelling (Semeraro et al. 2021). The main contribution of this paper lies in demonstrating a novel methodological approach that integrates backcasting as a participatory planning tool with Digital Twin technology as an implementation tool to support the development of Positive Energy Districts (PEDs).

2 Research Methodology

The methodology for this study integrates a participatory backcasting exercise with four steps in three ULLs and DT strategies alignment (Figure 2) to create a structured yet adaptable approach for achieving PED goals in urban settings.

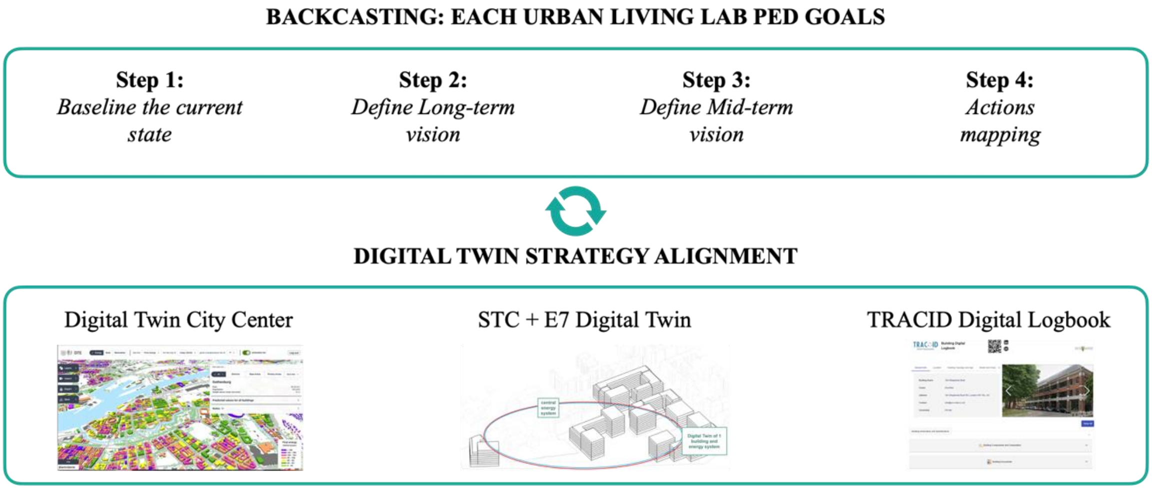

Figure 1. Overall study methodology. Integration of backcasting method and Digital Twin for three Urban Living Labs.

2.1 Urban Living Labs

Each ULL is strategically positioned at different stages of the urban development lifecycle, allowing for a comprehensive examination of DT applications in PEDs at various points from planning to operation. The three ULLs are outlined in Figure 2.

Figure 2. Urban Living Labs: Left: Am Kempelenpark ULL (Vienna, Austria); Middle: Jättesten ULL (Gothenburg, Sweden); Right: Camili ULL (Sakarya**,** Türkiye).

The Austrian ULL Am Kempelenpark is a 110,000 square meter campus located in Vienna's 10th district, near the main railway station. The area will comprise around seven buildings with mixed uses, such as individual and multi-family apartments (some subsidized), conference and seminar rooms, offices, counseling and education facilities, restaurants, coffee shops, and a primary school. The ULL aims to integrate residential and commercial spaces with cross-property concepts for open space, mobility, and energy supply, ensuring robust quality assurance in collaboration with the city of Vienna. Construction for all buildings is expected to be completed by 2029. The Swedish ULL in Gothenburg's Jättesten area focuses on both new constructions and retrofitting within an established residential neighbourhood, encompassing 527 existing apartments with plans for 124 additional units as well as a school and a kindergarten The ULL targets the early planning phase and emphasizes creating synergies between new developments and existing structures. This area has been chosen due to its potential for demonstrating how PED concepts can be applied in a mixed urban environment where existing infrastructure needs upgrades, and new constructions can serve as benchmarks for energy-positive solutions. The Turkish ULL, based in the Camili district of Sakarya, represents an operational phase within an expansive area comprising 853 apartments over 292,000 square meters. This ULL was selected due to its diverse urban setting that blends residential, commercial, and public spaces. Featuring diverse building types, the district leverages both static and dynamic data including natural gas and electricity consumption, renewable energy generation, and indoor environmental quality metrics to monitor energy use, integrate renewable sources, and ensure indoor comfort. The ULL aims to utilize DT technology during the operational phase to optimize energy management within the PED framework. The three ULLs represent different phases of PED development, allowing for a comprehensive analysis of PED implementation across diverse urban contexts. While each ULL has unique characteristics, they share common objectives such as integrating renewable energy sources, enhancing energy efficiency, and fostering stakeholder collaboration.

2.2 Backcasting workshop

Through the participatory workshop, the DT4PED partners collaboratively developed actionable strategies for planning towards PED, leveraging the collective expertise and commitment of all participants. In total, 12 people participated in the 4 hours workshop (3 from Austria, 7 from Sweden, 3 from Türkiye) representing property owners, energy consultants, architects, researchers. All participants were divided into four groups: Jättesten ULL (New buildings), Jättesten ULL (Existing buildings), Am Kempelenpark ULL and Camili ULL. The backcasting workshop thus served as both a planning tool and a community-building exercise, aligning diverse stakeholders around a shared vision for a sustainable urban future. The structure of the workshops included multiple phases, see also Figure 3.

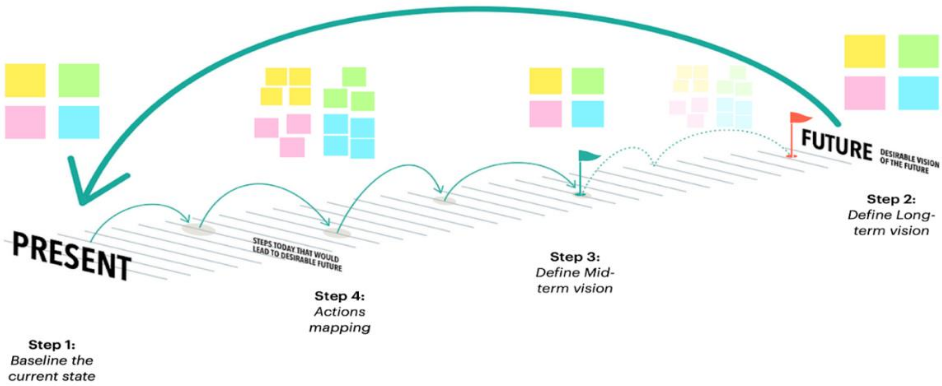

Figure 3. Backcasting exercise template with 4 steps applied in the workshop (Adapted: Natural Step)

Step 1: Establishing the present conditions of the neighborhood, capturing baseline energy use, infrastructure status, and environmental impacts. **Step 2:** Defining a long-term vision of a Positive Energy District, a concept where districts produce more energy than they consume on a net annual basis. **Step 3:** Identifying mid-term milestones that would mark significant progress toward achieving the PED vision, such as intermediate targets for energy efficiency, renewable energy generation, and community engagement. **Step 4:** Specifying actionable steps required in the short term, including policies, technologies, and community initiatives, that contribute to realizing the long-term vision.

2.3 Digital Twin strategies

The DTs in this study serve as dynamic, data-driven tools for planning, implementing, and operating PEDs, tailored to each ULL with real-time energy monitoring, scenario modelling, and predictive analytics. The DT alignment framework (Figure 4) maps DT functionalities across building stages, following the IoT Analytics (2024) and Malakhatka et al. (2024) hierarchical categorization: Digitize, Visualize, Simulate, Predict, and Orchestrate. In the Preparation Phase, Digitize and Visualize enable data collection for feasibility studies (Negri et al. 2017). In the Design Phase, Simulate and Predict support scenario modelling and energy forecasting (Madni et al. 2019). During Construction, Orchestrate ensures real-time coordination and tracking to meet PED standards. In the End-of-Life Phase, Simulate facilitates decommissioning, impact assessment, and recycling planning (Anderson et al. 2022). Compared to existing tools, DTs offer advantages over BIM, which supports 3D modelling but lacks real-time and predictive capabilities (Succar et al. 2009), and EMS, which monitors energy performance but lacks dynamic simulation (Cucchiella et al. 2017). By aligning DT applications with project phases, this framework enhances operational efficiency, resilience, and sustainability, supporting the DT4PED project's energy goals.

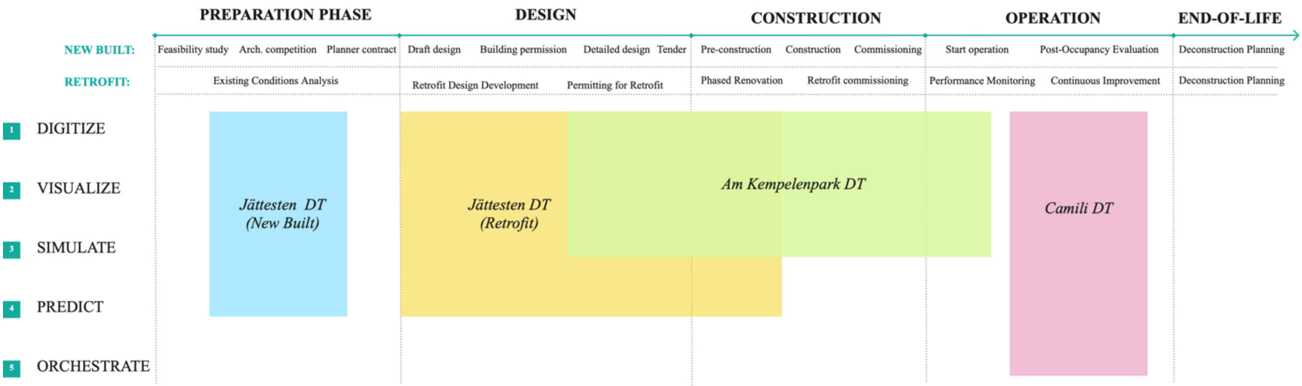

Figure 4. Digital Twins mapping across stages in the building process for each of the Urban Living Labs

3 Findings and Discussion

3.1 Backcasting outcomes

The backcasting workshop demonstrated how participatory foresight methods support PED development, providing a replicable framework for stakeholder-driven planning and decision-making. Findings highlight the need to integrate PED strategies across planning and operational phases for coherence and effectiveness (Figure 5). Short-term priorities focused on advanced EMS adoption and mixed-use urban spaces for energy efficiency. Mid-term milestones targeted reduced energy consumption and increased renewable integration, particularly as construction progressed. The workshop also emphasized cross-sector collaboration, showing that sustained stakeholder engagement is key for adapting strategies from design to implementation. ULL analysis underscored the balance between context-specific approaches and a unified PED vision. Am Kempelenpark integrated PED principles across design and construction, Jättesten combined retrofitting with new development, and Camili focused on iterative improvements in operation. These insights reinforce that PEDs require tailored baseline assessments while maintaining shared long-term goals. Active stakeholder engagement across ULLs proved essential for progress, trust-building, and sustainable urban transitions. This alignment of local and collective strategies illustrates how adaptable, participatory approaches translate high-level PED visions into actionable urban energy transformations.

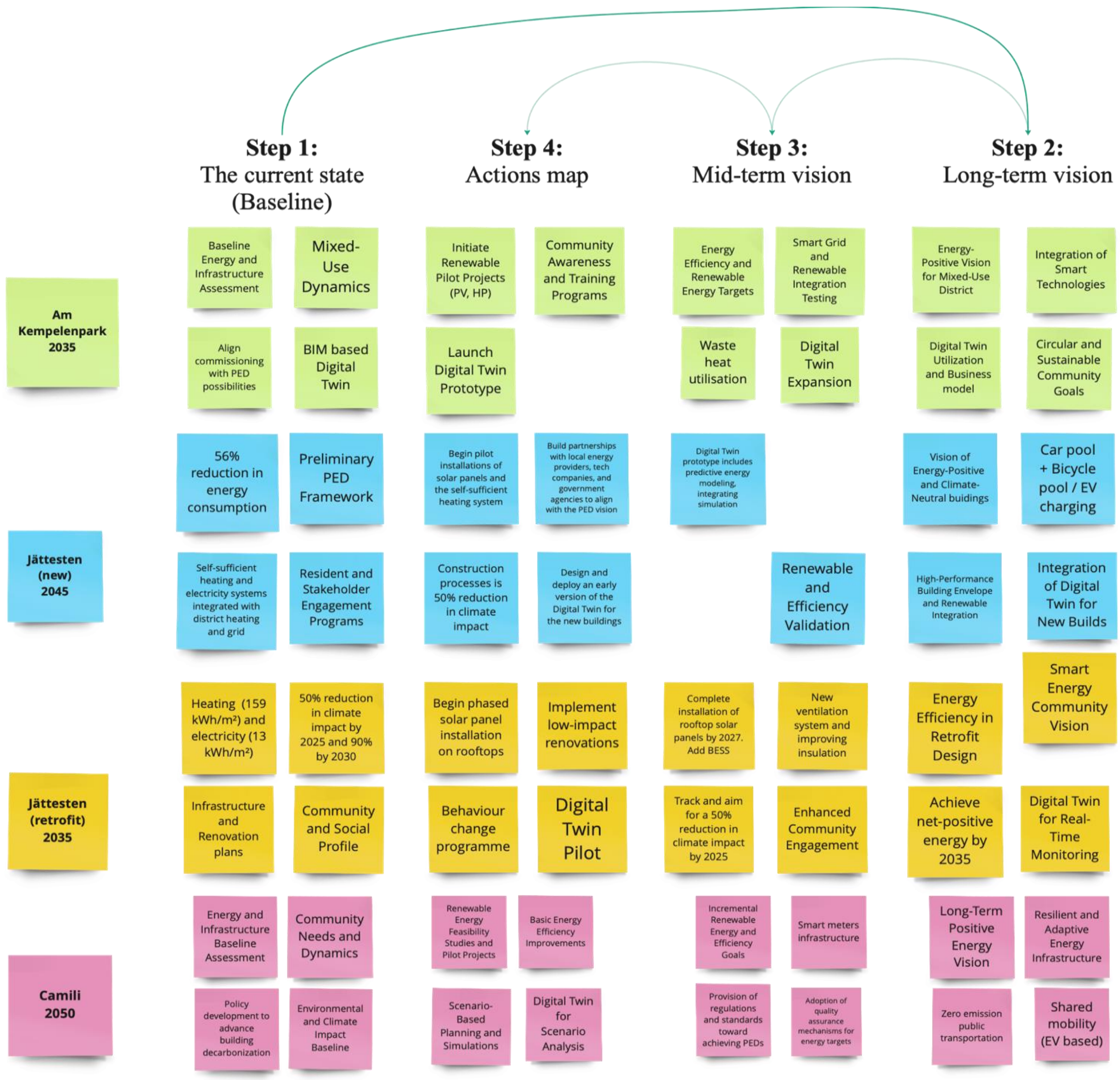

Figure 5. Backcasting workshop outcomes per each ULL.

3.2 Digital Twin strategies alignment

Building upon the backcasting outcomes, the integration of Digital Twin frameworks within the DT4PED project was instrumental in operationalizing the visionary goals identified during the workshop. Through case studies across the three ULLs, the alignment of DT functionalities with PED objectives highlights the potential for data-driven solutions to bridge the gap between high-level energy transition targets and practical urban sustainability actions. To operationalize the alignment of DT strategies within PEDs, it is essential to tailor these technologies to the unique characteristics and developmental stages of each ULL. The three ULLs illustrate the role of DTs in addressing context-specific challenges while supporting the broader PED vision (Figure 6). Each ULL leveraged Digital Twin strategies to enhance energy efficiency, stakeholder collaboration, and real-time decision-making across their respective urban environments. Am Kempelenpark distinguished itself by applying DT and openBIM technologies from the pre-design phase, avoiding complexities associated with retrofitting. The DT framework supported model-based planning, project visualization, thermal simulations, and real-time monitoring of HVAC systems.

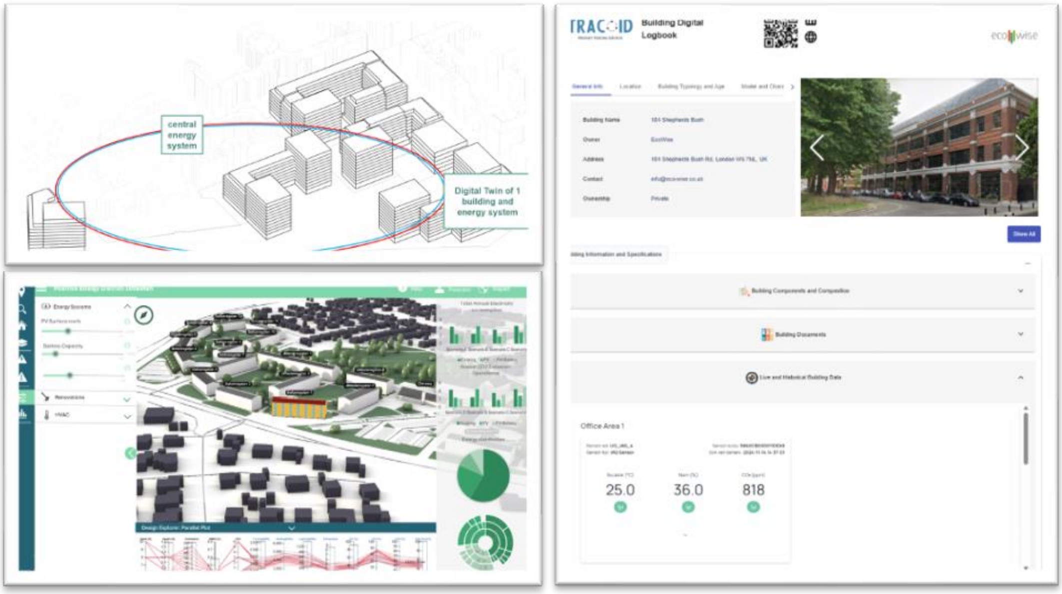

Figure 6. Digital Twin prototypes for the ULLs. Upper left: Am Kempelenpark (AT); Lower left: Jättesten (SE); Right: Camili (TR).

Jättesten DT focused on both retrofitting existing buildings and designing new PED-compliant constructions. The project adopted a Local Digital Twin (LDT) approach, leveraging Grasshopper-based parametric modelling continuously monitoring electricity consumption, renewable energy production, and indoor environmental conditions. The Camili DT facilitated performance benchmarking, real-time decision-making, and policy-driven optimization. The application of the TRACID Digital Building Logbook in this case study underscored the potential for scalable, data-driven urban sustainability strategies.

The findings from both the backcasting workshop and the Digital Twin applications reinforce the importance of an iterative, data-driven approach to PED development. While backcasting facilitated long-term visioning and stakeholder engagement, Digital Twins operationalized these visions into adaptive, real-time frameworks. The analysis highlights three key takeaways:

- PED strategies require continuous alignment between stakeholder-driven visions and data-driven implementation tools. Digital Twins provide a crucial feedback loop, allowing for iterative refinements as PED projects evolve.
- The application of DTs varies depending on the phase of PED development. Early-phase projects (e.g., Am Kempelenpark) benefit from BIM-integrated DTs, while mixed-development ULLs (e.g., Jättesten) require hybrid approaches integrating retrofitting with new construction modelling. Operational-phase ULLs (e.g., Camili) demonstrate the power of real-time monitoring and adaptive energy management in sustaining PED performance.
- Stakeholder collaboration remains critical across all phases. While backcasting workshops foster initial consensus-building, Digital Twins enable ongoing multi-stakeholder decision-making through data visualization, energy forecasting, and scenario modelling.

4 Conclusions and Further Research

This study integrates backcasting methodologies and DT strategies alignments to address the complexities of PEDs, demonstrating their combined potential for fostering sustainable urban energy transitions. Through the DT4PED project, the application of these frameworks in three distinct ULLs—Vienna’s Am Kempelenpark, Gothenburg’s Jättesten, and Sakarya’s Camili district—

provided insights into how visionary planning and advanced digital tools can collaboratively bridge the gap between long-term sustainability goals and actionable strategies. The backcasting workshop enabled diverse stakeholders to collaboratively define long-term visions, mid-term milestones, and short-term actions, fostering ownership and alignment across planning processes. Practical outcomes included identifying pathways for renewable energy integration, retrofitting strategies, and community-driven energy-saving initiatives. However, the workshop also revealed limitations, including difficulties in maintaining long-term stakeholder engagement and translating high-level visions into specific, actionable policies—a challenge noted in previous critiques of participatory planning methods (Quist et al. 2006). DT strategies complemented these backcasting insights by offering a platform for real-time monitoring, predictive analytics, and scenario modelling. Each ULL demonstrated how DT applications could be adapted to different urban contexts. These findings underscore the potential of DTs to enhance decision-making and operational efficiency, consistent with prior research on DT-enabled urban systems (Batty et al. 2018; Zhang et al. 2021). While backcasting provides a framework for aligning stakeholder visions and long-term sustainability goals, DTs operationalize these visions by enabling iterative, data-driven adjustments to energy systems. This dual approach advances the discourse on PED development by addressing both the visionary and operational dimensions of urban sustainability. Overall, while this research presents a replicable methodological framework that combines participatory foresight with digital simulation, it also underscores the need for further refinement, scalability testing, and long-term validation of this approach. The study contributes to the discourse on PED planning by illustrating both the potential and the limitations of integrating participatory and digital tools, offering a realistic and critical perspective on the complexities of sustainable urban energy transitions.

5 Acknowledgement

This project has received funding within the Joint Programming Initiative Urban Europe, financially supported by the Swedish Energy Agency (P2022-01028), the Austrian Federal Ministry for Climate Action, Environment, Energy, Mobility, Innovation and Technology (894291), and The Scientific and Technological Research Council of Türkiye (122N698). It is also part of the Digital Twin Cities Centre supported by Sweden's Innovation Agency Vinnova Grant No. 2019-00041.

6 References

Albert-Seifried, V., Murauskaite, L., Massa, G., Aelenei, L., Baer, D., Krangsås, S. G., ... and Vandevyvere, H., 2022. Definitions of positive energy districts: A review of the status quo and challenges. *Sustainability in Energy and Buildings 2021*, 493-506.

Anderson, J. and Rønning, A., 2022. Using standards to maximise the benefit of digitisation of construction product Environmental Product Declaration (EPD) to reduce Building Life Cycle Impacts. In *E3S Web of Conferences* (Vol. 349, p. 10003). EDP Sciences.

Baer, D., Loewen, B., Cheng, C., Thomsen, J., Wyckmans, A., Temeljotov-Salaj, A., and Ahlers, D., 2021. Approaches to social innovation in positive energy districts (PEDs)—a comparison of Norwegian projects. *Sustainability*, *13*(13), 7362.

Bibri, S.E., 2018. Backcasting in futures studies: a synthesized scholarly and planning approach to strategic smart sustainable city development. *European Journal of Futures Research*, *6*(1), 1-27.

Cucchiella, F., D'Adamo, I., and Gastaldi, M., 2017. Sustainable waste management: Waste to energy plant as an alternative to landfill. *Energy Conversion and Management*, *131*, 18-31.

Derkenbaeva, E., 2023. *Positive Energy Districts: A pathway toward urban energy transition?* (Doctoral dissertation, Wageningen University).

Dreborg, K.H., 1996. Essence of backcasting. *Futures*, *28*(9), 813-828.

European Commission. *Climate-neutral and smart cities. Research and Innovation.* Retrieved November 29, 2024. https://research-and-innovation.ec.europa.eu/funding/funding-opportunities/funding-programmes-and-open-calls/horizon-europe/eu-missions-horizon-europe/climate-neutral-and-smart-cities_en

European Commission, 2023. *Local Digital Twins: Forging the cities of tomorrow*. Retrieved November 20, 2024. from https://digital-strategy.ec.europa.eu/en/library/local-digital-twins-forging-cities-tomorrow

Geels, F.W., 2019. Socio-technical transitions to sustainability: a review of criticisms and elaborations of the Multi-Level Perspective. *Current opinion in environmental sustainability*, *39*, 187-201.

IoT Analytics, 2024. *6 main digital twin applications and their benefits*. Retrieved November 20, 2024. from https://iot-analytics.com/6-main-digital-twin-applications-and-their-benefits/

JPI, 2020. Urban Europe / SET Plan Action 3.2, White Paper on PED Reference Framework for Positive Energy Districts and Neighbourhoods. https://jpi-urbaneurope.eu/ped/

Quist, J. and Vergragt, P., 2006. Past and future of backcasting: The shift to stakeholder participation and a proposal for a methodological framework. *Futures*, *38*(9), 1027-1045.

Krangsås, S.G., Steemers, K., Konstantinou, T., Soutullo, S., Liu, M., ... and Maas, N., 2021. Positive energy districts: Identifying challenges and interdependencies. *Sustainability*, *13*(19), 10551.

Loorbach, D., 2010. Transition management for sustainable development: a prescriptive, complexity-based governance framework. *Governance*, *23*(1), 161-183.

Madni, A.M., Madni, C.C., and Lucero, S.D., 2019. Leveraging digital twin technology in model-based systems engineering. *Systems*, *7*(1), 7.

Maiullari, D., Nageli, C., Rudena, A., Isacson, Å., Dokter, G., Ellenbroek, I., Wallbaum, H., and Thuvander, L., 2024. Digital twin for supporting decision-making and stakeholder collaboration in urban decarbonization processes. A participatory development in Gothenburg. Environment and Planning B: Urban Analytics and City Science, 0(0).

Malakhatka, E., Wästberg, D., Wallbaum, H., Pooyanfar, P., Dursun, İ., Hofer, G., and Thuvander, L., 2024. Positive Energy Districts: Multi-criteria framework and Quality Assurance. In *IOP Conference Series: Earth and Environmental Science* (Vol. 1363, No. 1, p. 012085).

Negri, E., Fumagalli, L., and Macchi, M., 2017. A review of the roles of digital twin in CPS-based production systems. *Procedia manufacturing*, *11*, 939-948.

Pereverza, K., Pasichnyi, O., and Kordas, O., 2019. Modular participatory backcasting: A unifying framework for strategic planning in the heating sector. *Energy Policy*, *124*, 123-134.

Sareen, S., Albert-Seifried, V., Aelenei, L., Reda, F., Etminan, G., ... and Neumann, H.M., 2022. Ten questions concerning positive energy districts. *Building and Environment*, *216*, 109017.

Sassenou, L. N., Olivieri, L., and Olivieri, F., 2024. Challenges for positive energy districts deployment: A systematic review. *Renewable and Sustainable Energy Reviews*, *191*, 114152.

Semeraro, C., Lezoche, M., Panetto, H., and Dassisti, M., 2021. Digital twin paradigm: A systematic literature review. *Computers in Industry*, *130*, 103469.

Succar, B., 2009. Building information modelling framework: A research and delivery foundation for industry stakeholders. *Automation in construction*, *18*(3), 357-375.

Zhang, X., Shen, J., Saini, P. K., Lovati, M., Han, M., Huang, P., and Huang, Z., 2021. Digital twin for accelerating sustainability in positive energy district: a review of simulation tools and applications. *Frontiers in Sustainable Cities*, *3*, 663269