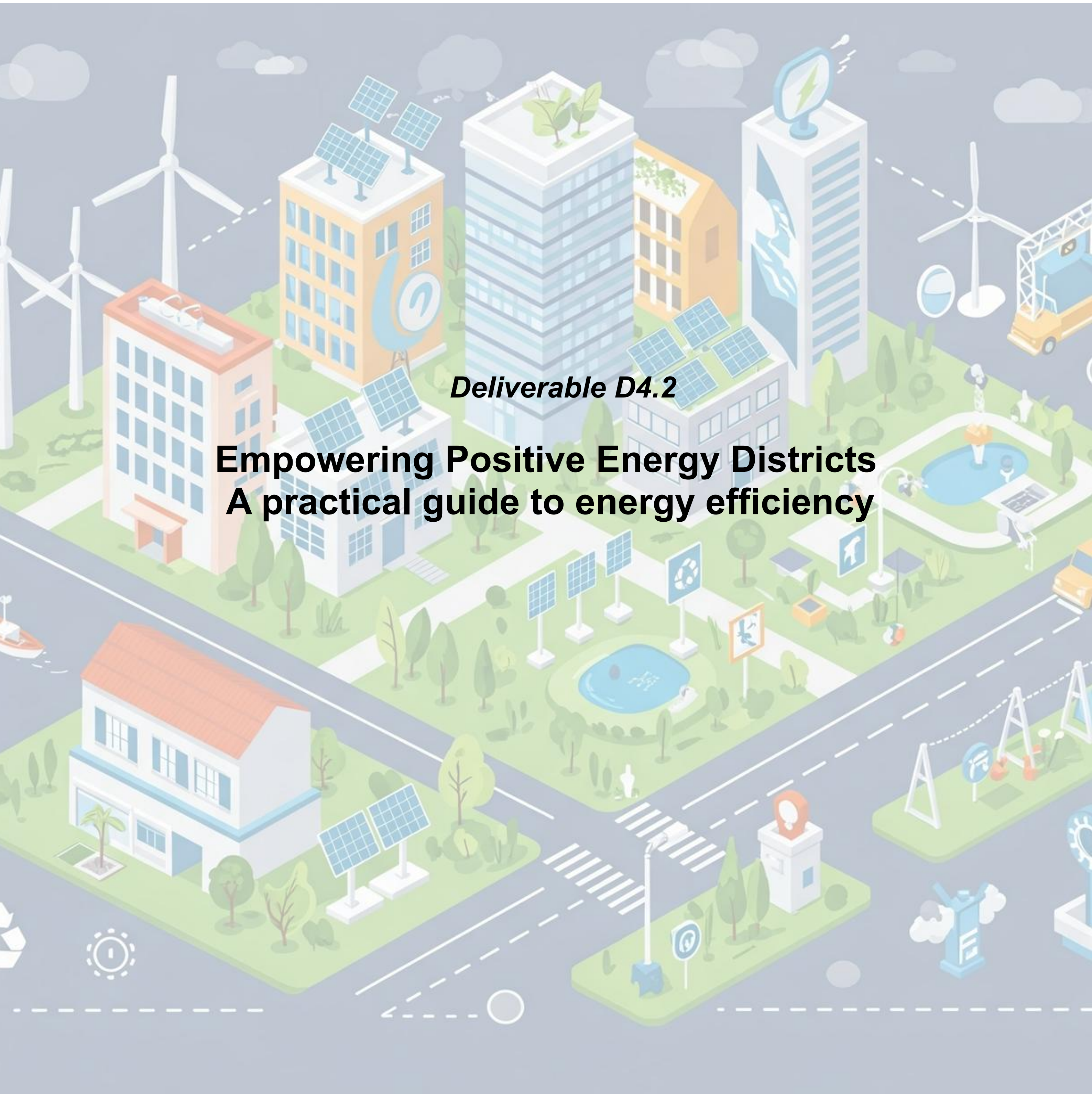
persist

positive energy districts
driven by citizens



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Empowering Positive Energy Districts
A practical guide to energy efficiency

Driving Urban Transitions

Co-funded by the European Union

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positive energy districts
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ABBREVIATION

PED	**Positive Energy District**
REC	**Renewable Energy Communities**
CEC	**Citizen Energy Community**
RRF	**Recovery and Resilience Facility**
KPI	**Key Performance Indicator**
RED II	**Renewable Energy Directive II (recast) 2018/2001**
RED III	**Renewable Energy Directive III**
NRRP	**National Recovery and Resilience Plan**
SECAP	**Sustainable Energy and Climate Action Plan**
EPC	**Energy Performance Contracting**
nZEB	**Near-zero energy buildings**
PACE	**property-assessed clean energy**
SME	**Small and medium-sized enterprises**
HVAC	**Heating Ventilation and Air Conditioning**
DSM	**Demand-Side Management**
GHG	**Greenhouse Gass**
BMS	**Building Management System**
SCADA	**Supervisory Control and Data Acquisition**
IoT	**Internet of Things**
AMI	**Advanced Metering infrastructure**
BAS	**Building Automaton System**
EMS	**Energy Management System**
EPBD	**Energy Performance of Buildings Directive**
FDD	**Fault Detection and Diagnosis**
CHP	**Combined Heat and Power**
SRI	**Smart Readiness Indicator**
BIPV	**Building Integrated Photovoltaics**
ROI	**Return on Investment**
EV	**Electric Vehicle**
V2G	**Vehicle to grid**
ICT	**Information and Communication Technology**
VPP	**Virtual Power Plant**
COP	**Coefficient of Performance**
DHC	**District Heating and Cooling**
SUMPs	**Sustainable Urban Mobility Plans**
CCS	**Carbon Capture and Storage**
CCUS	**Carbon Capture, Utilization and Storage**
DAC	**Direct Air Capture**
PV	**Photovoltaic pannels**

Executive summary

Empowering Positive Energy Districts: A Practical Guide to Energy Efficiency, serves as a comprehensive resource for city officials, planners, architects, engineers, policymakers, and community leaders committed to transforming this vision into reality. It outlines the imperative of energy efficiency within **Positive Energy Districts (PEDs)**, provides practical strategies and examples, and issues actionable recommendations to drive a paradigm shift towards energy-positive urban environments. By examining the policy framework, measurement methodologies, governance models, and on-the-ground solutions, the guide illuminates how PEDs can be planned, implemented, and sustained to contribute to climate goals and improve urban livability. The primary objective is to empower stakeholders with knowledge and tools to implement PEDs successfully, with energy efficiency as a central pillar. By providing practical guidance, real-world examples and evidence-based insights, it aims to accelerate the adoption of Positive Energy District (PED) principles in city districts, fostering innovation, collaboration and a shared vision for cities that produce more energy than they consume.

Key findings include:

- The European legislative landscape is **increasingly enabling PED development**. Recent EU directives on renewable energy and the internal electricity market define and empower *energy communities*, granting groups of citizens and local actors the right to produce, share, and sell renewable energy. These policies – along with EU initiatives like REPowerEU and Recovery and Resilience Facility funding – lay **a strong groundwork for cities to pursue PED initiatives** by removing regulatory barriers and providing financial incentives. A clear legal basis now exists for PED-style projects, allowing communities of prosumers to operate viable local energy systems on an equal footing with traditional market actors.
- Effective PED implementation relies on rigorous measurement and data-driven management, underlining the adage that *"what we cannot measure, we cannot improve."* Chapter 3 emphasizes establishing robust monitoring infrastructure and **Key Performance Indicators (KPIs) to evaluate energy efficiency at the district level**. By tracking these indicators, stakeholders can pinpoint inefficiencies, verify improvements, and ensure accountability toward the PED's net-positive energy goal. Data collection and analytics are shown to be critical for continuous optimization of building operations, grids and user behavior within PEDs.
- Coordinating a PED **involves complex governance challenges**, as multiple stakeholders must work in concert. Strong governance is the core of successful and scalable PEDs. Energy efficiency **must be a primary focus of governance**: districts can only achieve a positive energy balance by aggressively minimizing energy demand through efficiency measures at building, district, and system levels**. Leadership and policy support** are needed to drive the adoption of these measures, integrate them into urban planning, and maintain social inclusivity.
- Achieving PED's ambitious targets requires **deploying a portfolio of energy efficiency and clean energy solutions**. It catalogs a range of measures across buildings, energy infrastructure, mobility and societal behavior. Key strategies addressed include deep energy retrofits in buildings, installation of renewable energy, integration of energy storage to balance supply and demand, smart grids to optimize energy flows and electrification of heating and transport. The report highlights that **no single solution** is sufficient; rather, it is the **integration of these measures** that enables a PED to become net positive.

Empowering Positive Energy Districts: A Practical Guide to Energy Efficiency provides a clear blueprint for translating the PED concept into actionable reality. It underscores that energy efficiency is the foundational strategy – by reducing demand first, PEDs can more feasibly generate an energy surplus and achieve sustainability targets. The findings of this report affirm that through supportive policies, meticulous planning, stakeholder collaboration, and cutting-edge technologies, cities can develop districts that not only meet their own energy needs but also contribute excess clean energy back to the broader system. By acting on these strategies, urban decision-makers and communities can improve energy performance and move decisively toward the vision of positive-energy, zero-emission cities.

1. Introduction

The imperative for a sustainable future has never been more urgent. Faced with the escalating challenges of climate change, resource depletion, and the growing energy demands of urban populations, innovative and transformative solutions are essential. Among the most promising approaches is the concept of the (PED) – a visionary framework for urban development that transcends traditional energy consumption models. This practical guide, **Empowering Positive Energy Districts: A Practical Guide to Energy Efficiency**, is designed to be a comprehensive resource for stakeholders committed to realizing the potential of PEDs and driving a paradigm shift towards energy-efficient urban environments.

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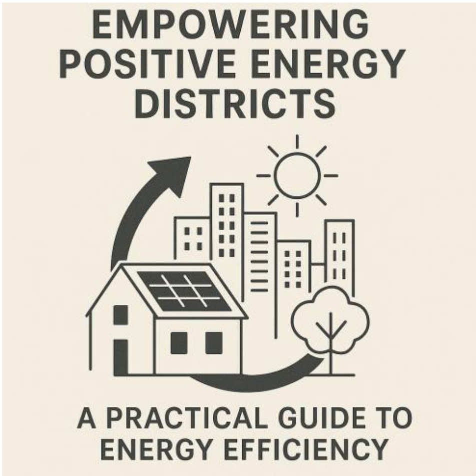

Imagine urban landscapes where buildings not only minimize their energy footprint but actively generate more renewable energy than they consume annually, on average, when accounting for energy exchange with the wider energy system. This is **the core ambition** of a Positive Energy District. More than just a collection of energy-efficient buildings, a **PED is a strategically planned and managed urban area** where energy flows are optimized through a holistic approach encompassing building design, renewable energy integration, smart grids, sustainable mobility and active engagement of its inhabitants.

The transition towards PEDs represents a fundamental shift in how we conceive, design, and operate our cities. It necessitates a departure from linear energy systems towards circular and integrated models. It requires a collaborative spirit, bringing together urban planners, architects, engineers, policymakers, energy providers, technology developers and the communities themselves. The journey towards widespread adoption of PEDs is multifaceted, presenting both **significant opportunities and complex challenges**.

This guide acknowledges **the complexity of this effort and aims to provide a clear, actionable pathway for stakeholders** at various stages of engagement. Whether you are a **city official** exploring sustainable urban development strategies, **an architect** designing the next generation of energy efficient buildings, an **energy provider** seeking to integrate distributed renewable energy sources, **a community promoted** sustainability initiative or **a researcher** exploring the frontiers of urban energy systems, this guide offers valuable insights and practical tools.

Energy efficiency forms the bedrock of any successful PED. By prioritizing the reduction of energy demand, we not only minimize the reliance on external energy sources but also significantly decrease the scale and cost of renewable energy generation required to achieve a positive energy balance. An **energy-efficient district inherently promotes resilience**, reduces energy poverty, improves air quality, and contributes to a more comfortable and healthy living environment for its residents.

By providing **practical guidance, real-world examples and actionable recommendations**, this guide aims to empower stakeholders to start on the journey of creating sustainable and energy-positive urban districts. It is a call to action, urging us to adopt innovation, collaboration and a shared vision for a future where the cities are not only consumers of energy but also active contributors to a sustainable planet.

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2. European legislative framework and support policies

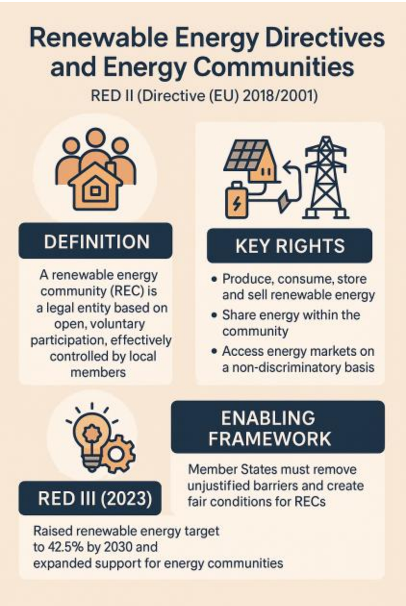
PEDs are a developing concept in Europe's urban energy transition. A PED is generally defined as an urban neighborhood that achieves an annual net-zero energy import and net-zero CO_2 emissions, **working towards a surplus of renewable energy generation**[1]. In practical terms, a PED involves a cluster of buildings and local energy infrastructure where residents, businesses, and public entities **collectively produce, consume, and share energy**, often utilizing renewable sources and storage to become net energy positive. While the term "Positive Energy District" itself is not yet a defined legal category in EU legislation, it aligns closely with the framework of **energy communities** introduced in recent EU directives[2].

Energy communities – notably **Renewable Energy Communities (RECs)** and **Citizen Energy Communities (CECs)** – provide the legal basis that enables groups of users (in a district or otherwise) to jointly engage in energy production, self-consumption, sharing, and storage. This report provides an overview of the European legal context shaping PED development, focusing on these energy community frameworks, as well as EU support policies like REPowerEU and the Recovery and Resilience Facility (RRF) that encourage urban PED initiatives.

2.1 EU legal framework enabling PEDs

2.1.1 Renewable Energy Directives (RED II and RED III) – Energy Communities

The EU's Renewable Energy Directive (recast) 2018/2001 (known as **RED II**) was a landmark in introducing **"renewable energy communities" (RECs)** into European law[2]. Article 22 of RED II defines a renewable energy community as a legal entity based on open, voluntary participation, effectively controlled by local members. Member States are required to **ensure** that **final customers (especially households) can participate in a REC without losing their consumer rights**, and that private enterprises may participate so long as it is not their main commercial activity[3].



Importantly, RED II **guarantees key rights for energy communities**: the right to **produce, consume, store and sell renewable energy**, including via power purchase agreements[3]; the right to **share energy within the community**[3]; and the right to **access all suitable energy markets** either directly or through aggregation, on a non-discriminatory basis[3]. These provisions enable the collaborative generation and use of energy – a core of PEDs – by legally empowering communities of prosumers.

RED II also obliges Member States to **remove unjustified regulatory and administrative barriers** and create an "enabling framework" for RECs[3]. This includes fair, proportionate network charges and streamlining of licensing or registration for community projects, so that energy sharing in a neighborhood is not unduly penalized[3]. For example, distribution system operators must cooperate with communities to facilitate energy transfers within the community, and community members should face **no discriminatory treatment or excessive fees** when sharing power on the grid[3]. By mandating an equal footing with other market actors, RED II allows PED-type setups to operate viably.

[1] jpi-urbaneurope.eu/ped/
[2] energy.ec.europa.eu/topics/markets-and-consumers/energy-consumers-and-prosumers/energy-communities
[3] Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources

In 2023, the EU adopted **RED III (Directive (EU) 2023/2413)**, which amends RED II. While RED III primarily raised the Union's renewable energy target to 42.5% by 2030 (up from 32% in RED II) and accelerated permitting, it also **reaffirmed and slightly expanded support for energy communities**. Notably, the 2023 amendments enable Member States to promote energy communities in new domains like **offshore renewable projects and district heating/cooling networks**.

2.1.2 Internal Electricity Market Directive (2019/944) – Prosumers and Citizen Energy Communities

Alongside the renewable's directive, the **Internal Electricity Market Directive (EU 2019/944)** provides a complementary framework focusing on electricity market participation. This directive introduced the concept of **"citizen energy communities"** (CECs) and detailed rights for **active customers (prosumers)** in the electricity market[4]. A citizen energy community, as defined in Article 2(11) of Directive 2019/944, is a legal entity that is **voluntarily and effectively controlled by members that are natural persons, local authorities (including municipalities), or small enterprises** – rather like a REC, but not limited to renewables[5]. The purpose of a CEC is generally to provide environmental, economic or social community benefits rather than financial profits. The directive requires Member States to create an enabling framework for CECs, ensuring open and voluntary participation and allowing members to leave the community as easily as changing electricity suppliers.

Directive 2019/944 **ensures that energy communities and prosumers can engage in the market on fair terms**[4]. It explicitly grants citizen communities the ability to **generate, consume, share or sell electricity, and to provide flexibility services such as demand response and energy storage**[4]. In other words, households in an urban district can form a CEC to collectively invest in solar panels or a battery and then trade electricity among themselves or offer surplus/storage capacity to the grid operator. The law stipulates that when CECs act in roles like suppliers or network operators, they must comply with the relevant obligations, but **regulations should be applied to them in a proportionate, non-discriminatory way**[5].

For instance, if a citizen community operates a micro-grid or local distribution network within a district, they can be exempted from some unbundling rules or be treated as a closed distribution system under certain conditions[5]. It also introduced **dynamic pricing rights and smart metering** for active consumers, so that prosumers in a community can optimize energy use and benefit from price signals. Overall, 2019/944 ensures that **"active customers" and communities can participate in all electricity markets** and are not excluded by traditional supplier-centric models[4]. This creates a fair marketplace in which a PED – effectively a cluster of active consumers and producers – can thrive and compete, selling excess energy or reducing demand at peak times for mutual benefit.

2.1.3 Other relevant EU instruments supporting PED development

Beyond the core directives on renewables and electricity markets, several other EU legal and policy instruments encourage the deployment of PEDs and community-led energy projects:

Energy Efficiency and Buildings Directives: The recast **Energy Efficiency Directive (EU) 2023/1791** recognizes the role of energy communities in heat planning, requiring local authorities to **assess the potential for energy communities to develop renewable-based heating projects** in their area[6]. Likewise, the proposed **recast Energy Performance of Buildings Directive (EPBD)** calls on Member States to report in their building renovation plans **how energy communities contribute**, and it acknowledges that renewable energy supplied by a community can count toward a building's zero-emission supply[6]. These provisions integrate community energy solutions into urban planning and building standards – for example, a block of flats retrofitted under a city's renovation plan could form a community to collectively install solar PV or a shared heat pump, thereby moving the district toward positive energy status.

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[4] energy.ec.europa.eu/topics/markets-and-consumers/energy-consumers-and-prosumers/energy-communities
[5] Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources link
[6] energy.ec.europa.eu/topics/markets-and-consumers/energy-consumers-and-prosumers/energy-communities

Clean Energy for All Europeans Package: PEDs benefit generally from the broader suite of measures in the 2019 Clean Energy Package (of which RED II and Directive 2019/944 were part). This includes regulations on electricity market access, energy storage rights, and consumer protections. For instance, active consumers have a right to **install storage and not be subject to double network charges** for stored electricity, and they can aggregate their production/consumption – critical for a positive-energy block to pool resources. The clean energy package also improved **demand response** frameworks, meaning PED participants can earn revenue by adjusting consumption, and it set groundwork for **smart grids** to accommodate many small-scale generators typical of a PED[6].

Social Climate Fund Regulation (EU) 2023/955: Though not an energy directive, this new Fund (part of the EU climate policy package) explicitly allows Member States to use its resources to support **energy communities involving vulnerable households[6]**. This is relevant where PED projects are used as a tool to alleviate energy poverty in urban areas – for example, installing community solar in a low-income neighborhood and sharing the benefits. The Social Climate Fund signals political support for community-led solutions to ensure a just transition.

EU's legal framework does not name "Positive Energy Districts" outright, but it provides **strong enabling legislation for community energy initiatives** which are the legal vehicle for PEDs. **Renewable Energy Communities (under RED II/III)** and **Citizen Energy Communities (under Dir. 2019/944)** grant urban stakeholders the right to jointly produce, share, and sell energy, backed by requirements on Member States to remove barriers and ensure fair market access[7,6]. Complementary policies in energy efficiency, buildings, and climate funding further support the incorporation of such community-driven projects into urban development. Together, these create a conducive European legal context for cities to develop PEDs.

2.2 European-level support policies for PEDs

2.2.1 REPowerEU and the Urban Energy Transition

REPowerEU is the EU's plan (launched in 2022) to rapidly transform its energy system in response to the energy crisis and the need to eliminate dependence on Russian fossil fuels[8]. It has significant implications for urban renewable integration and community energy, aligning with PED objectives. Under REPowerEU, the EU raised its 2030 renewables target (from 40% to 45%) and introduced a suite of measures to **accelerate local renewable deployment[8]**. One flagship initiative is the **EU Solar Energy Strategy**, which includes a **Solar Rooftop Initiative mandating solar panels on new buildings within the decade**. Specifically, the European Commission proposed that all new commercial and public buildings should have rooftop solar installations by 2027, and all new residential buildings by 2029[9]. This mandate – "ambitious but realistic" according to Commission President von der Leyen – directly drives urban areas towards onsite generation on schools, offices, malls, and homes, laying the hardware foundation for future PEDs[9]. Coupled with this, REPowerEU called for **"renewables go-to areas"** in all Member States where permitting is extremely expedited (approvals within 1 year, or even 6-9 months for small installations)[9]. Urban rooftops and brownfield sites are prime candidates for such go-to areas, meaning city-led PED projects can benefit from fast-tracked permissions. REPowerEU also explicitly acknowledges the role of communities and citizens in the energy transition. The plan's **EU Solar Strategy draws a clear distinction** between genuine **energy communities (social, citizen-driven)** and purely commercial collective schemes, and urges Member States to **lift barriers facing energy communities**[10]. In parallel, the Commission issued a

[7] Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources
[8] www.pv-magazine.com/2022/05/18/eu-wants-rooftop-pv-mandate-for-public-commercial-buildings-by-2025-residential-by-2029
[9] www.pv-magazine.com/2022/05/18/eu-wants-rooftop-pv-mandate-for-public-commercial-buildings-by-2025-residential-by-2029
[10] www.rescoop.eu/news-and-events/press/repowereu-plan-carves-out-role-for-community-energy-but-the-eu-still-needs-to-address-its-fossil-energy-import-addiction

Recommendation on permitting in 2022 stressing that authorities should **simplify procedures, especially grid connection, for renewable energy communities**[10].

This guidance targets one of the major challenges for PED-like projects – getting timely grid access to exchange energy within the district or export surplus. Moreover, REPowerEU emphasizes **energy inclusion**, recommending that policies ensure vulnerable households get access to renewables (for instance via community solar programs) so that the benefits of the green transition are shared[10]. All these measures strengthen the policy environment for PEDs by empowering local action: easier installation of urban renewables, clear support for community-driven projects, and faster bureaucracy. Another component of REPowerEU is its integration with EU funding mechanisms. The plan led to the introduction of dedicated **REPowerEU chapters in national Recovery and Resilience Plans**, directing additional EU funds to priority energy projects like renewable production, energy networks, and energy efficiency. This has reinforced financial support for urban energy initiatives. As described in the next section, many countries have funneled part of their recovery funds into local renewable projects, energy communities, and innovative pilots – often in cities – in line with REPowerEU objectives. In summary, REPowerEU acts as a **catalyst for urban energy transition**, combining regulatory urgency (higher targets, solar mandates, expedited permitting) with recognition and support of energy communities as key implementers[10]. For city authorities and stakeholders aiming to establish PEDs, REPowerEU provides both the trigger (through stricter renewable requirements and incentives) and improved tools (through guidance to ease community projects and new funding avenues) to turn plans into reality.

2.2.2 Recovery and resilience facility (RRF) and national plans supporting PEDs

The **Recovery and Resilience Facility (RRF)** – Europe's post-COVID investment instrument – has become a major vehicle to finance the green transition, including elements directly supporting PEDs and energy communities. The RRF, under NextGenerationEU, required each Member State to prepare a **National Recovery and Resilience Plan (NRRP)** with at least 37% of spending on climate-related measures. Many of these plans embraced the opportunity to invest in **renewable energy, energy efficiency, and local energy projects** that contribute to sustainable urban development. In fact, about **€34.2 billion RRF grants are allocated to accelerating renewable energy deployment across the EU**, and 23 countries included reforms to streamline renewables permitting. Notably, **nine Member States included specific reforms to enhance the regulatory framework for the operation of energy communities** as part of their recovery plans[11]. This means that through the RRF process, a third of EU countries committed to improving laws or regulations to support community energy (for example, by transposing the EU definitions of RECs/CECs into national law, simplifying licensing, or enabling energy sharing) – a clear boost to the viability of PED initiatives. These reforms were aligned with Commission guidance and the REPowerEU package, ensuring a consistent push for **community-driven energy projects in a fair market[11]**. Beyond regulatory reform, the RRF plans earmarked substantial **investments** for local renewable integration, often targeting urban or community-level schemes. For instance, **Italy's Recovery and Resilience Plan dedicated €2.2 billion to support energy communities and collective self-consumption** projects[12]. This huge investment – one of the largest single allocations in Europe for community energy – finances new renewable generation (like rooftop solar) in municipalities (especially towns under 5,000 inhabitants) and the infrastructure for citizens to share power locally[12]. In addition, Italy received approval for a €5.7 billion state aid scheme to incentivize renewable self-consumption up to 1 MW, including community projects[13]. While much of Italy's program targets smaller towns, it lays the groundwork for scaling up to urban neighborhoods as well.

[11] energy.ec.europa.eu/topics/funding-and-financing/recovery-and-resilience-facility-clean-energy
[12] www.iea.org/commentaries/empowering-people-the-role-of-local-energy-communities-in-clean-energy-transitions
[13] ec.europa.eu/commission/presscorner/detail/en/ip_23_5787

Similarly, **Spain's Recovery, Transformation and Resilience Plan explicitly target energy communities**: it channels funding from central government to all regions to **subsidize the creation of energy communities across Spain**[14]. Spain allocated roughly **€3.16 billion** of its plan to a component on renewable energy integration, one sub-component of which is the **"deployment of energy communities"** and launched dedicated calls with at least €120 million reserved for community-led renewable projects (including generation, e-mobility, and efficiency)[14]. This nationwide approach is supporting dozens of pilot energy communities – many in urban or peri-urban areas – which can evolve into full-fledged PEDs as they expand local generation and link with building upgrades.

Latvia's National Recovery and Resilience Plan (NRRP) also contribute to the development of Positive Energy Districts by prioritizing large-scale building renovation, renewable energy uptake, and digitalization of energy systems. Although the Latvian plan does not include a dedicated component for energy communities, it allocates a substantial share of RRF funding to deep renovation of residential and public buildings, smart building technologies, and distributed solar PV, all of which strengthen the technical foundations for PEDs. These measures improve energy performance, increase self-consumption potential, and enhance the readiness of buildings to participate in flexibility and demand-response schemes. Latvia's NRRP further supports grid digitalization and smart metering, enabling more accurate consumption data and reducing barriers for integrating new prosumers. Complementary regulatory reforms - aligned with Repower EU - aim to streamline renewable permitting and raise efficiency standards, gradually moving the national framework closer to enabling collective self-consumption and future energy communities[15].

Other countries have used RRF funds to back urban energy pilots and PED-like initiatives. **France** and **Germany**, for example, focused a significant part of their plans in building renovations and renewable heating in cities, indirectly supporting PED goals of efficient, low-carbon districts. **Luxembourg** concentrated its entire energy RRF allocation on renewables, likely including community solar for its towns[11]. **Poland** and **Czechia** invested in grid modernization and flexibility to enable more distributed resources and self-consumers on their networks[11]– critical for any future PED in their cities. A concrete example is the Czech plan's reforms to **maximize grid capacity for renewables and facilitate connections for self-consumption** projects[11], which will help urban renewable communities connect their installations without lengthy delays. Moreover, with the addition of REPowerEU chapters in 2023, several countries are topping up their plans with new initiatives (e.g. support for rooftop solar, heat pumps, or energy storage in urban communities) to further reduce fossil fuel reliance[11]. In summary, the Recovery and Resilience Facility has been a powerful support instrument for PEDs by providing **funding and policy impetus at national levels**. Through the RRF, EU countries are financing local renewable generation, encouraging energy community formation, upgrading grids and buildings, and enacting pro-community reforms – all of which directly feed into the realization of PEDs. European Commission analysis shows that **Italy, Spain and Poland** are among those allocating the largest absolute amounts to renewable energy in their plans[16], and many plans include measures to **ease the integration of distributed energy resources and demand response**[15], which are essential features of a PED. By coupling financial investment with structural reforms (e.g. simplifying how communities can share energy or how prosumers are compensated), the RRF is helping remove both the economic and regulatory barriers to PED projects.

Table 1.

Mechanism	Description	Example tools
Planning instruments	Integration of energy efficiency in land-use, zoning, and district design.	Sustainable Energy and Climate Action Plans (SECAPs), energy master planning
Financial governance	Structuring funding models that prioritize efficiency first.	Energy Performance Contracting (EPC), green loans, blended finance

[14] www.rescoop.eu/policy/financing-tracker/recovery-resilience-funds/spain-recovery-resilience-funds
[15] European Commission (2022). *Analysis of the Recovery and Resilience Plan of Latvia*.; https://www.kem.gov.lv/lv/fondi-un-investicijas
[16] energy.ec.europa.eu/topics/funding-and-financing/recovery-and-resilience-facility-clean-energy_en

Regulatory mechanisms	Applying or adapting building codes and efficiency standards at the district scale.	Near-zero energy buildings (nZEB) mandates, energy performance certificates
Data and digital governance	Ensuring data-driven decision making and building optimization.	Smart meters, building passports, open data platforms
Participation and co-governance	Co-design of energy efficient retrofits with residents and businesses.	Living labs, participatory audits, gamified energy challenges

3. PED Governance

Governance is associated with network structures, interdependence, trust, negotiations and power relations among different actors[17]. PED represents a novel system that involves many contributors, which leads towards a new governance model where multiple figures are expected to work together for a common purpose[18]. Optimal operation of PEDs requires **high interoperability among various stakeholders and technological systems**[19]. Managing all the aspects of a PED lies beyond the traditional governance and new and innovative forms of are needed, in which all stakeholders take part in the planning and decision-making process.[20]

While diverse governance models exist, collaborative and adaptive structures appear most promising for balancing innovation, equity, and long-term sustainability. A deep understanding of local institutional ecosystems, combined with flexible regulatory instruments and active citizen engagement, is **essential for the accomplishment of PEDs** as future-proof urban systems. To realize PED vision, energy efficiency must be a primary focus. Districts can only achieve a positive energy balance by actively minimizing their energy demand through comprehensive efficiency improvements at building, district, and system scales. Furthermore, effective governance is essential to drive the adoption, ensure the effectiveness, and guarantee the social fairness of these measures by aligning goals, coordinating actors, and implementing supportive policies.

Energy efficiency governance in PEDs refers to:

- Building retrofitting (envelopes, insulation, HVAC systems)
- High-performance new constructions
- Smart controls and energy management systems
- District-level efficiency (heating/cooling networks, waste heat recovery)
- Behavioral efficiency programs and citizen engagement

Achieving district-wide energy efficiency demands **a strategic governance approach employing diverse mechanisms**. These range from planning instruments integrating energy efficiency into urban design, to financial governance prioritizing green investments, regulatory mechanisms setting district-level standards, data and digital governance enabling optimization and participation, co-governance facilitating inclusive implementation. Together, these mechanisms form a comprehensive framework for minimizing energy demand and building sustainable districts.

Table 2.

Mechanism	Description	Example tools
Planning instruments	Integration of energy efficiency in land-use, zoning, and district design.	Sustainable Energy and Climate Action Plans (SECAPs), energy master planning
Financial governance	Structuring funding models that prioritize efficiency first.	Energy Performance Contracting (EPC), green loans, blended finance
Regulatory mechanisms	Applying or adapting building codes and efficiency standards at the district scale.	Near-zero energy buildings (nZEB) mandates, energy performance certificates
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[17] Trevisan, R.; Ghiani, E.; Pilo, F. Renewable Energy Communities in Positive Energy Districts: A Governance and Realisation Framework in Compliance with the Italian Regulation. *Smart Cities* **2023**, *6*, 563-585. https://doi.org/10.3390/smartcities6010026
[18] Mihailova, D; Schubert, I; Burger, P; Morgane M.C. Fritz. Exploring modes of sustainable value co-creation in renewable energy communities, Volume 330, 2022, https://doi.org/10.1016/j.jclepro.2021.129917.
[19] Positive energy districts solution booklet | EU Smart Cities Information Systems. link
[20] Krangsås, S.G.; Steemers, K.; Konstantinou, T.; Soutullo, S.; Liu, M.; Giancola, E.; Prebreza, B.; Ashrafian, T.; Murauskaitė, L.; Maas, N. Positive Energy Districts: Identifying Challenges and Interdependencies. *Sustainability* **2021**, *13*, 10551. https://doi.org/10.3390/su131910551

3.1 Specific governance challenges in energy efficiency

Effectively implementing energy efficiency measures across districts presents a unique set of governance challenges that must be strategically addressed to unlock their full potential. These hurdles, ranging from the misalignment of incentives between property owners and tenants to the complexities of coordinating fragmented ownership in existing neighborhoods, the financial barriers hindering upfront investments, and the difficulties in ensuring the real-world performance and accountability of energy-saving initiatives, demand carefully tailored governance responses. Examining these specific challenges and the corresponding strategies developed to overcome them is significant to support widespread adoption and achieving deep energy reductions in urban environments.

Table 3.

Issue	Challenge	Governance response
Split incentives	A classic governance problem: owners invest, but tenants benefit. This is particularly challenging in mixed-tenure PEDs or social housing	Use of EPCs where third parties assume the investment and are paid from the savings; legal frameworks enabling rent-based cost recovery with efficiency guarantees.
Fragmented ownership and decision-making	In existing neighborhoods, retrofits require coordination among multiple building owners or homeowners' associations.	Creation of "one-stop shops" and local energy renovation agencies to aggregate projects and guide collective decisions
Financing gaps	Upfront investment in deep retrofits can be a barrier, especially for lower-income districts or SMEs.	Municipal guarantees, EU recovery funds (NextGenEU), property-assessed clean energy (PACE)-style models.
Monitoring and accountability	Ensuring that energy efficiency measures achieve real-world savings (performance gap issue).	Mandated performance monitoring, digital twins, and transparent KPIs linked to funding disbursement.

3.2 Best practices in governance for energy efficiency within PEDs

Urban planning and governance play a pivotal role in advancing energy efficiency, ensuring sustainable development, and improving quality of life in cities. By embedding energy efficiency into zoning, land-use policies, and district-scale planning, municipalities can create structural frameworks that promote low-carbon urban growth. Vienna's Aspern Seestadt exemplifies this approach, integrating mandatory sustainability assessments, district heating, and public-sector-led governance to achieve energy performance benchmarks. Beyond top-down planning, participatory processes—such as Nottingham's tenant-led retrofit initiatives—demonstrate how engaging residents and local stakeholders can enhance the effectiveness and inclusivity of energy efficiency programs. These strategies highlight the need for innovative governance models that combine regulatory mandates with community collaboration.

To scale up energy efficiency, cities must also establish accessible support systems, performance-based financing, and data-driven decision-making. Bordeaux one-stop renovation hubs and Vienna's subsidy scheme illustrate how streamlined services and outcome-linked incentives can accelerate retrofits. Meanwhile, digital tools like Espoo's open-data platforms and Amsterdam's Energy Councils showcase the power of transparency and participatory governance in tracking progress and resolving conflicts. Malmö's integration of energy upgrades with social inclusion programs underscores the importance of equity in sustainability efforts.

Together, these case studies reveal that successful energy efficiency governance requires a mix of regulatory frameworks, financial innovation, community engagement, and adaptive learning mechanisms to drive lasting urban transformation.

Table 4.

1. *Make energy efficiency a structural element of zoning, land use, building permits, and urban development plans at the district scale.* Case study: Vienna (Aspern Seestadt, Austria). Vienna mandates sustainability assessments for new districts, linking land-use permits with building-level energy efficiency targets and district heating integration. **Governance innovation: *Public-sector-led master planning with clear energy performance benchmarks and integration of public housing agencies.***
2. *Co-design efficiency upgrades with residents, SMEs, and local institutions to ensure alignment with actual needs and habits.* Case study: Nottingham Energiesprong (UK). The city collaborated with tenants in council-owned housing to pilot prefab retrofits. Residents influenced installation timing, layout, and technology options. **Governance innovation:** Use of "tenant champions" and workshops to build trust and support informed decision-making.
3. *Create local hubs that offer guidance, funding access, technical advice, and social support to implement energy efficiency on scale.* Case study: Bordeaux (France). The city set up a public-private one-stop shop offering audit-to-retrofit services, including social assessments and citizen help desks. **Governance innovation: *Mix of local government, technical experts, and social workers under a single institutional umbrella.***
4. *Link financial support and incentives to actual performance outcomes (e.g., post-retrofit energy use) rather than forecasts.* Case study: Vienna Housing Subsidy Scheme (Austria). Subsidies are disbursed in tranches based on verified energy performance, encouraging contractors and property managers to ensure results. **Governance innovation: *Legal and contractual mechanisms that penalize underperformance and reward overachievement.***
5. *Govern data collection, accessibility, and transparency for energy monitoring and planning.* Case study: Espoo Smart Districts (Finland). Espoo uses a digital twin model that incorporates real-time energy and behavioral data. Residents and developers access the platform to monitor performance. **Governance innovation: *Collaborative data governance model with clear protocols for privacy, sharing, and usage rights.***
6. *Create participatory governance bodies to oversee implementation, track performance, resolve conflicts, and drive continuous improvement.* Case study: ZEC Amsterdam (Netherlands). An Energy Council composed of residents, businesses, and municipal representatives manages shared systems, monitors data, and approves investments. **Governance innovation: *Distributed leadership with rotating representation and direct decision-making power.***
7. *Govern efficiency programs with equity in mind—ensuring that vulnerable groups are not excluded and benefit from energy upgrades.* Case study: Malmö Lindängen Neighborhood Retrofit (Sweden). The city co-developed upgrades with low-income immigrant communities, coupling retrofits with employment training and language programs. **Governance innovation: *Socio-technical interventions paired with neighborhood social programs under a municipal social innovation unit.***
8. *Embed feedback, reflection, and revision cycles in governance structures to adapt to evolving conditions and learn from experience.* Case study: Trondheim's Brattøra District (Norway). The PED project includes annual public reporting, citizen science data collection, and structured reflection workshops with all stakeholders. **Governance innovation: *Learning contracts embedded in the project charter and EU funding requirements.***

The integration of energy efficiency into urban governance demands a multifaceted approach that combines regulatory frameworks, participatory processes, innovative financing, and data-driven decision-making. The case studies from Vienna, Nottingham, Bordeaux, and other cities demonstrate that success hinges on aligning policy mandates with community needs, ensuring equitable access to retrofits and fostering continuous learning through adaptive governance structures. By embedding energy efficiency into zoning laws, incentivizing performance-based outcomes, and empowering residents through co-design and transparent data platforms, cities can accelerate the transition to sustainable urban development. Ultimately, these strategies not only reduce energy consumption and emissions but also enhance social equity, resilience, and quality of life—proving that effective governance is key to building the low-carbon cities of the future.

Governance is the glue that turns good energy efficiency plans into real, lasting outcomes in PEDs. The most successful models blend **top-down vision**, **bottom-up participation**, and **adaptive institutional structures** that learn and evolve over time.

3.3 Policy recommendations for energy efficiency governance in PEDs

PEDs are neighborhoods or districts that are highly energy-efficient, flexible, and produce more energy than they consume through local renewables. They are emerging as a key strategy for urban decarbonization, but implementing PEDs is complex. Each PED involves many stakeholders (municipalities, owners, utilities, citizens, etc.) and interconnected systems[21], requiring strong governance to coordinate efforts. The following policy recommendations provide a globally relevant framework to govern energy efficiency in PEDs, ensuring these projects are effective, scalable, and deliver broad societal benefits.

Main recommendations in the framework of energy efficiency for PEDs could be:

- Mandate PED-level Energy Masterplans incorporating staged energy efficiency upgrades.
- Create integrated financing frameworks that combine subsidies, guarantees, and third-party performance models.
- Develop legal tools for collective retrofit governance in co-owned buildings or districts.
- Establish community benefit sharing models, e.g., using efficiency savings to fund local energy poverty programs.
- Institutionalize energy data governance, ensuring privacy and performance traceability across PED components

Governments should require each PED to develop a comprehensive **Energy Masterplan** that coordinates efficiency measures and upgrades in phases. An energy efficient PED cannot be established overnight – it involves continuous retrofitting of existing buildings and energy infrastructure over time. A masterplan lays out a staged retrofit roadmap, aligning building renovations with district energy systems (for example, linking insulation upgrades to the rollout of low-temperature district heating). This staged planning prevents lock-in of inefficient technology and ensures that early actions (like network improvements) pave the way for later deep renovations. By mandating such plans, policymakers provide clarity and direction for all stakeholders, making PED development more predictable and effective.

Scaling PEDs will require innovative **financing models** that blend public and private resources. Policy should integrate subsidies or grants (to lower upfront costs), public loan guarantees (to de-risk investments for lenders), and third-party performance contracting models. This combined approach addresses the high capital needs of district retrofits and attracts investment on a scale. For example, programs can offer soft loans for efficiency projects backed by a public guarantee fund and even combine them with grants – effectively creating a one-stop financing shop for PED upgrades. Such integrated frameworks leverage public funds to unlock private capital while ensuring accountability (via performance-based contracts), thereby enabling deeper energy renovations and renewable integration across the district.

Legal frameworks must empower building co-owners and communities to jointly implement energy upgrades. In many multi-owner buildings or mixed-ownership districts, consensus rules and split

[21] https://smart-cities-marketplace.ec.europa.eu/

incentives hinder efficiency investments. Governments should therefore introduce regulations that streamline collective decision-making and fairly allocate costs and benefits among owners and tenants[22]. For instance, condo laws could be reformed so that a qualified majority can approve district-wide retrofit plans, binding all owners to participate. Likewise, enabling the formation of energy communities or cooperatives gives residents a legal entity to manage shared assets and benefits. By providing these legal tools, policy ensures that co-owned properties and neighborhoods can overcome barriers and coordinate retrofits and efficiency measures at the scale needed for PEDs.

PED initiatives should include **mechanisms to share benefits** with the local community, reinforcing social sustainability. One recommendation is to channel a portion of the energy cost savings or revenues from surplus energy generation into programs that address energy poverty or community development. In practice, this could mean using efficiency savings to fund subsidies for low-income households' energy bills or investing in local job training in energy services. Successful examples show that PED projects can be designed to directly fight energy poverty – for instance, by sharing surplus renewable energy, some PED pilots have reduced public facility costs and given vulnerable households access to more affordable power[23]. By institutionalizing benefit-sharing, policymakers ensure PEDs improve quality of life for all residents, building public support and equity. This approach turns PEDs into models for inclusive sustainability, where efficiency gains help lift the community.

Achieving and maintaining a PED's positive energy balance requires robust **data governance** for monitoring and optimization. Policies should establish clear rules and infrastructure for managing energy data across the district – covering data collection, sharing, privacy, and usage. All PED components (buildings, grids, storage, etc.) should feed performance data into a governed platform to enable full traceability of energy flows and outcomes. It is fundamental to protect individual privacy and data security in this process, as emphasized by experts calling for PED data governance frameworks that include privacy management and data security measures[24]. At the same time, open data standards and real-time monitoring systems can be used to verify performance (e.g. ensuring that renewable generation and consumption are tracked and certified). By institutionalizing data governance (through regulations or dedicated data hubs), authorities can ensure transparency and trust in PED operations. This oversight allows continuous performance optimization and learning across projects, supporting the scalable rollout of PEDs while respecting citizens' rights and cybersecurity.

Energy efficiency governance in PEDs must go beyond conventional building-level interventions. It requires **district-scale integration**, **multi-actor coordination**, and **policy innovation** to align economic incentives, regulatory frameworks, and social justice concerns. Through a combination of **regulatory flexibility**, **participatory processes**, and **smart funding instruments**, PEDs can become lighthouses not just of technological advancement, but also of inclusive and transformative energy governance.

[22] European Comission, JRC Technical Reports, Energy efficiency upgrades in multi-owner residential buildings, 2018 available at: https://publications.jrc.ec.europa.eu/repository/handle/JRC110289
[23] Data Space for Positive Energy Districts (DS4PED)
[24] https://dutpartnership.eu/dut-call-2024/

4. How to measure energy efficiency in PEDs

The subsequent analysis will explore the evaluation metrics employed in measuring the efficacy of PEDs. Specifically, this section will present KPIs utilized to quantify PED performance concerning energy efficiency. Furthermore, the discussion will extend beyond purely technical assessments to encompass the broader societal ramifications and environmental externalities associated with the implementation and operation of these sustainable urban units, as detailed in the European Commission's report on integrated planning and management[25]. This holistic approach aims to provide a comprehensive understanding of the multifaceted impacts of PEDs, moving beyond energy balance calculations to consider their wider contributions to urban sustainability and quality of life.

Measuring energy efficiency within PEDs necessitates a comprehensive and multi-scalar approach, moving from individual building assessments to district-wide energy flow analysis. Establishing a clear system boundary, both geographically and temporally, is a fundamental first step[26]. Furthermore, defining a robust baseline of energy consumption prior to PED implementation is relevant for accurately quantifying improvements[27].

Data collection and continuous monitoring are essential for tracking energy efficiency. At the building level, metered energy consumption, data from Energy Performance Certificates (EPCs) and Building Automation Systems (BAS) provide valuable insights. District-level monitoring includes smart grid data, performance of district heating/cooling networks, the energy required for local infrastructures, mobility and supply systems.

The **efficiency of individual energy systems**, such as HVAC and lighting, is another significant metric. Furthermore, the **self-consumption rate of renewables** highlights the effective utilization of locally generated energy. **Demand-Side Management** (DSM) effectiveness in reducing peak loads also serves as an indicator of efficient energy use. Calculation and analysis involve normalizing data for external factors like weather and occupancy, benchmarking against established standards, and employing energy usage scans to identify optimization opportunities and areas[16].

Regular reporting and continuous improvement based on the measured KPIs are essential for ensuring the long-term success of PEDs in achieving their energy efficiency goals. Assessing the broader socio-economic benefits of these measures, further hilights the importance of a holistic evaluation framework[28].

4.1 "What We Cannot Measure, We Cannot Improve"

Evaluating the energy efficiency of PEDs needs a comprehensive framework that considers various factors, including minimum data requirements, relevant KPIs and standardized calculation methodologies. The success of PEDs is based on the efficient integration of renewable energy sources, implementation of smart grid technologies, and the adoption of energy-efficient building designs and retrofitting strategies. However, the implementation of PEDs can be more straightforward in suburban areas where energy infrastructure is less established, compared to retrofitting existing urban districts with complex energy networks[29]. Deploying PEDs and meeting carbon reduction targets are facilitated by declining costs in sustainable building materials and renewable energy technologies, reflecting a broader trend of embracing sustainable practices. Despite the increasing recognition of PEDs as a

[25] European Commission. (2020). Positive Energy Districts and Neighbourhoods: Towards Integrated Planning and Management. Publications Office of the European Union
[26] ISO 50001. Energy management systems — Requirements with guidance for use. International Organization for Standardization.
[27] International Energy Agency (IEA). (2024). Energy Efficiency Report 2024. IEA, Paris https://www.iea.org/reports/energy-efficiency-2024
[28] Ntafalias, A.; Papadopoulos, P.; van Wees, M.; Šijacic, D.; Shafqat, O.; Hukkalainen, M.; Kantorovitch, J.; Lage, M. The Benefits of Positive Energy Districts: Introducing Additionality Assessment in Évora, Amsterdam and Espoo. Designs 2024, 8, 94. https://doi.org/10.3390/designs8050094
[29] E. A. Atiba and D. Chwieduk, "Design of a Positive Energy District: A Nigerian Case Study," Renewable Energy, p. 121635, Oct. 2024, doi: 10.1016/j.renene.2024.121635.

promising approach to urban sustainability, several challenges remain such as the lack of a universally accepted definition or the need for standardized methodologies for evaluating their performance.

Quantifying the energy performance of PEDs requires careful consideration of the data needed to accurately assess energy flows, consumption patterns, and renewable energy generation. Minimum data requirements typically include detailed information on building energy consumption (heating, cooling, lighting, and appliances), renewable energy generation from various sources, energy storage capacity and utilization, and grid interactions. Building energy consumption data should incorporate electricity, heating and cooling demands, disaggregated by building type and end-use. Renewable energy generation data should specify the type of renewable energy source, installed capacity, and hourly or sub-hourly energy production. To replicate the energy demands of PEDs specific instruments and techniques are required, enabling a full understanding of energy consumption patterns within the district. Data about energy storage systems should include capacity, charge/discharge rates, and state of charge, while grid interaction data should capture energy imports and exports, as well as grid services provided by the PED. Furthermore, gathering relevant data requires effective monitoring technologies and data management systems to ensure accuracy and reliability.

These indicators provide a quantitative measure of the district's progress towards its energy goals and enable comparison across different PEDs and overtime. Relevant KPIs for PEDs typically include the On-site Energy Ratio, GHG emissions, energy consumption and production[30]. The On-site Energy Ratio measures the extent to which the district's energy demand is met by on-site renewable energy generation. The CO_2 emissions related KPI assesses PED’s contribution to climate change mitigation, accounting for both direct and indirect emissions associated with energy consumption and production. PED performance can also be assessed using KPIs to continuously monitor progress toward sustainable development objectives[22].

Moreover, evaluating energy efficiency in PEDs should extend beyond technical aspects and incorporate social, economic, and environmental considerations. Macroeconomic methods quantify the employment impacts and society savings, incorporating metrics like Net Present Value or Internal Rate of Return. It is important to integrate not only environmental effects, such as greenhouse gas emissions, but also socioeconomic factors, to ensure that PEDs contribute positively to urban sustainability and community well-being. Standardized methodologies for calculating KPIs are essential to allow comparison and benchmarking of PED performance across different PEDs and overtime. Although existing methodologies often focus on energy balance, it is important to include greenhouse gas emissions to achieve carbon neutrality[22]. Ultimately, it is relevant that stakeholders work together to create standards that advance the acceptance and implementation of PEDs as a vital component of sustainable urban development. Existing frameworks can be used to characterize the district being analyzed from the energy perspective for verifying the accomplishment of positive energy balance and carbon neutrality goals on an annual basis[23].

4.2 Operational framework for energy efficiency in PEDs

The European Commission has strongly promoted PED development[31] as a key step toward climate-neutral cities. Key focus areas (**Error! Reference source not found.**) include data acquisition and monitoring, smart technology integration, energy flow management, performance indicators, standardized calculation methods and operational optimization strategies.

[30] L.-N. Sassenou, F. Olivieri, P. Civiero, and L. Olivieri, “Methodologies for the design of positive energy districts: A scoping literature review and a proposal for a new approach (PlanPED),” Building and Environment, vol. 260. Elsevier BV, p. 111667, May 22, 2024. doi: 10.1016/j.buildenv.2024.111667.
[31] Krangsas, S.G.; Steemers, K.; Konstantinou, T.; Soutullo, S.; Liu, M.; Giancola, E.; Prebreza, B.; Ashrafian, T.; Murauskaite, L.; Maas, N. Positive Energy Districts: Identifying Challenges and Interdependencies. Sustainability 2021,13, 10551. https://doi.org/10.3390/su131910551

Figure 1. Key focus areas for energy efficiency

Data acquisition and monitoring infrastructure

Robust **data acquisition and monitoring** are the foundation of energy-efficient PED operations. Each building and energy asset in the district should be equipped with smart meters and sensors to continuously measure electricity, heating/cooling, and water usage. **Advanced metering infrastructure (AMI)** provides high-resolution consumption and generation data, enabling real-time visibility of energy flows. For example, deploying smart electricity meters and heat meters at building level allows tracking of demand profiles and the output of local renewables or cogeneration units. These meters, along with additional IoT sensors (for temperature, occupancy, HVAC status, etc.), feed into a district-wide monitoring system. A centralized **Building Management System (BMS)** or Building Automation System (BAS) can aggregate data from individual buildings, while an IoT platform or Supervisory Control and Data Acquisition (**SCADA**) system integrates data from distributed energy resources (solar PV, battery storage) and infrastructure (electric vehicle chargers, district heating networks). Comprehensive data collection enables operators to identify inefficiencies and adjust operations promptly.

In practice, many zero/positive energy communities have found that data transparency is very important – interviews with European PED projects highlight the *"need for data [and] monitoring methodologies"*, which are often missing in current district energy initiatives[32]. Thus, establishing an infrastructure of smart sensors, metering, and communication networks (wired or wireless) is a first technical step. All data should be transmitted to a secure central database or cloud in real-time, forming the "digital backbone" of the PED. Such an **energy monitoring platform** allows continuous tracking of key parameters (e.g. building energy use intensity, renewable output, state of charge of storage) and provides the situational awareness needed to optimize energy efficiency.

Integration of smart technologies

Achieving a positive energy balance at district scale requires tight integration of various **smart energy technologies**. At the building level, **automation and control systems** (BAS/BMS) regulate heating, cooling, ventilation, lighting, and appliance use for maximal efficiency. These systems should be interoperable across the district, communicating through standard protocols to a central energy management platform. All buildings in a PED effectively become "smart buildings" connected to a **smart grid**. The district's smart grid manages bidirectional energy flows with the wider utility grid and coordinates local generation units. Integration means that building controllers, renewable energy

[32] Shnapp, S., Paci, D., Bertoldi, P. Enabling Positive Energy Districts across Europe: energy efficiency couples renewable energy, JRC Technical Report, Luxembourg: Publications Office of the European Union, 2020

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inverters, battery management systems, and even smart appliances can respond in unison to control signals. For example, a demand-side management system might instruct several buildings to precool or preheat during times of excess solar production, or to curtail non-critical loads during peak demand periods.

The European PED framework emphasizes that such districts *"require integration of different systems and infrastructures and interaction between buildings, users and the regional energy, mobility and ICT systems"*[33]. This implies that **building automation**, **smart grid controls**, and even electric mobility (e.g. smart EV charging) must work together. Best practices include deploying intelligent HVAC controls that adjust setpoints based on occupancy and weather forecasts, integrating **renewable energy systems** with building controls and using **energy storage** in concert with generation and loads. A fully integrated PED will also utilize **demand response** capabilities: buildings can receive price or grid signals and automatically reduce or shift their energy usage to support grid stability and efficiency. In summary, all smart technologies – from automated building systems to grid-interactive demand management – should be **interconnected via an ICT architecture** that allows data exchange and coordinated control.

Energy flow management and analysis

With data and integration in place, the PED's operational framework must actively **manage energy flows** across the district's systems. This involves monitoring and controlling how energy is produced, distributed, stored, and consumed in real time. A district-level **Energy Management System (EMS)** is often used to analyze these flows and make optimization decisions. The EMS gathers inputs from all meters and sensors and builds a live picture of the energy balance. It tracks electricity flowing through the local distribution network, heat circulating in district heating/cooling loops, and any fuel or gas use, as well as the output of on-site renewables (e.g. PV generation curves) and the state of charge of batteries or thermal storage. Based on this, the EMS can perform **load balancing** – ensuring that at any given moment, the district's energy demand is met either by on-site generation or by controlled import from the grid, while maximizing the use of renewables. **Energy flow analysis** tools (potentially including AI-driven analytics or digital twins) help identify patterns and inefficiencies, such as peak demand times, distribution losses, or under-utilization of local generation. Importantly, PED energy management is often **multi-vector**: coordinating electrical, thermal, and even mobility energy streams simultaneously. Studies note that optimal PED operation requires considering *"thermal, electrical and gas flows… together"* for multi-vector optimization[25].

Energy flow management also extends to enabling energy exchange among buildings: one building's surplus can cover another's needs through the local grid, effectively creating an internal energy market. Some PED implementations even explore **peer-to-peer energy trading** platforms that settle energy exchanges between prosumer buildings in real time. In all cases, maintaining a stable and efficient operation involves using storage as a buffer and scheduling loads/generation optimally. A schematic in recent research illustrates that the district energy balance *"depends on the available elements on both supply and demand sides by effectively interacting with the storage units as the energy buffer"*[25]. In practice, this means charging batteries or thermal stores when local renewables are in surplus, and discharging them when there is a shortfall, thereby smoothing out fluctuations. Advanced control software running on the EMS evaluates these energy flow decisions continuously, guided by the twin goals of meeting energy demand reliably and minimizing external energy import. By actively managing flows, a PED can ensure that its renewable production and efficiency measures translate into tangible energy-positive performance.

Standardized methodologies for calculation and benchmarking

To support the above KPIs and ensure comparability, **standardized methodologies** for calculating and benchmarking energy efficiency metrics are needed. A key challenge in PED implementation has been the lack of a common approach to assess a district's energy balance and performance. Different

[33] JPI Urban Europe, White paper on reference framework for positive energy disctricts and neighbourhoods, 2020

projects might use different system boundaries, different primary energy conversion factors, or different assumptions about which energies count as “renewable” or “on-site”. Such inconsistencies make it difficult to benchmark one PED against another or to certify that a district truly achieves positive energy status. Therefore, developing a unified methodology is a priority in Europe. Researchers note that *“there is no standard at this point to calculate the positivity of an energy balance at the district level”*, and decisions about *“which loads/elements should be included…, which renewable energy technologies… and which primary energy factors should be used”* are currently case-specific[25]. Standardization would address these gaps.

One emerging approach is to extend existing building energy performance standards to the district scale. The EU’s Energy Performance of Buildings Directive (**EPBD**) provides a framework for calculating building energy needs and primary energy use (exemplified by standards like **ISO 52000-1**). The European Commission’s Joint Research Centre has suggested that *minimum energy performance requirements from the EPBD could be applied to a cluster of buildings* in a district, essentially aggregating building calculations to set a district-level target[26]. In practice, this means summing up the energy use of all buildings (after efficiency measures) and the energy generation within the district, then evaluating if the overall balance meets a “zero or positive” criterion using the same methodology one would apply to a single building. By using common metrics like primary energy demand and renewable contribution (with standardized conversion factors for grid electricity, fuels, etc.), cities can benchmark PEDs against familiar references (e.g., a district’s performance could be compared to an equivalent collection of NZEBs or to an established energy code).

Standardized calculation methodologies also involve setting **clear system boundaries**. Typically, a PED’s boundary is drawn around the district and one must define which energy flows across that boundary are counted as imports or exports. Methodologies need to clarify if electric vehicle energy use is included, how to account for shared infrastructure, and how to treat “nearby” renewable generation (just outside the district but feeding it). The development of a **PED Reference Framework** in Europe (through initiatives like JPI Urban Europe) is tackling these questions. For example, common definitions are being worked out for what constitutes on-site generation, how to use national conversion factors for electricity and heat, and how to account for climate differences. Having these standards in place allows the use of consistent KPIs across projects. It also supports **benchmarking**: cities can compare the Specific Energy Consumption or On-site Energy Ratio of their PED against reference values or against other European PED demonstrations.

Operational strategies for optimal energy use

Beyond planning and design, it is the **day-to-day operational strategies** that ensure a PED maintains energy efficiency and an energy-positive balance. These strategies are essentially the control policies and practices applied, leveraging the technologies in place to optimize performance. A fundamental strategy is applying the **“energy efficiency first” principle**: minimize energy waste at the end-use level before relying on generation. This involves continuous commissioning and tuning of building systems – for instance, adjusting HVAC schedules seasonally, optimizing setpoints, and fixing any anomalies (like an out-of-calibration sensor or a malfunctioning damper) that cause inefficiencies. Modern BMS can detect when a building’s consumption deviates from expected patterns and trigger an investigation or automated correction (this falls under Fault Detection and Diagnostics, FDD). Keeping each building performing at its best (low specific consumption) is the first layer of optimization.

Next, **demand-side management (DSM)** is employed to shape the load profile of the district. Through DSM, operators shift flexible loads to better align with renewable supply. Examples include pre-heating water in thermal storage tanks when there is excess solar PV output at midday or temporarily pausing certain industrial processes during the evening peak demand. Many PEDs incorporate **energy storage** (battery banks, thermal storage like water tanks or building thermal mass) explicitly to enable this load shifting. An operational strategy might be *charging batteries when local PV generation exceeds demand or when grid electricity is cheap/low-carbon, and discharge batteries to supply power during peak demand or when the sun is down*. Likewise, if the district has a combined heat and power (CHP) unit, its operation can be scheduled based on thermal and electric needs – for example, turning on the CHP in the early morning to supply heat and use the co-generated electricity for early power demand, thereby avoiding drawing from the grid at a high-tariff time. These strategies ensure **peak shaving** and **valley filling**, flattening the demand curve which improves overall efficiency of the energy system.

Real-time optimization is of key importance. The EMS (Energy Management System) will often use predictive control algorithms that consider weather forecasts (to predict solar output and heating/cooling demand), as well as knowledge of occupant behavior or schedules (to anticipate when buildings will need more energy). With this, the system can proactively adjust. For example, if tomorrow is forecast to be very sunny and mild, the EMS might choose to run heating a bit more tonight (storing heat in the building mass) and charge batteries early, knowing that solar production tomorrow will cover a lot of daytime loads – thus it can then curtail grid import tomorrow morning. Conversely, if a cloudy period is coming, the system might preserve battery charge for critical times. This **anticipatory control** maximizes renewable utilization and minimizes reliance on backup sources.

Another operational aspect is **energy flow orchestration among buildings**. *If building A is generating surplus solar power, and building B has an active cooling load, the control strategy should transfer that energy to building B in real time rather than exporting to the main grid and simultaneously importing power next door.* Technologies like **local energy trading platforms** or community energy management can automate this exchange. Essentially, the district controller behaves like an internal marketplace or dispatcher, ensuring locally generated energy finds a local use whenever possible (thus improving the on-site energy ratio). In some PED demonstrations, this is facilitated by smart contracts or blockchain-based transactions between prosumers, though a simpler approach is having a central controller allocate power flows. The concept of **energy flexibility** is imperative – buildings might at times operate below their maximum comfort settings (dimming lights slightly or tweaking thermostat by a degree) to help the district balance, without significantly affecting occupants.

According to EU experts, a PED benefits from *"energy cooperation" and **flexibility** measures that allow better-managed demand and generation* across the larger pool of buildings[25]. This collective flexibility means the district can respond to variability more smoothly than any single building could.

Operational strategies also extend to **maintenance and continuous improvement**. Regular energy audits at the district scale can identify if certain assets are underperforming (e.g., a solar array producing less than expected due to dirt shading, or a battery whose efficiency has degraded). Addressing these issues keeps the PED on track.

Moreover, occupant engagement programs can support operational goals – for instance, informing residents about peak times to avoid or encouraging them to use smart home features that tie into the district's DSM programs. While human behavior is not a "technical process," integrating user-friendly feedback displays or apps (part of the digital infrastructure) can significantly enhance energy-saving behavior, effectively becoming an operational strategy to cut waste.

4.3 Input data

The foundation of any energy efficiency initiative within an energy community lies in the availability of comprehensive and accurate data, which acts as the bedrock for informed decision-making and effective strategy implementation. This data contains a wide spectrum of information, including energy consumption patterns, building characteristics, renewable energy potential, and environmental conditions. Granular data on energy consumption at the household and community levels is essential for identifying areas with high energy usage and potential inefficiencies[34].

Building characteristics, such as insulation levels, window types, and HVAC systems, provide valuable insights into the energy performance of buildings within the community. In PED planning phase, data

[34] Klass, Alexandra B. and Wilson, Elizabeth J., Energy Consumption Data: The Key to Improved Energy Efficiency (May 5, 2015). 6 San Diego Journal of Climate and Energy Law 69 (2015), Minnesota Legal Studies Research Paper No. 15-13, Available at SSRN: https://ssrn.com/abstract=2602974

regarding the potential for renewable energy sources, such as solar irradiance, wind speed and biomass availability, is fundamental for assessing the feasibility and optimal deployment of renewable energy technologies.

Meteorological data, including temperature, humidity, and solar radiation, is necessary for modeling energy demand and optimizing energy supply strategies. In the context of existing districts, data pertaining to thermal, cooling, and electric energy demand can be obtained from sources such as bills, surveys, and smart meters[23]. The strategic deployment of smart meters plays a central role in gathering real-time data on energy consumption, enabling accurate monitoring and analysis of energy usage patterns. Furthermore, gathering data from smart buildings equipped with sensors can significantly improve the precision of building energy modeling and optimization efforts. The input data for an energy scan will be diverse and gathered from various sources within the energy community. It can be broadly categorized as follows:

- **Member-Specific Data:**
    - Energy consumption data: historical electricity, heating, and cooling consumption data (monthly or annually) for households, businesses, and community buildings. This includes meter readings, utility bills, smart meter data and storage capacity if available.
    - Energy generation data (if applicable): data on existing RES installations, including capacity, generation output and self-consumption rates.
    - Building characteristics: information about the building stock within the community, including building type, age, size, insulation levels, window types, and heating/cooling systems.
    - Appliance and equipment inventory: information about major energy-consuming appliances and equipment used by members, including their age, efficiency ratings, and usage patterns.
    - Transportation data: information on vehicle ownership, fuel types and transportation habits of community members, if considering electric vehicle adoption or shared mobility initiatives.
    - Member surveys and questionnaires: data on energy awareness, behaviors, investment intentions, and willingness to improve PED implementation.
- **Community-Level Data:**
    - Local climate data: temperature profiles, solar irradiation levels, wind speeds, and other relevant meteorological data for the community's location.
    - Grid infrastructure data: information on the capacity and constraints of the local electricity grid, potential for grid connection of new RES, and existing energy storage infrastructure.
    - Local energy resources: assessment of locally available renewable energy resources
    - Additional energy infrastructure: details about district heating/cooling networks.
    - Land use information: data relevant to the potential deployment of RES installations.
    - Socio-economic data: information about the community's demographics, economic activities, and energy affordability concerns.
    - Policy framework: relevant local, regional and national energy policies and regulations.

4.4 Relevant KPIs for evaluating PED energy efficiency

Based on the data collected with the above infrastructure, a series of KPIs can be defined to evaluate the energy efficiency of the PED, divided into 5 categories: technological, social, energy, environmental and economical. A more detailed presentation of the KPIs is developed in the deliverable D5.2 *Assessment Protocol for PEDs* developed within PERSIST project.

Technology

Modern PEDs use smart technologies to optimize energy use and management. KPIs in this category assess the deployment of intelligent solutions that make the PED's infrastructure more efficient and responsive.

Table 5.

KPI	Description	Implications
IoT devices, smart electrification technologies, and building optimization solutions	Tracks the integration of IoT sensors/controls and advanced building systems. High value indicates widespread use of smart devices that improve energy efficiency – studies show IoT-based building management can cut consumption by up to 30%[35]. It reflects how well the PED is **instrumented** for data-driven optimization, enabling real-time monitoring and control to minimize waste and match energy supply with demand.	These tools reduce unnecessary energy consumption by responding to occupancy, weather, and pricing signals, avoiding overcooling, overheating, or equipment overuse.
Smart Readiness Indicator	Measures the district's capability to **adapt and intelligently respond** to changing conditions via technology. Often informed by the EU's Smart Readiness Indicator (SRI), it evaluates if buildings and grids can sense and react to occupant needs or grid signals[36]. A high smart-readiness score means the PED's infrastructure is prepared for advanced energy management – from building automation to grid-interactive demand response – which is crucial for achieving positive energy balance and seamless integration of new innovations.	A high SRI ensures energy systems can adjust in real-time, improving energy utilization and aligning energy use with renewable availability, thereby minimizing waste.

Social

Social KPIs ensure that PED initiatives yield community-wide benefits and promote equity. These indicators focus on how the PED improves quality of life, particularly for vulnerable groups, and how the economic gains are shared locally.

Table 6.

KPI	Description	Implications
Energy poverty level and/or *Energy poverty reduction*	Evaluates the PED's impact on alleviating energy poverty. A successful PED should lower energy bills or offer affordable clean energy to low-income residents, thereby reducing the number of energy-poor households. These KPIs underscores inclusive development: by producing surplus renewable energy and implementing efficiency measures, PEDs can directly combat energy poverty in urban districts[37].	Efficient buildings use less energy for heating and cooling, reducing bills and enhancing affordability, which is essential for inclusive, low-carbon transitions.
Returned investments in PED social projects from energy surplus sharing proceeds	Tracks how much revenue from selling or sharing surplus energy is reinvested into the community. When a PED generates more energy than it consumes, the excess can be fed into the grid or traded in local energy markets, creating financial returns. This KPI measures the extent to which those returns are funnelled into local projects or services (such as funding energy retrofits, public amenities, or community programs). A high value indicates a virtuous cycle where the PED's success funds further local improvements, exemplifying community benefit-sharing. It reflects strong community engagement and trust	Revenue recycling encourages continuous upgrades that drive deeper reductions in community-wide energy demand.

Environmental

[35] Poyyamozhi, M.; Murugesan, B.; Rajamanickam, N.; Shorfuzzaman, M.; Aboelmagd, Y. IoT—A Promising Solution to Energy Management in Smart Buildings: A Systematic Review, Applications, Barriers, and Future Scope. Buildings 2024, 14, 3446. https://doi.org/10.3390/buildings14113446

[36] European Commission, Smart readiness indicator available at: https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/smart-readiness-indicator_en

[37] Ntafalias, A.; Papadopoulos, P.; vanWees, M.; Šijacic, D.; Shafqat, O.; Hukkalainen, M.; Kantorovitch, J.; Lage, M. The Benefits of Positive Energy Districts: Introducing Additionality Assessment in Évora, Amsterdam and Espoo. Designs 2024, 8, 94. https://doi.org/10.3390/designs8050094

Environmental KPIs measure PED's contribution to climate and ecological objectives. They capture how effectively it cuts emissions and other environmental impacts, aligning with sustainability goals.

Table 7.

KPI	Description	Implications
GHG emissions level and/or *Reduction in GHG emissions* and *Environmental Impacts*	Measures the decrease in greenhouse gas emissions attributable to the PED, typically in CO_2-equivalent tons reduced per year versus a baseline. This is a core indicator of environmental performance: a PED is expected to produce more clean energy than it uses, driving down net emissions toward zero or even net negative. Achieving a high reduction demonstrates the PED's role in mitigating climate change[30]. Beyond GHGs, it can also incorporate other impacts like improved air quality or lower pollution.	Every kWh saved through efficient systems directly reduces emissions and environmental strain, contributing to climate goals.

Energy

Energy KPIs are at the heart of PED energy efficiency evaluation. They cover the generation and consumption of renewable energy, as well as the efficiency, flexibility and reliability of the local energy system. Together, these indicators show whether the PED is achieving its positive energy balance and how robust its energy network is.

Table 8.

KPI	Description	Implications
Total renewable energy production by type	Include all renewable energy generated within the PED, broken down by source. This reveals the energy mix and scale of local generation. A higher production, especially across diverse sources, means the district can meet more of its demand sustainably and even export surplus. Tracking by type identify which technologies ensure a balanced approach to RES deployment.	High renewable production indicates low fossil dependency, especially when combined with storage capacities and demand-side management.
Local energy storage capacity by type	Tracks energy storage in the PED (batteries, thermal storage, hydrogen, etc.), measured in capacity (kWh). Storage is key—storing excess renewable energy for later use, balancing supply and demand. Higher values mean greater self-reliance and resilience, helping avoid waste, stabilize the grid, and ensure continuous renewable supply despite intermittency.	Properly sized and managed storage allows for time-shifting energy use, increasing the efficiency of renewable utilization and reducing curtailment.
On-site Energy Ratio	Logs how much renewable energy is consumed in the PED and in what forms. It shows to what extent local consumption is being served by renewables. A high value indicates effective local use of green energy, reducing external reliance. Identifies gaps to guide improvements, measuring self-sufficiency and usage patterns.	Efficient systems make better use of generated renewable energy, increasing the share that's self-consumed locally.
House energy efficiency rating	Tracks residential energy efficiency in the PED using ratings (e.g., Energy Performance Certificates). Reported as average scores or % of high-efficiency homes. Efficient buildings—through insulation, appliances, and design—lower demand, helping renewables exceed usage. Higher ratings show retrofits and smart design are cutting consumption, balancing "negawatts" (energy saved) with energy produced. Top-performing buildings support a net-positive energy balance and improve comfort.	Improved ratings reflect better insulation, airtightness, and efficient HVAC systems, lowering heating and cooling demand significantly.
Load flexibility	Assesses the ability to shift or modulate energy demand in response to supply conditions or grid signals. It could be quantified by the percentage of load that is shiftable or the capacity of flexible demand under management. High load flexibility lets the PED shift consumption to match renewable peaks or grid demands. This balances the energy system, reducing curtailment, easing peak loads and preventing grid stress. Flexible loads boost renewable	Flexible loads avoid peak demand charges, improve system balance, and enable better alignment with intermittent renewable generation—reducing the need for backup power.

KPI	Description	Implications
	self-use and enable grid services, showing advanced energy management.	
Grid reliability	Tracks local grid stability and reliability in the PED, measuring outages, voltage quality, and power continuity. As PEDs add distributed generation and new loads, maintaining grid reliability is crucial. Strong performance shows RES and smart controls aren't disrupting the grid—PEDs can even improve reliability through microgrids and backup systems.	Stable, efficient networks reduce the need for redundant capacity and enable smarter, leaner distribution.
Grid capacity	Assesses local grid capacity to manage PED energy flows, measured by maximum load/generation tolerance or grid headroom. Tracks infrastructure readiness for two-way power flows and increased electrification. Improved capacity (less congestion) reflects successful grid upgrades, enabling more renewables and loads while maintaining stability—key for scaling PED impact.	Enhancing grid capacity reduces bottlenecks and allows for smoother, more efficient operation, minimizing losses and interruptions.

Economic

Economic KPIs evaluate the financial aspects of PED implementation and operation. They highlight the scale of investments mobilized for sustainable infrastructure and whether those investments pay off over time, indicating the PED's economic sustainability and replicability.

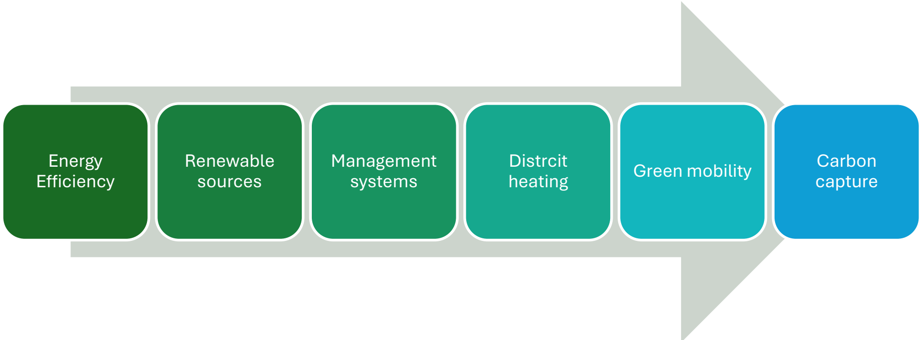
Table 9.

KPI	Description	Implications
Investment in renewable energy sources	Tracks total investment in PED renewable installations. Growing figures show strong commitment, driving higher clean energy capacity. Reflects economic activity and confidence in the green transition, whether funded publicly, privately, or via crowdfunding. Helps assess resource allocation and cost-effectiveness against energy output and ROI.	Investments in decentralized renewables often go together with efficiency upgrades, creating synergies that lower total energy demand.
Public and private investment in grid upgrades	Tracks funding for PED grid modernization (public and private), covering smart meters, line upgrades and transformers. Balanced investment reflects collaborative infrastructure development. Ensures grid readiness for bidirectional flows and new technologies, highlighting financial commitment to reliability and futureproofing.	An upgraded grid reduces losses, supports flexible load integration, and ensures the benefits of efficiency are realized system wide.
Return on Investment over the PED equipment lifetime	Tracks PED financial viability by comparing lifetime benefits (energy savings, revenue) to costs (investment, O&M). Positive ROI (>1 or >0% net gain) confirms cost recovery and profitability—some PEDs achieve payback in 6-7 years with 20-30% returns. A strong ROI attracts investors and enables scaling, proving environmental and economic sustainability. Low/negative ROI signals need for better business models or subsidies.	A positive ROI confirms that efficiency investments are not only sustainable but economically justified, encouraging replication and scale.
Local energy market	Tracks local energy trading platforms within the PED, including peer-to-peer exchanges, flexibility markets, or power-to-X systems. A high value shows active market innovation—enabling economic optimization of energy use. These platforms boost renewable utilization, empower prosumers, and create local revenue streams, advancing the PED toward an integrated energy economy	These markets promote optimal use of local energy, reduce transmission losses, and incentivize energy-saving behavior

Implementing a minimum infrastructure for measurement and monitoring, covering the technical parameters mentioned, is essential to obtain accurate and relevant data for evaluating the energy efficiency of a PED. This allows us to obtain a detailed analysis of energy flows, the identification of areas of inefficiency, and the monitoring of the impact of implemented improvement measures, contributing to the achievement of the district's sustainability goals.

5. Measures to increase Energy Efficiency

PEDs target net-zero greenhouse emissions and an annual surplus of renewable energy, achieved through integrated systems linking buildings, energy grids and users[28]. In practice, this means retrofitting buildings for efficiency, deploying solar and other renewables, using batteries and thermal storage, electrifying heating and transport and managing energy flows intelligently. This section presents a library of collective and individual energy efficiency measures for PEDs in EU urban areas.



5.1 Building energy efficiency upgrades

Improving building energy efficiency is the **first pillar** of a PED, as reducing demand minimizes the required renewable generation. Key retrofit measures include: **Insulation & glazing** - adding wall/roof insulation and high-performance windows cuts heating/cooling losses considerably; **Efficient lighting & appliances** - LED lighting and energy-efficient appliances lower electricity use and **Smart controls** - thermostats and building management systems optimize HVAC and lighting schedules.

Relevance: By refurbishing existing buildings to near zero-energy standards, districts can slash energy demand, making it easier to achieve a net-positive balance[38]. Efficiency retrofits also improve comfort and reduce energy bills for residents. In many European cities with aging building stock, this is an imperative step to achieve EU climate goals, not to mention PEDs.

Deep Retrofit in Tartu, Estonia: *In the SmartEnCity project, the city of Tartu retrofitted 18 Soviet-era apartment blocks with insulation, new windows, and ventilation systems. The average energy use of these buildings dropped by* ***over 66%****, from about 270 kWh/m² yearly to ~90 kWh/m²* [39]*. This drastic improvement (nearly a three-fold efficiency gain) demonstrates the impact of comprehensive retrofits on legacy buildings. Such retrofitting not only cuts heating costs for residents but also dramatically lowers the PED's baseline energy demand, easing the burden on local renewable supply. The Tartu example shows that a* ***two-thirds reduction*** *in apartment energy use is achievable in practice*[30]*. Similarly, in Oulu, Finland, the Making-City PED project prioritizes retrofitting residential buildings to maximize efficiency before adding renewables*[40]*. These cases prove that aggressive efficiency measures can halve or more than halve building energy consumption, providing the foundation for PEDs.*

Deep energy retrofits often involve significant upfront investment, but they yield long-term savings. Many EU retrofit projects report payback periods in the range of 10–20 years depending on energy price and subsidy. Non-financial returns include enhanced property values and health benefits from better indoor conditions. For example, after Tartu's renovations, surveys indicated higher resident satisfaction along with the energy savings, illustrating co-benefits beyond the 66% consumption cut[30]. Overall, building efficiency is a high-impact, if sometimes capital-intensive, measure – one that virtually all PED implementations pursue first to maximize the effectiveness of subsequent renewable and smart solutions.

[38] Rueda Castellanos, S. & Oregi, X. (2021). Positive Energy District (PED) Selected Projects Assessment, Study towards the Development of Further PEDs. Environmental and Climate Technologies. 25. 281-294. https://doi.org/10.2478/rtuect-2021-0020
[39] Transforming living environment with smart and scientific solutions: results from SmartEnCity project in Tartu link
[40] EUROPE TOWARDS POSITIVE ENERGY DISTRICTS | A compilation of projects towards sustainable urbanization and the energy transition link

5.2 Renewable energy generation

Renewable energy installations – primarily PV in urban settings – are therefore core to PEDs. Rooftops, facades, and other available surfaces could be equipped with PV panels or building-integrated photovoltaics (BIPV), sometimes complemented by small wind turbines or solar thermal collectors where feasible. Renewable generation is often distributed across many buildings in the district.

Relevance: Local renewables directly supply buildings with green power and heat, offsetting grid imports and lowering carbon emissions. In a PED, the total annual renewable output should exceed the district's consumption, creating a net-export of energy to neighboring grids[31]. This reduces reliance on external energy and improves urban resilience. Integrating PV on buildings also engages property owners in the energy transition and makes use of otherwise idle roof space. Modern solutions like BIPV even allow solar panels to blend into historic or aesthetic contexts, expanding applicability (e.g. solar roof tiles that mimic traditional tiles in heritage districts).

Solar PV in Évora, Portugal: *The historic city of Évora (a PED Lighthouse city in H2020 POCITYF) is deploying extensive solar generation while respecting its UNESCO World Heritage architecture. Over **40 building-integrated PV installations** are planned in the protected central district[41]. Innovative terracotta-colored solar tiles and camouflaged PV panels have been used on heritage buildings, providing 1.8 MW of renewable capacity without altering the city's appearance[32]. This BIPV rollout is expected to supply a significant share of the district's electricity – by 2025 Évora is targeting **40% of its energy demand** met through these integrated solar arrays[32]. In real terms, the city projects cutting over **500 tons of CO_2** annually via the core BIPV initiatives[32]. The Évora case study validates that even in historic urban areas, creative PV integration can yield substantial energy generation and emissions savings, moving the district toward net-positive status. Other PED demos confirm strong solar results: for instance, the city of **Alkmaar, Netherlands** installed PV on public buildings and homes, helping the two PED pilot cities (Évora + Alkmaar) achieve a combined **16.2 GWh/year** of local renewable production and reduce CO_2 emissions by 9,743 tons/year[42]. Likewise, the Plus Energy Building "Hikari" in Lyon's Confluence district produces more energy than it consumes through solar panels and advanced design[43], exemplifying how individual plus-energy buildings contribute to district-level surpluses. These examples underscore that a robust deployment of solar PV (often on the order of 1–5 MW in a district) is both feasible and effective – supplying on the order of **15–50%** of a PED's total energy needs and creating the renewable surplus needed for PED status.*

The cost of PV has fallen dramatically, making solar one of the most cost-effective PED measures. Many projects use third-party or community investment models. In Évora, for example, a local utility installed PV systems at no upfront cost to the municipality, selling the power at a rate below grid prices[44] – an attractive model with immediate savings. Typical solar payback times are now ~5–10 years in sunny EU regions. Returns are further enhanced when surplus power is sold to the grid or used to charge EVs, as excess PV can displace expensive peak electricity[45]. Overall, renewable generation is a **pillar** of PED economics and sustainability, with numerous EU cases demonstrating strong performance and payback.

5.3 Heat pumps for efficient heating and cooling

Heating and cooling of buildings – traditionally provided by burning fossil fuels – is transformed in PEDs by widespread adoption of **heat pumps**. Heat pumps use electricity (preferably from renewables) to move heat from one place to another, providing space heating, water heating, or cooling with far higher efficiency than combustion. In individual buildings, air-source or ground-source heat pumps replace gas/oil boilers. At district scale, large central heat pumps can upgrade waste heat (from sewage, rivers, or industrial processes) into useful heat for district heating networks. Because they deliver 3–5 kWh of

[41] soularinnovations.com/bipv-in-evora
[42] www.pv-magazine.com/2023/03/30/bipv-solutions-for-historical-cities
[43] Hiroki Ichinomiya, Case Study: Smart Community Demonstration Project in Lyon, France
[44] www.edp.com/en/innovation/pocityf-smart-cities
[45] EUROPE TOWARDS POSITIVE ENERGY DISTRICTS, A compilation of projects towards sustainable urbanization and the energy transition

heat per kWh of electricity, heat pumps dramatically reduce primary energy demand for heating[46]. They also enable sector coupling – using surplus electrical energy (e.g. excess solar) to meet thermal needs by storing it as heat.

Relevance: Converting to **high-efficiency electric heating** via heat pumps is essential for PEDs to cut carbon and reach positive energy status. Buildings often have the largest energy loads (heating can be 50% of energy use in European buildings). Replacing fossil heating with heat pumps can reduce final energy use for heat by around 50–75% immediately, and when powered by PED renewables, eliminates on-site emissions. Heat pumps also provide flexibility: thermal storage (building mass or water tanks) allows their operation to be shifted in time. In a PED, a heat pump can run when there is surplus solar or wind power, and pause when electricity is scarce, effectively acting as a thermal battery. This demand-side flexibility is very valuable for balancing. Moreover, heat pumps can provide **cooling** in summer (often reversing operation), which is increasingly needed in cities – doing so with far less energy than traditional electric AC. In summary, heat pumps are a key technology for PEDs to **decarbonize heating/cooling and significantly lower energy input needs**, thereby helping achieve a net-positive balance.

Vienna's Wastewater Heat Pump Plant, Austria: *Vienna has been aggressively deploying large heat pumps to decarbonize district heating. One notable project is a* ***2 MW heat pump*** *installation that draws heat from treated wastewater at the city's main sewage plant. This central heat pump delivers about* ***~7,000 MWh of heat per year*** *into the district heating network, replacing what would have been gas-fired heat production[47]. With a coefficient of performance (COP) around 4, it uses ~1,750 MWh of electricity (sourced from renewables) to provide that 7,000 MWh heat – effectively* ***saving ~5,250 MWh of primary energy*** *annually compared to gas boilers. The* ***carbon savings*** *are on the order of* ***1,000+ tons*** ***CO_2/year****. This large heat pump runs mostly when electricity is cheap and abundant (including at night and when wind power surges), and it turns down when the grid is under stress. By doing so, it balances the grid and provides almost free cooling to the wastewater (a bonus). Vienna's example shows how even existing district heating can be augmented with heat pumps to significantly cut energy use and emissions. A PED can emulate this by using ambient or waste heat sources too:* ***Oulu, Finland*** *is doing it with geothermal boreholes and central heat pumps to export* ***1,020 MWh_th/year of surplus heat*** *to its network[48]. This means Oulu's PED will contribute heat back to the city grid thanks to heat pumps performing above 100% efficiency (in primary energy terms).*

Residential Heat Pumps in Nottingham, OK: *Within Horizon 2020 REMOURBAN 10 homes in Nottingham's Sneinton area had replaced old gas boilers with modern air-source heat pumps and better insulation. Monitoring showed a* ***30–40% reduction in total energy use*** *for heating in these homes, and because the electricity was partly supplied by a neighborhood solar farm, the CO_2 emissions dropped by about 45%[49]. Residents reported similar or improved comfort. The project estimated a payback of ~8 years for the heat pumps when considering the fuel cost savings (UK's low carbon heat incentives helped as well). This small-scale example demonstrates the quick wins of individual heat pumps: dramatic efficiency gains (COP ~3, so ~66% less energy for same heat) and readiness to integrate with renewables.*

The efficiency of heat pumps (3-5 output vs input) means **operational savings** are large, especially when displacing expensive heating fuels like oil or delivered heat. For example, the Wienerberger brick factory in Austria replaced a gas boiler with an industrial heat pump, saving about **€425,000 per year** in energy costs[50]. While industrial, it underlines the economic upside. In residential contexts, heat pumps often save households 300–600 € annually on heating (depending on previous fuel), meaning paybacks of 5-10 years when subsidies are available. Upfront cost can be a barrier; however, many countries now provide grants[51]). Maintenance costs are low, and lifespans are long (~20 years). From a PED perspective, heat pumps add value by enabling **renewable heating** – every unit of electricity

[46] e360.yale.edu/features/europe-industrial-heat-pumps
[47] Gasser et al. (2021) "Large-scale heat pumps in European district heating systems: Case studies and policy insights" (Energy Policy).
[48] Rueda Castellanos, Sofia & Oregi, Xabat. (2021). Positive Energy District (PED) Selected Projects Assessment, Study towards the Development of Further PEDs. Environmental and Climate Technologies. 25. 281-294. https://10.2478/rtuect-2021-0020
[49] REMOURBAN Consortium. (2019). D5.3: Nottingham Lighthouse City Final Report. Horizon 2020. [Available via CORDIS: https://cordis.europa.eu/project/id/646511]
[50] e360.yale.edu/features/europe-industrial-heat-pumps
[51] European Heat Pump Association, Subsidies for residential heat pumps in Europe

from solar/wind can provide 3+ units of heat to buildings. This multiplier effect is why the IEA calls heat pumps *"crucial for a heat revolution,"* being *"three to five times more efficient than gas boilers"* [59]. Importantly, heat pumps eliminate local combustion, improving air quality. In dense cities, replacing gas boilers with heat pumps can significantly reduce NOx emissions and improve indoor safety. All these factors combined make heat pumps an indispensable measure with high returns in energy efficiency, carbon reduction, and synergy with the PED's renewable supply.

5.4 Energy storage solutions

Because renewable output (sun, wind) is variable, **energy storage** is vital in PEDs to balance supply and demand. Storage comes in two main forms: **electrical batteries** (typically lithium-ion) that store surplus PV power, and **thermal storage** (like hot water tanks or phase-change materials) that store excess heat or cold. Storage can be deployed on both building scale (e.g. home batteries, water heaters) and district scale (community battery banks or large thermal accumulators).

Relevance: Storage provides energy **flexibility**, the third pillar of PED design[52]. By storing daytime solar power for nighttime use, batteries raise the self-consumption of local renewables and ensure the district can run on clean energy even when generation is low[53]. Thermal storage allows waste heat or cheap nighttime electricity to be stored as hot water for later heating use, reducing peak demand on boilers or heat pumps. Overall, storage smooths out the PED's import/export profile – minimizing imports during peaks and enabling exports of surplus at optimal times. This flexibility is essential to managing an annual positive balance without straining the grid. It also provides resilience, allowing critical loads to ride through outages using stored energy.

Second-Life Battery Storage in Gothenburg, Sweeden: *In Gothenburg, Sweden, an innovative project repurposed* ***used electric bus batteries*** *as a communal energy storage for a housing complex. Fourteen retired bus battery packs (Lithium-ion) were connected, creating a ~**200 kWh** "energy warehouse" in an apartment block's basement[54]. During sunny hours, rooftop PV panels charge these batteries; later, the stored energy is used to power the building in the evening. The system is also programmed to charge from the grid when electricity is cheap (e.g. at night) and discharge during expensive peak hours[39]. This strategy successfully* ***cut the building's peak grid power draw*** *and even allows selling power back to the grid at high demand times[39]. Importantly, it extends the life of EV batteries (deferred recycling) and lowers the cost of storage for the community. Volvo, the bus manufacturer, reported that this second-life battery installation – one of Europe's first in housing – created a 200-kWh storage unit that allows a larger share of the solar energy to be used on-site[39]. By shaving peak demand and storing surplus solar, the complex uses more locally generated energy and less grid energy, directly contributing to its positive energy balance.*

Thermal Storage in Taarnby, Denmark: *A PED-adjacent project combined a large-scale heat pump system with a* ***2,000 m³ cold-water tank*** *to store thermal energy for a district heating/cooling network[55]. In winter, the tank and heat pumps store excess heat (e.g. from wastewater and ground sources) to deliver heating at peak times, while in summer the system provides district cooling and stores chilled water. This smart thermal storage integration improved overall efficiency and allowed the use of more renewable/ambient heat sources year-round. The project delivered cost-effective energy (serving a new mixed-use district by Copenhagen airport) and saved the community* ***DKK 80 million*** *(~€10.7M) compared to conventional solutions [40]. This illustrates how thermal storage can yield huge economic and energy benefits at district scale.*

Energy storage costs have been a challenge, but they are decreasing considerably. Batteries provide high value in PEDs by enabling participation in energy markets (arbitraging prices) and avoiding peak tariffs. In the Cork, Ireland PED demo, smart optimization of a battery resulted in **11% energy cost savings** for a campus microgrid[56]. Second-life batteries, as in Gothenburg, are ~30% cheaper than

[52] Han Vandevyvere, Positive Energy Districts Factsheet
[53] Rueda Castellanos, S. and Oregi, X. (2021). Positive Energy District (PED) selected projects assessment, Study towards the Development of further PEDs. Environmental and Climate Technologies
[54] www.volvobuses.com/au/news/2018/dec/electric-bus-batteries-used-to-store-solar-energy
[55] https://www.ramboll.com/en-us/projects/energy/taarnby-city-of-smart-solutions
[56] Rueda Castellanos, S. And Oregi, X. (2021). Positive Energy District (PED) Selected Projects Assessment, Study towards the Development of Further PEDs. Environmental and Climate Technologies. 25. 281-294..

new ones[39], improving ROI and sustainability. Thermal storage is often even more cost-effective (water tanks are inexpensive per kWh of heat). For instance, Taarnby's integrated heat pump and storage plant demonstrated a **strong business case**, covering 60% of the area's heating needs and paying for itself via the 80 million DKK savings over alternatives[40] . Overall, storage investments in PEDs tend to have moderate paybacks (~5-10 years for batteries with smart use; even less for well-utilized thermal storage) while delivering flexibility. They are increasingly seen not as an extra cost but as an enabling asset that maximizes the value of renewable generation and keeps a PED reliably positive year-round.

5.5 Electric vehicle infrastructure and V2G integration

Electric vehicles (EVs) and charging infrastructure are an important part of PED strategies, representing the convergence of clean transport and smart energy. PEDs promote electrification of mobility – from cars to buses to e-bikes – powered by local green energy. This requires ample **EV charging stations**, including fast chargers and smart chargers that can modulate charging times. Leading PED projects also implement **vehicle-to-grid (V2G)** or vehicle-to-building technology, whereby EVs act as mobile batteries that can discharge power back when needed. EV charging systems are usually managed to align with renewable production (charging cars when solar output is high, for example).

Relevance: Transportation accounts for a large share of urban energy use and emissions. Greening this sector via EVs (charged on renewable electricity) is key for PEDs to hit climate targets and reduce overall energy demand for mobility. Strategically, **integrating EVs into the energy grid** turns a potential load into a flexible asset: smart chargers can pause or slow charging to avoid grid peaks, and V2G-capable cars can supply power during shortages, effectively functioning as distributed storage units. As noted in EU PED definitions, e-mobility is emerging as the "fourth pillar" of PED energy systems[57], since widespread EV adoption can be leveraged to provide demand response and storage capabilities. In sum, building extensive EV charging infrastructure in a district enables a shift to electric transport and creates synergies with the electricity system that help balance the PED's energy flows.

Utrecht's Bi-Directional EV Network: *The city of Utrecht in the Netherlands is at the forefront of EV integration. As part of the IRIS Smart Cities project and related initiatives, Utrecht is rolling out* ***2,600 public EV charging points****, with many of them being* ***bi-directional V2G chargers***[58]*. This will make Utrecht the world's first city with a citywide vehicle-to-grid ecosystem. Already, hundreds of these smart chargers have been installed – they not only charge the growing fleet of electric cars but also can feed electricity from car batteries* back into *the grid when needed*[59]*. In practice, when solar generation is high, midday, EVs across the city are signaled (via the smart charging platform) to top up their charge. In the evening peak, the charging stations can reverse flow if required, delivering power from idle cars to support the local grid. This approach avoids expensive grid upgrades and helps manage the intermittency of renewables. City officials note that* ***many of these stations provide cheap, green power for EVs while also reducing peak strain on the grid***[43]*. The Utrecht program, which includes partnerships with carmakers (e.g. Hyundai) and the We Drive Solar car-sharing scheme, demonstrates that a* ***"battery on wheels" fleet can collectively act as a virtual power plant****. It's estimated that about 10,000 V2G-enabled EVs could balance the entire city's electric demand on certain occasions*[60]*. This large-scale integration of EV infrastructure is a template for PEDs: enabling clean mobility for residents and using smart charging/V2G to contribute to the positive energy balance and grid stability.*

EV Infrastructure in Évora, Portugal: *In Évora's PED project, alongside solar rollout, the city installed* ***multiple EV charging hubs*** *at sites like the city hall, a business park (SONAE), and public parking lots*[61]*. These are being integrated into an advanced Energy Management Platform that schedules charging based on renewable availability. The project also deployed* ***second-life EV batteries*** *at a community scale in Évora's Valverde district to support EV charging and local grid services*[46]*. Early results show that the availability of convenient charging, powered by the PV installations, has accelerated EV adoption locally. By coupling solar panels with EV chargers*

[57] Han Vandevyvere, Positive Energy Districts Factsheet
[58] irissmartcities.eu/vehicle-grid-ecosystem-scale-utrecht-case-study
[59] spectrum.ieee.org/vehicle-to-grid
[60] chargedevs.com/newswire/utrecht-plans-to-be-a-bidirectional-city-turning-its-evs-into-a-giant-battery
[61] European Commission. (2024). SPRING Project (Synergies in Positive Energy Regions). CORDIS. Available: https://cordis.europa.eu/project/id/864400

(some on solar carports), the PED ensures that a higher fraction of transport energy is coming from on-site renewables. This approach reduces fossil fuel use in transport and provides a flexible load to absorb solar surplus (EVs charging act as a sink for midday PV output).

Smart EV infrastructure yields both energy and economic returns. Utrecht's bi-directional charging is expected to **reduce peak grid load by up to 20%** in neighborhoods with high EV uptake (by intelligently timing charging/discharging), and it provides revenue streams to EV owners who can earn from grid services[62]. In Nottingham (UK), a pilot with 40 V2G chargers found that each EV could offer **~$400/year** worth of grid services back to the network in addition to charging on cheap off-peak power[63] (these figures are indicative and depend on energy prices). From an emissions perspective, replacing gasoline cars with EVs charged on PED renewables directly cuts transport CO_2 – a single electric car can avoid ~1.5–2 tons of CO_2 per year. Thus, wide EV adoption in a PED can easily contribute to **several thousand tons of CO_2 reduction** annually at the district scale. Moreover, improving air quality and noise levels through electric transport enhances the urban living environment, aligning with PEDs' social sustainability goals.

5.6 Smart energy management systems (EMS) and autonomous controls

A **Smart Energy Management System (EMS)** is essentially the "brain" of a PED, typically implemented through IoT sensors, real-time monitors, and optimization software. These systems may include predictive algorithms (forecasting weather, loads, prices) and autonomous controls that adjust equipment in response to conditions. For example, an EMS might ask to pre-heat a building when surplus solar is available or shift an industrial load to off-peak hours. At the district level, platforms (sometimes called Digital Twins or City Information Platforms) aggregate data from all buildings and infrastructure to manage energy flows optimally.

Relevance: Without smart control, the full benefits of PED technologies cannot be realized. **Autonomous energy management** ensures that energy supply and demand are continuously balanced in the most efficient way[48]. It unlocks demand response potential – flexing loads to match renewable availability – and prevents energy waste. In PEDs, where multiple buildings and assets interact, a centralized or federated control system is key to orchestrate the collective performance. Such systems also provide measurement and verification of the PED's performance (tracking KPIs, calculating the energy balance in real-time). Overall, smart EMS allow PEDs to achieve higher renewable penetration and efficiency than would be possible with static or manual controls[48]. They effectively enable **energy flexibility** – the ability to dynamically adapt – which is identified as a pillar for integrating renewables in urban areas[64].

Cork's Nimbus "Energy Internet" System, Ireland: *In the CIT Bishopstown campus from Cork, Ireland (+CityXchange project), a sophisticated energy management system was deployed to optimize three campus buildings with on-site generation and storage. The EMS included: real-time monitoring of all building loads and generation, weather and price forecasting inputs, and a predictive optimization engine[48]. This system autonomously decided when to run the CHP unit, when to charge or discharge the battery, and how to adjust HVAC setpoints across the buildings, interacting with individual Building Management Systems (BMS). During a trial, the EMS was able to* ***reduce energy costs by up to 11%*** *for the campus through optimal control[65]. For example, it charged the battery at night when electricity tariffs were low and solar output was absent, then discharged the battery and ramped down grid purchase during peak price hours[50]. It also coordinated the CHP operation to ensure its waste heat was used when heating demand was high and turned off the CHP when cheaper or cleaner grid electricity was available[50]. By comparing the EMS-controlled scenario to a baseline, the project demonstrated significant* ***energy and cost savings*** *– verifying that smart control is a "fundamental energy service to reduce costs" in a PED[50]. Notably, this was achieved without sacrificing comfort; in fact, the system improved reliability by anticipating*

[62] irissmartcities.eu/vehicle-grid-ecosystem-scale-utrecht-case-study
[63] Rueda Castellanos, Sofia & Oregi, Xabat. (2021). Positive Energy District (PED) Selected Projects Assessment, Study towards the Development of Further PEDs. Environmental and Climate Technologies. 25. 281-294. https://10.2478/rtuect-2021-0020.
[64] Han Vandevyvere "POSITIVE ENERGY DISTRICTS FACTSHEET" link
[65] Rueda Castellanos, Sofia & Oregi, Xabat. (2021). Positive Energy District (PED) Selected Projects Assessment, Study towards the Development of Further PEDs. Environmental and Climate Technologies. 25. 281-294.

peaks and shortfalls. The Cork demonstration highlights how digital ***supervisory control*** *can harmonize multiple energy assets (CHP, battery, flexible demand) at district scale and deliver quantifiable savings and better use of local resources.*

Digital Twin for Limerick's Positive Energy Block, Ireland: *In Limerick, the +CityXchange project created a 3D digital model and data integration platform for a downtown Positive Energy Block. This "digital twin" EMS tested various interventions virtually and then implemented optimal ones in reality[66]. It grouped buildings into a coordinated block that shifts consumption to periods of surplus renewable generation. Through this platform, Limerick identified combinations of retrofits and control strategies to reach net-positive energy, such as scheduling electric heating in some buildings slightly earlier to use solar electricity from others in the block. The EMS also engaged occupants by visualizing energy use and savings in real-time, helping achieve additional behavior-driven efficiency. While results are pending, the interim analysis suggests the digital twin approach can raise the block's renewable self-consumption significantly and pave the way for community-driven optimizations.*

Smart EMS consistently show **5–15% energy savings** in buildings through improved control and up to **20–30% peak load reduction** when coordinating multiple assets[50]. In Helsinki (MySmartLife project), a smart district heating controller reduced peak heat demand by ~20% in one neighborhood by preheating buildings before peak hours, thus flattening the load curve (utility data, 2019). In Amsterdam, a machine-learning based building control in an ATELIER PED demo improved solar self-consumption by ~10% by forecasting PV output and adjusting loads accordingly. These numbers may seem modest, but in aggregate they make a relevant difference: 10% energy saving and peak shaving can tip a district from net-neutral to net-positive. Economically, EMS investments have quick paybacks – Cork's 11% cost saving[50] would recoup the system cost in just a few years. Furthermore, EMS are required for tapping into external revenue: they enable PEDs to participate in demand response programs or frequency regulation markets by automating the response. This can bring in new income (for example, a PED microgrid selling 1 MW of flexible capacity could earn tens of thousands of euros annually in grid service payments). Thus, **smart energy management is a high return, enabling measure** in PEDs, ensuring all hardware operates synergistically and efficiently.

5.7 Smart grid technologies and demand response

While EMS often refers to on-site control, **smart grid technologies** include broader integration with the utility grid and advanced infrastructure like smart meters, grid automation, and energy marketplaces. In a PED context, smart grids enable the district to operate as a microgrid or a flexible node on the larger grid. Key technologies include **smart meters** for granular monitoring, **automated distribution systems** (to handle bi-directional power flows from many generators), **ICT platforms for energy trading** (peer-to-peer or with the grid), and demand response mechanisms that can enlist buildings to adjust consumption in response to external signals (e.g. price spikes or grid constraints). Some PEDs implement local microgrids that can island from the main grid in emergencies, using control inverters and protection devices. Others focus on virtual power plant (VPP) concepts, aggregating the PED's assets to act collectively in the energy market.

Relevance: PEDs do not exist in isolation – they interact with the city's electricity and heating networks. **Smart grid integration is important to share surplus energy with neighbors and to import/export efficiently**[67]. It ensures stability when a district produces a lot of solar (preventing back-feed issues) and when it draws power (avoiding local congestion). By employing smart grid tech, a PED can **feed its surplus to where it's needed** (for example, selling excess solar to a nearby school) and can draw on the main grid at times in a controlled way. Demand response, facilitated by smart grids, allows PED buildings to collectively reduce load at peak national demand times – contributing to grid reliability and earning incentives. Moreover, smart grids allow the creation of **energy communities** or local markets: PED residents can trade energy peer-to-peer, giving price signals that encourage more efficient and

[66] movethedate.overshootday.org/533745-limerick-positive-energy-block
[67] Han Vandevyvere "POSITIVE ENERGY DISTRICTS FACTSHEET" link

flexible energy use. In summary, smart grid capabilities amplify a PED's impact beyond its boundaries and integrate it into the wider energy transition, all while maintaining power quality and reliability.

Positive Energy Community Grid in Groningen, Netherlands: *The Making-City PED project is implementing a **smart grid with a local market platform** in a residential district of Groningen. The PED consists of a mix of retrofitted and new buildings with solar PV, a neighborhood battery, and heat pumps. A smart grid controller at the district substation monitors real-time voltage, current, and power flows. When the solar output is high and begins to push power back to the feeder, the controller automatically signals heat pumps to turn on and charge thermal storage (heating water), absorbing the excess instead of exporting it[68]. Conversely, during the evening when solar is down, the controller can draw on the community battery and even temporarily lower certain loads via demand response agreements (e.g., shifting EV charging by an hour) to prevent peak import spikes. Groningen also introduced a virtual trading scheme: prosumer homes earn credits for supplying surplus power to others in the district before importing from the grid, incentivizing local energy sharing. Preliminary results show that this smart grid operation can maintain the local feeder within voltage limits even at **100% PV penetration**, avoiding expensive grid reinforcements. Additionally, the **annual PED energy balance calculation for Groningen shows a slight surplus (~0.14 GWh)** after smart controls – an outcome that relied on coordinating storage and flexible loads via the smart grid[69]. This demonstrates that advanced grid management can enable a high-renewable district to function smoothly and positively within an existing urban grid.*

Barcelona's Energy Network and Flexibility, Spain: *Barcelona, aiming for multiple PEDs via its **Superblocks** program, has coupled mobility changes with smart grid upgrades. The Urban Mobility Plan (which reduces traffic by 21% as noted later) goes together with deploying **smart traffic-responsive street lighting** and smart meters citywide[70]. In the Glòries district, a pilot "Energy Island" was set up with its own DC microgrid linking solar roofs, battery storage, and LED streetlights. This microgrid can disconnect from the main AC grid and run autonomously in case of outages (using its battery for up to 4 hours). During normal operation, smart inverters keep power quality stable even as solar output fluctuates. The district also trialed a demand response with a local shopping mall: at times of peak grid demand, the mall agreed to precool and then cycled its HVAC, dropping its grid load by ~150 kW on command (with compensation). This was automated via signals from the utility using the city's smart grid communication network. Such measures allowed the **deferral of a grid transformer upgrade** that would otherwise be needed – a cost savings for the utility and community. While not a full PED yet, this example shows how integrating smart grid tech (like islandable microgrids and automated DR) helps manage and optimize a high-efficiency urban zone.*

Smart meters and grids primarily enable other savings rather than energy savings alone. However, the introduction of time-of-use tariffs and feedback via smart meters in pilot projects has led to **5–10% reductions in energy consumption** by end-users (due to increased awareness and shifting of usage). For instance, in a Spanish PED demo, residents with a real-time pricing app shifted ~20% of their load to off-peak times, cutting peak demand by 10% and saving money[71]. On the infrastructure side, demand response in PEDs can often shave peaks by 10–20% as seen in multiple cases above, which translates into avoiding grid upgrades and improving the positive balance. Another key metric: **hosting capacity for renewables** – smart grids can substantially raise the amount of PV that can be connected without issues. The NICE Grid project in France found that using a battery and demand response increased a neighborhood's PV hosting capacity by 30% (from 50% to ~80% of homes with PV)[72]. This is directly relevant to PEDs that aim for high PV penetration. Economically, the value of flexibility is rising – PEDs can earn revenues in flexibility markets: INTERFLEX[73] project reported that a community battery + DR in Eindhoven could earn ~€50 per household per year by providing grid services (2019 data), partially offsetting the investment. In summary, smart grid technologies are **enablers** that ensure PED's innovations don't create grid problems and in fact turn them into opportunities (through flexibility

[68] Rueda Castellanos, Sofia & Oregi, Xabat. (2021). Positive Energy District (PED) Selected Projects Assessment, Study towards the Development of Further PEDs. Environmental and Climate Technologies. 25. 281-294. https://10.2478/rtuect-2021-0020.
[69] Gabaldón, A.; Olivadese, R.; Alpagut, B.; Sanz, C.; Huitema, G.B. Positive Energy Balance Calculation in Two Case Studies. *Environ. Sci. Proc.* **2021**, *11*, 5. https://doi.org/10.3390/environsciproc2021011005
[70] www.c40.org/case-studies/barcelona-superblocks
[71] European Commission. (2021). Stardust Project (Horizon 2020). [Online]. Available: https://www.stardustproject.eu
[72] Bogdanovic, M., Wilms, H., Cupelli, M., Hirst, M., Salmeron, L.A., & Monti, A. (2018). INTERFLEX – SIMRIS – Technical management of a grid-connected microgrid that can run in an islanded mode with 100% renewable generation. link
[73] European Commission. (2019). INTERRFLEX (Innovation and Transmission System Operators for Europe). [Online]. Available: https://www.interflex-h2020.com

revenues and deferred infrastructure costs). They make the PED a good "citizen" in the larger grid, able to support stability rather than hinder it.

5.8 High-efficiency district heating & cooling systems

Beyond individual building systems, PEDs often implement **advanced district heating and cooling (DHC)** solutions to distribute thermal energy efficiently across the neighborhood. High-efficiency DHC entails low-temperature district heating (to reduce losses), recovery of waste heat, cogeneration, and sometimes the use of new vectors like geothermal or hydrogen blending. Modern **4th or 5th generation district heating** networks operate at lower temperatures (e.g. 40–60°C instead of 80–100°C), which increases heat pump COPs and allows more waste heat integration. Cooling can be provided centrally via efficient chillers or absorption units, with chilled water piped to buildings (or even using natural sources like sea/river water). **Waste heat recovery** is a key strategy: capturing heat from data centers, metros, industrial processes, incineration plants, etc., and using it in the DHC network instead of rejecting it to the environment. Coupling heating and cooling in the same system (using one's waste as the other's input) also boosts efficiency, as seen in some Scandinavian projects.

Relevance: High-efficiency heating and cooling networks allow a PED to address thermal demand collectively, which can be more efficient than each building acting alone. By pooling loads, a central plant can operate at optimal efficiency, and diversity of demand means less installed capacity is needed overall. Utilizing waste heat or renewable heat (like geothermal) that individual buildings couldn't tap on their own turns a district system into a **low-carbon heat source**. This is especially relevant in dense urban PEDs where not every building can have its own heat pump or solar thermal system – a district solution can fill the gap. Moreover, efficient DHC cuts primary energy: for example, combined heat and power (CHP) units in a DHC can reach 80–90% total efficiency by using waste heat for buildings, far higher than separate generation[61]. In PED context, CHP might be used with biofuels or hydrogen for near-zero emissions. Carbon capture (next section) can also be applied at a central plant more easily than at dozens of individual sources. In short, a state-of-the-art district heating/cooling grid can dramatically lower the carbon intensity of heating, reduce losses, and incorporate multiple sustainable heat sources, all contributing to the PED's net-positive goal.

Taarnby Integrated Heating/Cooling, Denmark: An array of large industrial heat pumps in Taarnby's energy center provides both district heating and cooling with high efficiency. *The Taarnby project is a **world-first integration** of heating, cooling, wastewater and ground storage[74]. It uses heat pumps to simultaneously produce chilled water for a business park's cooling needs and hot water for the district heating network. Heat extracted from buildings during cooling is not wasted – it's funneled into the district heating loop. Additionally, heat from the local wastewater treatment plant and seasonal ground heat storage are captured. This synergy means **nothing is wasted: when cooling is produced, heat is by-produced and sold to heat customers** [61]. The outcome is an extremely efficient system: the large heat pump plant meets ~60% of Taarnby's heating demand (including Copenhagen Airport) at a much lower cost and emission level than previous gas/wood boilers[61]. The project saved 80 million DKK versus separate systems[61], and it demonstrates how integrating multiple systems yields big efficiency gains. Essentially, the heat pump COP is effectively boosted by the fact it's doing two jobs at once (heating and cooling), and the network ensures both hot and cold are use. For PEDs, this shows the ideal of sector coupling – the PED's cooling demand can help satisfy its heating demand and vice versa.*

Waste Heat Recovery in Berlin, Germany: *A **data center heat recovery** project (part of ReUseHeat, H2020) connected a medium-sized data center to a low-temperature district heating network. A heat pump recovers about 0.3 MW of waste heat from the data center's cooling system and feeds it into the network at ~50°C[75]. This provides roughly **1,000 MWh/year** to heat nearby homes, covering a substantial part of their heating needs with essentially free energy. The only cost is running the heat pump, which is powered by renewable electricity. This installation demonstrated that even **small-scale waste heat** can be viably used in urban districts – the **CO_2 savings are ~370 tons/year** (since the waste heat displaces natural gas that would have been burned)[76]. The system achieved a*

[74] www.ramboll.com/en-us/projects/energy/taarnby-city-of-smart-solutions
[75] www.euroheat.org/dhc/knowledge-hub/re-use-heat-project-funded-by-horizon-2020
[76] ReUseHeat Consortium. (2021). Final Report: Demonstration of Urban Waste Heat Recovery. Horizon 2020. [Available via CORDIS: https://cordis.europa.eu/project/id/767429]

COP of around 5, thanks to the low output temperature, exemplifying 5th-generation district heating principles. Such waste heat recovery is highly replicable: across Europe, countless data centers, supermarkets (refrigeration heat), and metro stations release low-grade heat that PEDs can harness. By doing so, PEDs drastically improve overall energy efficiency (using energy twice) and reduce net import needs. Berlin's case is one of three ReUseHeat demonstrators, others being a hospital and metro – each showing 20–50% gains in efficiency by capturing heat that was formerly lost.

High-efficiency DHC can bring enormous energy and carbon reductions. Studies by Euroheat estimate that moving from individual gas boilers to a modern district system with heat pumps and waste heat can **cut heating primary energy by ~50%** and emissions by even more if the electricity is green (near 100% reduction in on-site emissions). In Amsterdam's Houthavens district, a new low-temp network using aquifer thermal storage achieved a **30% reduction in primary energy use** for heating/cooling compared to baseline (per City of Amsterdam data). In Paris, expanding the cooling network that uses the Seine River water has saved an estimated 35 GWh/year of electricity (by avoiding individual chillers) – translating to €3–4M saved annually. These figures illustrate the scale of efficiency possible. While district systems require significant infrastructure, their ROI can be strong: the Taarnby business plan showed profitability through energy sales, and many cities (e.g. Dublin, Bristol) found that capturing industrial waste heat can pay back in under 5 years given high gas prices. For PEDs, any available **free heat source** (industrial, geothermal, etc.) can dramatically tilt the energy balance positively. By deploying heat pumps and advanced DHC, PEDs leverage every unit of energy to the max, often using it multiple times. This holistic approach to heating/cooling is a key element in reaching climate neutrality and positive energy operation on an urban scale.

5.9 Green mobility and sustainable transport

A PED isn't only about buildings and grids – it also encompasses the **transportation system** within the district. **Green mobility** measures aim to reduce fossil fuel use and energy consumption in transport by promoting modal shift and clean transportation modes. This includes expanding public transit, creating pedestrianized and bike-friendly streets, car-sharing schemes, electric mobility, and "last-mile" logistic solutions like cargo bikes. In PEDs, mobility planning often goes hand-in-hand with energy planning: by redesigning urban space to favor walking, cycling, and transit, a district can significantly cut the energy spent on transportation. Some PED initiatives coordinate with Sustainable Urban Mobility Plans (SUMPs), implement low-emission zones, reduce parking availability, or introduce traffic calming (like the **Superblock** concept). The net effect is fewer car trips, shorter necessary travel distances, and more trips done with zero or low energy.

Relevance: Mobility currently accounts for a large chunk of urban energy use (often 30%+). A PED cannot ignore this if it aims for holistic sustainability. **Green mobility measures reduce overall district energy demand and emissions, improving the PED's energy balance and livability**. By reducing private car usage, fuel consumption is lowered, and often urban space is freed up and could be repurposed for green areas or renewable installations. Active mobility (like walking, biking) requires virtually no energy and yields health benefits. Public transportation can move people far more efficiently per energy unit than private cars. Moreover, reducing traffic can directly lower the district's CO_2 emissions and improve air quality. For PEDs that span neighborhoods, ensuring that residents can conveniently commute or travel within and out of the district via sustainable means is significant for long-term energy positivity. Green mobility keeps the PED concept holistic, addressing both stationery and transport energy. Many European PED pilots explicitly include mobility in their scope – e.g., adding electric buses, bike lanes, or mobility hubs – underlining that **energy-positive means not just buildings with PV, but also people moving in an energy-efficient way**.

Barcelona Superblocks and Modal Shift, Spain: *Barcelona's* ***Superblocks*** *program provides a compelling case of urban mobility transformation. By reorganizing city blocks to restrict traffic and prioritize pedestrians and cyclists, Barcelona is removing vehicles from large swaths of the city. The city's Urban Mobility Plan, integrated with the*

Superblocks rollout, is projected to ***reduce private car and motorcycle use by 21% citywide***[77]*. This is achieved by expanding bike lanes to 233 km, creating a new orthogonal bus network with higher coverage and frequency, and calming traffic in residential clusters*[66]*. In already implemented pilot superblocks, like Poblenou, car traffic dropped by* ***~85%****, with a negligible increase on boundary roads*[78]*. As a result, many residents switched to walking or cycling for local trips. The city has estimated that full implementation of 503 superblocks could prevent ~667 premature deaths annually due to lower pollution and traffic accidents*[79]*. From an energy perspective, a 21% cut in private vehicle use translates to enormous energy savings: Barcelona expects to eliminate around* ***230,000 daily car trips****, saving on the order of* several million liters of fuel per year *(and associated CO_2 emissions). These trips will be absorbed by a ~10% increase in public transport and a doubling of cycling mode share*[80]*. Essentially, the same mobility needs will be met with far lower energy input. The Superblocks thus show how rethinking urban design can yield a massive drop in transport energy consumption – which for a PED means the overall energy balance of the district improves and the local quality of life improves. The* ***reclaimed streets (over 23 hectares turned into public space)***[81] *additionally benefit from lowered urban heat islands and encourage community activities within walking distances. Barcelona's approach is being emulated in other EU cities, like Paris, and is a powerful tool in the PED toolbox for slashing transport energy use by double-digit percentages.*

Green Mobility in Hamburg Bergedorf, Germany: *In Hamburg's MySmartLife PED demo*[82] *a bundle of mobility actions were implemented alongside energy retrofits. The city introduced* ***electric buses*** *on a new circular route around the district, installed several public* ***e-charging stations****, and created a bike-sharing program with e-bikes. A mobility hub was created where residents could transfer easily between different transportations modes. Therefore, public transit usage in the area increased by ~****8%*** *and cycling by 12%, while private car use decreased. Another flagship action was subsidizing* ***cargo e-bikes*** *for local businesses, resulting in 10 logistics companies replacing some van deliveries with e-bikes, cutting fuel use (one company alone avoided 2,500 L of diesel in a year). In terms of energy, replacing a diesel bus with an e-bus saved ~500 MWh of fuel energy annually (the e-bus uses about 170 MWh of electricity instead, largely supplied by renewable energy in Hamburg) – a 66% reduction in vehicle energy use thanks to higher efficiency. Hamburg also trialed* ***hydrogen blending*** *in a district heating plant to decarbonize that last bit of energy supply*[71]*, but from a mobility standpoint, the key takeaway is the multi-pronged approach: electrify vehicles, encourage active modes, and discourage unnecessary car trips. Residents in the intervention area were also engaged in "smart mobility" workshops and given incentives (like one-year transit passes). Hamburg's experience shows that even without dramatic superblock-style changes, a PED can chip away at transport energy use via electrification and behavioral nudges, achieving noticeable shifts in a five-year period.*

The impact of green mobility measures on energy is significant. For example, if a PED reduces car traffic by 20%, that might equate to **thousands of liters of fuel saved per day** in a busy area. In terms of energy, 1 liter of petrol contains ~9 kWh; so, eliminating 1,000 car trips of 5 km (assuming 7 L/100km consumption) saves ~315 liters, or ~2,835 kWh, per day. Scaled annually, that's over 1 GWh/year saved – just from mode shift of a modest number of trips. Multiply across a district and add improvements like more efficient driving, EVs, etc., and the transport energy reduction can be on the order of **10-30 GWh/year for a mid-sized district**. CO_2 emissions drop correspondingly: Barcelona's 21% traffic reduction is tied to an estimated **~300,000+ ton CO_2 reduction by 2030**.

In economic terms, less traffic can mean less road maintenance costs and more productivity (less congestion). Health and livability benefits are also monetizable. From a PED strategy view, **green mobility is essential to reduce overall district energy demand**, and it often costs less than high-tech fixes – painting bike lanes or expanding a bus line is relatively low cost for the return. There is, however, the need for political will and community buy-in, as it changes how people move. Successful examples like Barcelona, Ghent, and Copenhagen indicate strong support once people experience the benefits (cleaner air, safer streets). PED initiatives thus incorporate stakeholder

[77] www.c40.org/case-studies/barcelona-superblocks/
[78] citychangers.org/barcelona-superblocks
[79] tti.tamu.edu/news/superblocks-project-could-prevent-almost-700-premature-deaths-every-year-in-barcelona
[80] N Mueller, D Rojas-Rueda, H Khreis, M Cirach, D Andrés, J Ballester, X Bartoll, C Daher, A Deluca, C Echave, C Milà, S Márquez, J Palou, K Pérez, C Tonne, M Stevenson, S Rueda, M Nieuwenhuijsen, Changing the urban design of cities for health: The superblock model, Environment International, Vol. 134, 2020, https://doi.org/10.1016/j.envint.2019.105132.
[81] www.c40.org/case-studies/barcelona-superblocks/
[82] eurocities.eu/stories/a-playground-for-energy

engagement on mobility. For instance, Vitoria-Gasteiz (Spain) engaged citizens in redesigning streets for their PED, achieving consensus that led to a 38% drop in car use in the city center over a decade[83].

Green mobility measures are an integral part of PEDs – **reducing energy consumption and emissions from transport, improving public space, and often catalyzing community support for the PED concept**. They make the "district" truly sustainable in all aspects, not just net-positive at buildings level. European projects validated that ambitious mobility shifts are achievable and have profound energy impacts, complementing the building and grid measures in the PED framework.

5.10 Carbon capture and storage (CCS)

After maximizing energy efficiency and renewables, some PEDs may still have residual emissions – for example, from a waste-to-energy plant, a biomass CHP, or other unavoidable combustion (or historic building constraints). **Carbon capture and storage** is an emerging measure to neutralize these emissions by capturing CO_2 before it enters the atmosphere and either storing it underground or using it in products (CCUS – Carbon Capture, Utilization, and Storage). In an urban PED context, CCS might be applied at a central facility that serves the district (like a local energy-from-waste incinerator or a district heating plant). While not yet common at small scale, there are pilot projects in Europe demonstrating CO_2 capture from city heat plants and even from ambient air (direct air capture).

Relevance: CCS is essentially a **complementary "last resort" measure** to achieve net-zero or net-negative emissions when further emissions cuts are difficult. A PED aims for net-zero greenhouse gases[84]; if a certain emission source cannot be eliminated (e.g. waste incineration for district heating or industrial processes within the district), capturing the carbon can offset that. In some cases, a PED might capture CO_2 and supply it to other industries (e.g. greenhouses, carbonated beverage plants) as a form of utilization. Though CCS is capital-intensive and complex, it can enable urban areas to tackle emissions from sources like waste management that otherwise impede climate targets. Additionally, if **bioenergy** is used in a PED (like burning biomass for backup heat), capturing its CO_2 leads to negative emissions (because the CO_2 absorbed by plants is then permanently stored) – this can compensate for other sector emissions. Thus, CCS can effectively "erase" the hardest-to-abate emissions, ensuring the PED's overall carbon balance is positive (or neutral at worst). It's considered an enabling technology in scenarios where 100% electrification or elimination of combustion isn't feasible in the near term[85]. The EU and IPCC have identified CCS as essential for reaching climate neutrality, especially for urban waste and industrial emissions[64]

Oslo Klemetsrud Waste-to-Energy CCS, Norway: *Oslo is pioneering carbon capture at its main waste incineration plant in Klemetsrud – a facility that handles the city's non-recyclable waste and produces heat for district heating. This plant is Oslo's single largest emitter[64]. The city, in collaboration with Norway's Longship CCS project, is building a full-scale capture unit to remove* ***90% of the CO_2 emissions*** *from the plant's flue gas[86]. That equals roughly* ***400,000 tons of CO_2 per year*** *that will be captured and stored deep under the North Sea[64] [65]. To put it in perspective, that is equivalent to the annual emissions of ~200,000 cars being negated. Once operational (expected by 2026–2027), this will effectively make Oslo's waste management sector nearly carbon-free[64]. For Oslo's climate strategy – essentially its PED initiatives citywide – this CCS project is* "crucial" *and a major step toward the 2030 goal[64]. It also sets a blueprint for the ~450 other waste incineration plants across Europe that face similar challenges[64]. Financially, the project is supported by government funding (NOK 3 billion from the state) given its importance[64]. When complete, the PED effect is that a huge source of emissions is eliminated; Oslo can then claim that burning city waste no longer contributes net CO_2. This allows the district heating from this plant to be truly low carbon. The Klemetsrud CCS will make Oslo's energy-from-waste* ***essentially emissions-free, capturing ~400k tons CO_2/year at 90% efficiency[65]****, which showcases the potential scale of impact.*

[83] European Commission. (2020). Urban Transport Roadmaps: Case Study – Vitoria-Gasteiz. [Available via ELTIS: https://www.eltis.org]
[84] Han Vandevyvere "POSITIVE ENERGY DISTRICTS FACTSHEET" link
[85] www.klimaoslo.no/what-the-carbon-capture-project-means-for-oslos-climate-targets
[86] www.fortum.com/no/media/2021/03/norways-fortum-oslo-varme-ccs-project-makes-shortlist-eu-innovation-funding

Biomass CHP with CCS in Stockholm, Sweden: *A pilot project by Stockholm Exergi has tested capturing CO_2 from a biofuel-fired combined heat and power plant. In 2021, their pilot plant captured about **700 tons of CO_2** from the flue gas of a biomass boiler over several months[87]. Since the CO_2 came from renewable biomass, capturing it results in negative emissions. The utility found that if scaled up, capturing ~800,000 tCO_2/year from their bio-CHP (which provides a large chunk of Stockholm's heat) could make the entire district heating system carbon-negative, offsetting other emissions in the city. The pilot achieved a capture rate above 85% of CO_2 and helped refine cost estimates. While still in development, Stockholm is planning to implement full-scale BECCS by 2025–2030, which would contribute significantly to the city's PED ambitions by removing more CO_2 than the system emits. This highlights a path where cities with existing biomass heat plants can go beyond net-zero to* net-negative*, essentially acting as urban carbon sinks.*

Carbon capture at scale is expensive – the Oslo project's total cost is around €500 million. However, the **cost per ton** of CO_2 captured can be comparable to high carbon prices (~€100–150/ton initially, expected to drop), and these costs are often justified for lack of alternatives. Moreover, many projects get funding through climate programs. As technology matures, costs are expected to fall into the €40–60/ton range. PED planners typically consider CCS only after other measures; it's a **late-stage measure** when nearing full decarbonization. But its inclusion can future-proof as a PED. Any central plant built today can be made "CCS-ready" to add capture later. The benefit is measured in emissions: for Oslo, capturing 400k tons CO_2/year is like negating the emissions from **all** energy use of tens of thousands of homes. In climate accounting, that is invaluable. Also, if carbon prices/taxes rise above capture cost, CCS becomes financially sensible. Additionally, by achieving negative emissions (via bio-CCS or direct air capture), a PED or city could sell carbon removal credits on voluntary markets, creating a revenue stream. Direct Air Capture (DAC) is also emerging in PED discussions (e.g. Zurich has a DAC unit capturing ~900 tCO_2/year for reuse in greenhouses). While DAC is even more costly, it might play a role in the future as costs drop and if districts aim to compensate historical emissions.

Carbon capture is not yet a common PED measure, but the **first EU implementations are underway** and proving that urban emissions can be virtually eliminated with this technology. It serves as the "finishing touch" for a PED: after reducing 90+% of emissions via efficiency and clean energy, CCS can tackle the remaining few percent to truly hit net-zero or net-positive GHG emissions. As Europe moves towards climate neutrality by 2050, we can expect more PEDs to incorporate CCS for waste treatment plants, industrial hubs, or other fixed emitters, following the example of Oslo and Stockholm. This ensures that even hard-to-abate urban emissions do not prevent districts from achieving positive energy and climate status.

5.11 Energy culture related measures

This section presents a set of educational and engagement measures designed for residents, students, professionals, local administration and policymakers that could lead to energy efficient behavior and planning within PEDs. Each measure is described with its role as promoting behavior change, increasing technical literacy, and helping community participation, along with real-world examples and, where available, quantified benefits. This educational toolkit complements technological efforts by building the human capacity and public support needed to plan, implement, and sustain PEDs.

Community awareness and behavior change campaigns

Community-focused campaigns are essential to create broad public buy-in for PED initiatives. By raising awareness and encouraging energy-saving behaviors, these measures help reduce demand and carbon footprint at the grassroots level, complementing the high-tech solutions. They also empower residents as active partners in the PED, rather than passive consumers. Key tactics include:

[87] Stockholm Exergi press release, 2021 available at: https://www.stockholmexergi.se/content/uploads/2022/03/Stockholm-Exergi-2021-in-brief_pages.pdf

- **Public Awareness Campaigns:** Outreach via workshops, town-hall meetings, social media, and local events to educate citizens on PED goals, energy efficiency tips, and available incentives. For example, many European cities run "energy days" or info sessions under the Covenant of Mayors framework to inform residents about saving energy at home and the community benefits of PEDs. These campaigns build a shared vision and normalize sustainable habits (turning off lights, reducing waste, etc.).
- **Community Energy Challenges:** Friendly competitions and pledge programs that motivate households to conserve energy through team-based challenges or gamified goals. For instance, the *Energy Neighborhoods* program in Europe saw neighborhoods compete to cut consumption, achieving around 9–13% average household energy savings purely through behavior changes[88]. Such challenges leverage social motivation and peer support to make energy saving fun and rewarding.
- **Energy Ambassadors & Coaching:** Training local volunteers or hiring energy coaches to work one-on-one with households and businesses. These "energy ambassadors" help others perform energy scans, understand their bills, and adopt low-cost efficiency measures (like adjusting thermostats or eliminating standby power). In Amsterdam, personalized coaching, with detailed energy use feedback has proven highly effective: **50% lower energy bills on average**, lifting 75% of participants out of energy poverty[89]. This dramatic result shows how tailored guidance can translate awareness into sustained actions.

Relevance: Community campaigns directly promote the behavior shifts and public acceptance that technological PED measures alone cannot achieve. Every bit of energy saved through lifestyle change means less demand that the PED's systems must supply, making net-positive energy goals more attainable. Just as important, informed residents are more likely to embrace new PED technologies (smart meters, demand-response programs, etc.) rather than resist them. By giving citizens, a sense of collective mission and demonstrating real benefits: like lower bills or cleaner air, these initiatives build trust in PED projects. They also address equity: outreach can be customized to include vulnerable groups, ensuring the PED transition is inclusive. Ultimately, community engagement creates a culture of sustainability in the district – a social environment where the investments in solar panels, insulation, and smart grids can fully flourish with public support.

Energy Coaching in Amsterdam, The Netherlands: *A recent experiment in Amsterdam vividly illustrated the power of community energy coaching. Researchers provided 67 low-income households with detailed data on their energy usage plus periodic one-on-one coaching on how to reduce waste. Over the course of the program, participating families* ***cut their energy expenses by half on average****, a savings significant enough that 0three-quarters of them were lifted out of energy poverty. Coaches helped residents find "quick wins" (like eliminating standby power, fixing inefficient appliances, and better managing heating) and reinforced habits over time. The dramatic 50% reduction highlights how education and support can unlock efficiency – even without any costly technology upgrades. It also showcases the human side of PED benefits: lower bills improved families' finances and comfort, while the community at large saw reduced demand on the energy network. This example underlines that technical solutions alone are not enough; empowering people with knowledge and support can achieve deep energy cuts and ensure the PED's positive energy balance is reached in practice, not just on paper.*

Education programs for students and youth

Educating young people is a long-term investment in the sustainable future of PEDs. Schools and youth programs can cultivate energy literacy from an early age, instill pro-sustainability values, and even harness the enthusiasm of students to influence their families and neighborhoods.

School buildings can be transformed into living labs where students would actively participate in energy management activities. This should involve installing sensors and student-readable energy dashboards in the school, forming students lead "energy teams" to track consumption and designs energy saving plans. The approach engages youth in data-driven problem solving. The EU-funded **ENERGE project**,

[88] Tools of Change
[89] MIT, School of Architecture and Planning, Cutting Household Energy Costs

implemented in 13 secondary schools across France, Germany, Luxembourg, Ireland, the Netherlands and UK, is a prime example how student involvement can reduce emissions[90]. ENERGE equips schools with sensors to monitor electricity and indoor climate, and an integrated online platform that feeds data into classroom activities. Teachers incorporate the data into lessons, and students work on projects to improve their school's energy efficiency (like optimizing heating schedules or campaigning to turn off lights). This initiative not only teaches engineering and climate concepts in a tangible way but also promotes a culture of energy awareness in the entire school community.

Relevance: Engaging students and youth have both immediate and future payoffs. In the near term, schools that implement energy-saving programs can reduce their consumption (often 5–15% as reported by various "green school" initiatives), contributing to city energy goals. More importantly, young people often act as multipliers: they bring energy-saving ideas home to their parents, spreading behavior change to households. Over the longer term, today's informed students will become tomorrow's architects, engineers, consumers, and voters. Their early exposure to PED concepts means the future workforce and electorate will be more receptive and knowledgeable about sustainable energy. This generational shift is critical for the longevity of PED efforts beyond the initial project timeline. Additionally, youth-driven projects can energize the broader community – for example, a student proposal for a solar panel on the school roof can rally parents and local businesses to donate and participate. In sum, educational measures in schools create a foundation of technical literacy and environmental stewardship that PEDs can build upon for decades.

Schools as Living Labs (ENERGE Project), EU: *The ENERGE: Energising Education to Reduce GHG Emissions project demonstrates how secondary schools can become microcosms of a PED. Spread across six countries, ENERGE combines technology and pedagogy: each pilot school is outfitted with sensors to gather real-time data on electricity use, heating, and indoor air quality, turning the school into a live energy lab. An interactive platform then integrates these data with teaching materials, enabling students and teachers to analyze their own school's performance[79]. Students take on roles as energy auditors and innovators – for instance, they might investigate why one classroom uses more power than another and implement changes. Students are involved in co-designing solutions and even in executing efficiency interventions, guided by their teachers (who receive training in the new tools). Early results show increased awareness and engagement: surveys indicate students better grasp the link between daily actions and climate impacts, and participating schools report behavioral changes like more consistent lights-off policies. While final energy savings data are still being collected, the expected outcome is a measurable drop in each school's energy use due to these no-cost actions and optimized controls. ENERGE's transnational approach also studies different education governance models to see how student-led energy projects can be replicated widely. By treating schools as living labs, this project equips a whole generation with practical knowledge on energy efficiency and empowers them to be ambassadors of the PED vision in their communities.*

Training and capacity building for professionals

Professionals – from construction workers and engineers to urban planners and energy managers – require up-to-date skills and knowledge to design, build and maintain PEDs. Educational measures for this group focus on upskilling the workforce and disseminating best practices so that PED technologies and designs are implemented effectively.

Large-scale training programs for tradespeople could equip electricians, plumbers, builders, HVAC installers, etc. with the required skills to implement/install high-performance buildings and renewable energy systems: The European Union's **BUILD UP Skills** initiative, launched in 2011, exemplifies this approach. Until now, it has supported more than 100 EU and national projects in over 30 countries to identify skill gaps and roll out training and certification for blue-collar workers in areas like insulation, airtightness, heat pump installation, and solar PV mounting. This is now part of the EU's broader goal to **reskill at least 25% of the construction workforce (about 3 million workers) in the next five years**[83]. Through this program, numerous builders and contractors have attended courses leading to qualifications in nearly zero-energy building (nZEB) techniques. By standardizing curricula and

[90] van Wees, M.; Revilla, B.P.; Fitzgerald, H.; Ahlers, D.; Romero, N.; Alpagut, B.; Kort, J.; Tjahja, C.; Kaiser, G.; Blessing, V.; et al. Energy Citizenship in Positive Energy Districts—Towards a Transdisciplinary Approach to Impact Assessment. Buildings 2022, 12, 186. https://doi.org/10.3390/ buildings12020186

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certifications, these programs ensure that when a PED project calls for, say, a complex retrofit or smart lighting system, the local labor force is competent to deliver it.

Programs for engineers, architects, energy auditors, and planners to stay current with cutting-edge PED solutions can take the form of short courses, workshops, or e-learning modules. Topics range from integrated design for renewable generation and consumption to advanced software tools like building information modeling or power flow analysis for PED infrastructure and grid simulation. For example, the EU-funded **PROF/TRAC** project developed an open training platform for building professionals, offering courses on nZEB design and interdisciplinary teamwork in PED projects. Similarly, some cities have established “energy academies” where municipal engineers and local consultants jointly learn about new PED technologies before they are deployed. Such Continuing Professional Development (CPD) opportunities often award certificates or professional credits, incentivizing participation. They directly improve the quality of PED implementations by bringing state-of-the-art knowledge to practitioners. Examples include manufacturer-led sessions for battery storage installation or mock-up buildings for retrofit practice. Innovative methods like VR simulations and mobile training units enhance accessibility. This ensures local skills retention post-project and high-quality execution of complex PED systems like energy-efficient retrofits and smart grids.

A skilled workforce is critical and proper training leads to better performance and safer operations. It also speeds up adoption of PED innovations across other projects while creating local green jobs. Economically, trained professionals reduce costly errors, boost ROI, and extend system lifespans. Ultimately, capacity building turns PED plans into reality by empowering implementers.

Final remarks

The current report showcases that PEDs are not just an aspirational concept, but an achievable model for sustainable urban living. Each chapter of the guide reinforces a common theme: **energy efficiency is the bedrock of any successful PED**. By continuously reducing energy demand across buildings, transport, and infrastructure, PEDs can minimize reliance on external energy sources and reduce the scale (and cost) of local renewable generation needed to reach the net-positive status. In practical terms, this means that efficiency improvements – from insulating homes and upgrading HVAC systems to optimizing energy use through smart controls – directly translate into higher renewable energy contributions and lower emissions for the district. Energy-efficient PEDs inherently generate greater resilience (through reduced exposure to energy price fluctuations and improved grid stability), alleviate energy poverty by lowering consumption and bills, enhance air quality, and create more comfortable living environments for residents. The implications are clear: **prioritizing energy efficiency in PED design and exploitation is not only an environmental necessity but also a social and economic opportunity**.

Delivering PEDs requires coordination across technology, policy, and community engagement. While integrated technologies can greatly improve energy efficiency, their success depends on supportive governance and active public participation. PEDs should be part of a wider urban sustainability strategy, with updated regulations and inclusive planning. When done well, PEDs reduce emissions, create green jobs, ease infrastructure demands, and enhance quality of life—making them key drivers of the energy transition at the neighborhood level.

It is also evident that PEDs have a critical role to play in meeting regional and global climate objectives. As Europe moves towards its goal of climate neutrality by 2050, PEDs are poised to become integral building blocks of low carbon cities. The PED approach exemplifies how climate action can be localized – making abstract targets tangible through concrete projects in our cities and towns. By pushing the envelope on efficiency and renewable integration, today's PED pilots are creating models that can be scaled up across urban Europe and beyond. Importantly, the lessons learned from these early projects inform future policy and market adjustments – demonstrating what level of emissions reduction is possible and how regulatory or financial frameworks might be tuned to support wider adoption. Each successful PED serves as proof of concept that a climate neutral energy future is within reach, showing policymakers that consistent energy efficiency measures combined with renewables can deliver results on the ground. In turn, this builds confidence to pursue even more ambitious initiatives, creating a virtuous cycle of innovation and policy support.

Reaffirming the importance of energy efficiency in PED implementation, the report makes clear that **energy efficiency is not merely one component of a PED – it is the prerequisite that makes the positive energy balance achievable and sustainable**. Without first maximizing efficiency, efforts to add renewable generation or novel technologies will be less effective and more costly. By contrast, an efficiency-first approach yields compounding benefits: every kilowatt-hour saved is a kilowatt-hour that does not need to be generated or stored, simplifying the path to net positivity. This principle should remain front and center as stakeholders plan and execute PED projects. Energy efficiency measures often represent the most cost-effective and immediate actions, and they lay a strong foundation upon which renewable energy systems and smart technologies can build. In the long run, maintaining an emphasis on efficiency ensures PEDs continue to perform as intended even as conditions change (such as population growth or climate variations), because a lean energy system can adapt more easily and maintain balance.

Looking ahead, several forward-looking priorities emerge for policymakers, urban planners, and stakeholders to scale up PEDs and ensure their lasting impact:

- Governments at all levels should incorporate PED targets and guidelines into urban development plans, building standards, and climate policies. This includes establishing clear definitions and criteria for PEDs, setting ambitious yet achievable targets for energy positivity in new developments or district retrofits, and streamlining approval processes for PED-related projects. By embedding PED concepts into the regulatory framework, policymakers provide long-term vision and certainty, encouraging more cities to initiate such projects.

- Scaling PEDs from pilot projects to common practice will require dedicated funding channels and incentive structures. Public authorities and financial institutions should expand grants, low-interest loans, tax incentives, and public-private partnership opportunities specifically for energy efficiency and PED initiatives. For instance, national or EU-level funds could be earmarked to co-finance deep energy retrofits or smart grid installations in districts that commit to PED outcomes. Consistent financial support de-risks these innovative projects and signals commitment, attracting private sector investment and reducing the burden on local budgets.
- Continued innovation is a key issue to improve PED performance and drive down costs. Stakeholders should prioritize research, development, and deployment of cutting-edge solutions such as advanced energy storage, digital twins for city energy modeling, next-generation photovoltaics, and ultra-efficient building materials. Demonstration projects and living labs in PED contexts can validate these technologies. Moreover, open data platforms and interoperability standards should be promoted so that various technologies could seamlessly work together in a PED ecosystem. Embracing innovation will ensure that PEDs remain at the forefront of efficiency and can adapt to incorporate new breakthroughs – including solutions for residual emissions like carbon capture if needed – to reach climate neutrality.
- Policymakers and educational institutions need to invest in developing the human capital required for PED implementation. This involves training programs for architects, engineers, urban planners, technicians, and energy managers on integrated district design and energy-efficient technologies. Sharing best practices through networks of cities and professional forums will accelerate learning. The report underlines that without a skilled workforce and informed decision-makers, even well-funded PED plans could falter in execution. Therefore, establishing capacity-building initiatives (workshops, certification courses, on-site training during pilot projects) is a forward-looking necessity. Over time, this will create a knowledgeable community of practice, equipped to replicate and maintain PEDs, while also creating local green jobs and expertise.
- A forward-looking approach to PEDs requires robust monitoring and a commitment to continuous improvement. Policymakers and project leaders should establish transparent monitoring and evaluation frameworks, where data from PED operations are regularly analyzed and reported. This performance feedback will help to fine-tune strategies and validate which measures deliver the best results. Just as importantly, successful PED models should be documented and promoted as templates for other cities and districts. Creating knowledge exchange platforms – for instance, an online repository of case studies and data or an annual PED practitioners' conference – can disseminate lessons learned. As more data becomes available from various PED implementations, stakeholders can make benchmark progress and develop standards or certification for PED excellence. In time, replicating effective PED strategies on a scale across multiple districts and cities will contribute significantly to national and EU energy and climate objectives, amplifying the impact well beyond individual projects.

PEDs represent a bold shift in urban development, transforming neighborhoods into self-sustaining, low-carbon energy communities. This report shows that the tools and knowledge to achieve this vision already exist. Realizing it will require long-term commitment and collaboration, but the payoff is significant: more efficient, resilient, and inclusive cities. By acting on key recommendations, leaders can scale PEDs from pilots to standard practice, empowering communities to drive sustainable change and meet climate goals. The future of positive energy cities is within reach—and the time to act is now.

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APPENDIX – Energy efficiency measures summary

Table 10.

MEASURE	TYPE	DESCRIPTION & RELEVANCE TO PEDS	QUANTIFIED BENEFIT (IMPACT)	SOURCE
BUILDING INSULATION RETROFIT	Individual	Upgrading a building's envelope to minimize heat loss. Improves thermal efficiency and significantly lowers heating/cooling demand in PED buildings.	*Up to ~45% reduction in heating energy use* after deep insulation upgrades	BPIE, bpie.eu
HEAT PUMPS (ELECTRIC)	Individual	Replacing fossil-fuel boilers with efficient electric heat pumps (air-source or ground-source) for heating and cooling. They transfer heat instead of generating it, drastically improving building energy performance.	*3–5× higher efficiency than gas boilers*: COP ~3.0–5.0 vs ~0.9 for combustion, *cutting heating energy ~70% and enabling low-carbon heat with renewable power.*	EECA/IEA, eeca.govt.nz
HEAT RECOVERY VENTILATION (HRV)	Individual	Mechanical ventilation systems that recover heat from exhaust air to pre-heat incoming fresh air or vice versa. This maintains indoor air quality with minimal energy waste – a key efficiency measure in airtight PED buildings.	*Recovers ~60–95% of exhaust heat* that would otherwise be lost, *greatly reducing HVAC energy needed for ventilation.*	Wikipedia, en.wikipedia.org
SMART ENERGY MANAGEMENT SYSTEMS (EMS)	Individual	Intelligent building energy management systems that use sensors, automation and controls to optimize energy use in real time. Enhances energy flexibility and efficiency in PED buildings.	*A ~29% average reduction in building energy use* with advanced automation and controls, *by optimizing equipment schedules and eliminating waste.*	DOE/PNNL, energy.gov
SMART THERMOSTATS	Individual	Wi-Fi enabled learning thermostats that automatically adjust heating/cooling based on occupancy and preferences. They improve residential energy efficiency by avoiding unnecessary HVAC use in PED homes.	*Save ~10–12% on heating and ~15% on cooling* energy on average, *by smarter scheduling and temperature setbacks (lower bills and peak load).*	Nest Studies, whatissmartenergy.org
LED LIGHTING & SMART CONTROLS	Individual	Upgrading lighting to LED technology and adding smart controls (occupancy/daylight sensors). Apply to indoor lighting and public/street lighting in PEDs, drastically lowering electricity use for illumination.	*75–90% less energy use* than traditional incandescent or fluorescent lighting, *with much longer lamp life. Smart controls further eliminate waste in unoccupied spaces.*	Industry Data, prideindustries.com
ENERGY-EFFICIENT APPLIANCES	Individual	High-efficiency household appliances (refrigerators, washing machines, etc.) and equipment that carry Energy Star or A^{+++} ratings. They perform the same tasks with significantly less electricity, reducing PED load.	*Use ~10–50% less energy* than standard models, *delivering substantial electricity savings over the appliance lifetime (e.g. efficient fridges, HVAC, etc.).*	ENERGY STAR, workmoney.org
ROOFTOP SOLAR PV	Individual	Installing solar photovoltaic panels on building roofs to generate on-site renewable electricity. Key for PEDs to produce energy locally, offsetting grid imports and contributing to a positive energy balance.	*High generation potential:* rooftop PV could technically supply ~45% of a region's electricity demand if fully utilized. Typical home PV systems can cut a household's grid consumption by ~20–50%.	Environment America, environmentamerica.org

MEASURE	TYPE	DESCRIPTION & RELEVANCE TO PEDS	QUANTIFIED BENEFIT (IMPACT)	SOURCE
BUILDING-INTEGRATED PV (BIPV)	Individual	Integrating photovoltaic cells into building components so that the building envelope itself generates power. Enables renewable energy in PEDs even on limited urban roof space, with aesthetic integration.	*Large contribution potential:* BIPV could technically cover ~32% of buildings' electricity demand across the EU *as PV efficiencies improve and building surfaces are utilized for generation.*	EU BuildUp, build-up.ec.europa.eu
SOLAR THERMAL COLLECTORS	Individual	Solar thermal panels (e.g. flat plate or evacuated tubes) that capture sunlight to provide hot water or space heating. Lowers fossil fuel is used for heating PED buildings or can feed into a district heating network.	*Provides majority of heating needs:* A well-designed domestic solar water heater can supply up to ~85% of a home's hot water demand. *In larger systems with seasonal storage, solar thermal can cover 50–97% of annual heat demand for district heating*	Wikipedia, en.wikipedia.org
SMALL WIND TURBINES	Individual	Small-scale wind turbines that generate electricity from wind within the district. Useful PEDs with sufficient wind resource to complement solar generation.	*Notable energy output if sited well:* a ~1.5 kW wind turbine in ~6.3 m/s average winds can produce ~3,600 kWh/year (roughly an average household's annual power use)	US DOE, windexchange.energy.gov
BATTERY ENERGY STORAGE SYSTEMS	Individual	On-site electrochemical storage (home or building batteries) that stores excess solar PV energy or cheap off-peak power for use during peak times or outages. Enhance self-consumption and resilience in PED buildings.	*Boosts self-sufficiency:* adding ~6 kWh of battery storage can raise a household's solar self-consumption from ~20–30% to **over 70%**, *drastically reducing grid dependence and bills.*	NEA (UK), nea.org.uk
HIGH-EFFICIENCY DISTRICT HEATING & COOLING	Collective	Modern 4th-generation district heating/cooling (4GDH) networks that deliver thermal energy at low temperatures (60–70 °C) to multiple buildings. They integrate renewable sources, waste heat, and heat pumps, and use smart controls to maximize efficiency in the PED.	*Lower losses and energy use:* 4GDH systems have ~6% lower distribution heat losses and ~4.5% lower primary energy needs than older systems. *Low supply temperatures also enable use of waste heat (e.g. from data centers) and large heat pumps, further improving efficiency and sustainability*	IRENA, irena.org
THERMAL ENERGY STORAGE	Collective	Large-scale heat/cold storage for the district (e.g. hot water tanks, borehole or aquifer thermal energy storage (ATES), ice storage). Stores surplus thermal energy (from solar or waste heat) for later use, adding flexibility and seasonal balance to PED heating/cooling systems.	*Enables high renewable heat usage:* one community achieved >90% solar fraction for annual heating using seasonal thermal storage, *dramatically reducing fossil fuel requirements.*	Okotoks Project, okotoks.ca
CARBON CAPTURE & STORAGE (CCS)	Collective	Capturing CO_2 emissions from local energy sources or industries and storing it underground or utilizing it. This helps PEDs neutralize residual fossil carbon emissions and reach climate targets.	*Highly effective at emission reduction:* modern carbon capture systems are designed to trap ~90% of CO_2 from flue gases, *, greatly lowering the carbon footprint of the captured source.*	IEA, iea.org
SMART GRID INTEGRATION	Collective	Deploying smart grid technologies and/or a local microgrid within the PED. Provides real-time monitoring and control of electricity flows, allows integration of distributed renewables, and enables the PED to interact intelligently with the broader grid.	*Increases reliability and renewable uptake:* real-time smart controls allow the grid to operate closer to capacity without sacrificing reliability. *Smart grids minimize outages by isolating faults and let PED absorb more local solar/wind output by managing demand in real time.*	IEA, iea.org

MEASURE	TYPE	DESCRIPTION & RELEVANCE TO PEDS	QUANTIFIED BENEFIT (IMPACT)	SOURCE
DEMAND RESPONSE PROGRAMS	Collective	Systems that encourage or automate shifting of electricity use away from peak periods (through time-of-use pricing, incentives, or direct load control). Engages PED residents/buildings to reduce or delay non-critical loads during grid peaks, improving overall efficiency.	*Significant peak shaving:* robust demand response can lower peak power demand by ~10% on average (and up to ~20+% in some regions). *By flattening peaks, PEDs avoid expensive peak power and reduce strain on the grid infrastructure.*	ACEEE, aceee.org
DIGITAL TWIN & CITY DATA PLATFORMS	Collective	Creation of a digital replica of the district's energy systems (buildings, grids, transport) combined with data analytics. Allow PED planners and stakeholders to simulate scenarios, optimize system design and monitor performance to inform data-driven decisions for energy efficiency.	*Optimizes retrofit and grid planning:* e.g., a digital twin analysis of 5,000+ buildings in Ithaca identified that insulating first limits electrification-driven peak load increase to ~13% (vs 33% with no insulation), *helping avoid costly grid upgrades and prioritize investments for maximum impact.*	RMI/Cornell, rmi.org
EV CHARGING INFRASTRUCTURE	Collective	Deployment of electric vehicle chargers (public or shared) throughout the district, with smart charging management. Facilitates a shift to electric mobility among PED residents and enables charging to be aligned with renewable generation or off-peak hours.	*Enables cleaner transport:* Electric vehicles use ~4–5 times less energy per km than conventional gasoline cars. *Widespread EV adoption (supported by ample charging) significantly cuts transportation energy demand and emissions in the district.*	NREL/AFDC, afdc.energy.gov
VEHICLE-TO-GRID (V2G)	Collective	Integrating bi-directional charging so electric cars in the PED can feed energy back to the grid/buildings when parked. EVs then act as distributed storage, providing peak shaving, backup power, and grid services – enhancing the PED's energy flexibility and renewable utilization.	*Valuable grid resource:* studies show V2G can yield **2–3×** the grid benefits of one-way smart charging. For example, ~300,000 V2G-enabled EVs could provide ~$39 million/year in peak demand reduction value to California's grid. *This reduces the need for peaking plants and can generate revenue for PED.*	EPRI, eprijournal.com
ACTIVE/GREEN MOBILITY INITIATIVES	Collective	PED-level programs and infrastructure that promote walking, cycling, e-biking, and public transit use over private cars (e.g. bike lanes, pedestrian zones, transit incentives, car-sharing). Reduces transport energy consumption and emissions while improving urban livability.	*High impact on emissions:* switching just one daily car trip to cycling cuts an individual's transport CO_2 footprint by ~0.5 tons/year. *If 10% of the population shifts to active travel, overall car emissions drop ~4%. These modal shifts substantially lower PED transport energy use and pollution.*	Oxford Univ., ox.ac.uk