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DESIGN PRINCIPLES FOR POSITIVE ENERGY DISTRICTS

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Abstract. Positive Energy Districts (PEDs) are a cornerstone of the European Union's strategy for climate neutrality by 2050. A PED is an urban area that annually produces more renewable energy than it consumes, while maintaining affordability, livability, and social acceptance. Designing such districts requires an integrated and multidisciplinary approach that goes beyond building-level optimization and addresses district-scale synergies.

This paper outlines the key design principles for PEDs:

– Energy efficiency first, through passive architectural strategies and high-performance building services

– Renewable energy integration, maximizing local solar, wind, geothermal, and bio-based resources

– Smart energy management, using digital platforms, storage technologies, and demand-side flexibility

– Multi-scale integration, connecting buildings, infrastructure, and mobility into a coherent energy ecosystem

– Stakeholder engagement and governance, ensuring participatory planning and long-term acceptance

The study emphasizes that PEDs represent not only a technological innovation but also a socio-economic transition, requiring strong collaboration across disciplines and sectors. By applying these principles, PEDs can significantly contribute to urban decarbonization, energy resilience, and the achievement of the EU's climate and energy objectives.

Keywords: Positive Energy Districts; Energy efficiency; Renewable integration; Smart energy management; Urban decarbonization

1. Introduction

Urban areas are responsible for over 70% of global energy consumption and greenhouse gas emissions (IEA, 2021). As cities expand, their energy systems face increasing challenges in terms of sustainability, resilience, and affordability. To address this, the European Union's SET-Plan Action 3.2 introduced the concept of Positive Energy Districts (PEDs) – urban areas that produce more renewable energy annually than they consume (Kozłowska et al., 2024). PEDs are not isolated technological experiments; they represent a paradigm shift toward system-level integration of buildings, infrastructures, and communities. Unlike zero-energy buildings, which focus on single-building optimization, PEDs operate across multiple scales, incorporating spatial planning, governance, mobility, and citizen participation (Casamassima et al., 2022). The purpose of this paper is to identify and elaborate on the key design principles that underpin successful PED development. These principles are extracted from current European initiatives, scientific literature, and ongoing demonstration projects.

2. Conceptual Background of Positive Energy Districts

2.1. Definition and objectives

The Joint Programming Initiative Urban Europe (JPI UE) defines PEDs as "districts that have an annual positive energy balance achieved through energy efficiency, local renewable energy generation, and integration with the wider energy system" (JPI UE, 2023).

Their main objectives include:

– Reducing overall energy demand;
– Increasing renewable energy penetration;
– Enhancing flexibility through storage and smart control;
– Promoting stakeholder participation and social acceptance.

2.2. Evolution from NZEBs to PEDs

The evolution from Nearly Zero Energy Buildings (NZEBs) to PEDs reflects a shift from building-level to urban-scale energy management (Gondeck et al., 2024). While NZEBs focus primarily on balancing operational energy use, PEDs incorporate spatial and temporal energy exchanges between buildings and infrastructure, aiming for net-positive performance (Haase et al., 2025).

2.3. European framework and policy context

PEDs align with several EU frameworks, including the European Green Deal (EC, 2019), (REPowerEU, 2022), and the Energy Efficiency Directive (EED, 2023). The EU's long-term vision foresees the creation of at least 100 PEDs by 2025 (JPI UE, 2023), serving as experimental living labs for future carbon-neutral cities.

3. Key Design Principles for Positive Energy Districts

3.1. Energy Efficiency First

Energy efficiency is the foundation of any PED. The energy efficiency first principle implies reducing demand before investing in generation capacity (Haase et al., 2025). Building-level strategies include:

– High-performance envelopes (airtightness, insulation, thermal bridges);
– Passive solar design and adaptive shading;

– Efficient HVAC systems (heat recovery ventilation, heat pumps);
– Smart operation and user awareness programs.

At the district scale, shared heating/cooling networks, such as 4th and 5th generation district heating systems, can significantly improve system efficiency (Capone & Guelpa, 2023). Furthermore, building retrofitting must be prioritized. Europe's existing building stock accounts for 40% of total energy use (EC, 2020). Integrating renovation waves into PED planning is thus essential to achieve scalability and cost-effectiveness (Casamassima et al., 2022).

3.2. Renewable Energy Integration

Local renewable energy generation forms the backbone of PEDs. The design should maximize the use of solar, wind, geothermal, and bio-based resources, depending on climatic and spatial conditions (Braeuer et al., 2021). Photovoltaic (PV) integration is typically dominant, complemented by heat pumps and seasonal thermal storage (Gouveia et al., 2021). Energy communities (ECs) offer an institutional framework for managing distributed generation and consumption within districts (Casamassima et al., 2022). Through peer-to-peer energy sharing and cooperative governance models, ECs enhance local autonomy and resilience (Gondeck et al., 2024). Hybrid renewable systems – such as solar-assisted district heating, PVT (photovoltaic-thermal) panels, and biogas microgrids – can improve resource utilization and achieve a balanced, positive energy outcome (Haase et al., 2025).

3.3. Smart Energy Management

Effective energy management ensures that generation, storage, and demand interact efficiently. Smart systems rely on **data analytics, IoT sensors,** and **predictive control** to optimize district energy flows (Darivianakis et al., 2016). Key elements include:

– **Energy Management Systems (EMS)** integrating real-time data;
– **Demand Response (DR)** to shift loads according to renewable availability;
– **Thermal and electrical storage** (batteries, phase change materials, district thermal storage);
– **Digital twins** for continuous monitoring and optimization (Natanian et al., 2024).

The integration of AI-driven forecasting improves both reliability and cost efficiency (Pan et al., 2016). For instance, predictive algorithms can anticipate solar generation peaks and adjust HVAC setpoints or EV charging schedules accordingly. District-scale platforms, like **Smart Energy Hubs**, enable multi-carrier coordination, linking electricity, heat, and mobility networks in a unified control structure (Capone & Guelpa, 2023).

3.4. Multi-Scale Integration

PEDs are not limited to individual buildings—they represent **urban ecosystems** connecting infrastructure, public spaces, and mobility (Haase et al., 2025). Spatial planning and system design must occur simultaneously. Tools such as *Urban Building Energy Modelling (UBEM)* and *City Energy Analyst (CEA)* help simulate energy exchanges between components (Natanian et al., 2024). **Mobility integration** is another key aspect. Electric vehicles (EVs) act as mobile storage units, enabling **Vehicle-to-Grid (V2G)** operations that support grid stability (Casamassima et al., 2022). Shared charging infrastructure also promotes sustainable transport. At higher scales, PEDs should align with **district heating/cooling, waste-to-energy,** and **smart grid** systems, ensuring interoperability with the broader city infrastructure (Gondeck et al., 2024).

3.5. Stakeholder Engagement and Governance

Technical optimization alone cannot ensure a PED's success; **social acceptance and participatory governance** are equally critical (Casamassima et al., 2022). Stakeholder engagement should involve local authorities, residents, investors, utilities, and academia throughout all project phases. Participatory design processes – co-creation workshops, focus groups, and living labs – foster collective ownership and trust (Kozłowska et al., 2024). Governance models must be transparent and adaptable. **Community-led business models**, such as energy cooperatives, ensure that financial benefits remain within the district (Braeuer et al., 2021). Long-term sustainability depends on establishing governance frameworks that balance technological performance with inclusiveness, equity, and long-term maintenance (Gondeck et al., 2024).

4. Methodology

This paper synthesizes findings from recent EU-funded PED projects (e.g., MAKING-CITY, ATELIER, +CityxChange, SPARCS). The analysis combines literature review, policy mapping, and conceptual modeling. For illustration, a hypothetical district scenario was simulated using EnergyPlus and City Energy Analyst (CEA) tools, representing a mixed-use urban block in a Central European climate zone. Input parameters included passive design features, PV arrays, air-to-water heat pumps, and battery storage.

Performance indicators used:

– Annual energy balance (kWh/m²/year);
– Renewable share (%);
– Peak load reduction (%);
– Stakeholder participation index (qualitative);

These indicators align with JPI Urban Europe's PED framework (JPI UE, 2023).

5. Results and Discussion

Simulation results demonstrated that applying the five design principles can lead to a net-positive annual energy balance at the district scale. Energy efficiency measures showed a clear reduction in heating and cooling demands, while renewable energy integration through PV systems and heat pumps contributed to an overall energy surplus. Smart control strategies and demand-response mechanisms improved operational stability and load management across buildings. Furthermore, participatory processes enhanced user awareness, acceptance, and engagement in the transition toward a more sustainable district energy system.

Challenges identified include:

– High initial investment costs (Capone & Guelpa, 2023);

– Difficulties in integrating data across heterogeneous digital platforms;

– Unclear ownership and business models for shared energy assets;

– Variability in policy and regulatory frameworks among EU member states.

Overall, the findings confirm that systemic integration – across technical, social, and governance dimensions – is essential for achieving climate-neutral and resilient urban districts (Haase et al., 2025).

6. Conclusions

PEDs are emerging as one of the most promising pathways for urban decarbonization. They require multidisciplinary collaboration, combining energy engineering, architecture, ICT, and social sciences. The five design principles discussed – energy efficiency, renewable integration, smart energy management, multi-scale integration, and stakeholder engagement – form a comprehensive blueprint for developing sustainable, resilient urban districts. Future work should focus on refining assessment tools, enabling data interoperability, and strengthening governance models that support citizen-led energy transitions. By embracing these principles, cities can move beyond neutrality toward positive energy futures – where energy production, social well-being, and climate resilience coexist harmoniously.

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