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Replicated Solutions for Positive Energy Districts in Maia, Reykjavik, Kifissia, Kladno, and Lviv

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Abstract

Cities undoubtedly play a crucial part in efforts to mitigate climate change. Many urban areas worldwide have pledged to pursue sustainability shifts by adopting environmentally friendly approaches. In recent years, Europe has seen a notable increase in smart city initiatives and progress toward building more sustainable urban environments. Currently, the idea of Positive Energy Districts (PEDs) is motivating districts and municipalities to move away from conventional practices and strive for greater carbon neutrality. This article examines five municipalities—Maia, Reykjavik, Kifissia, Kladno, and Lviv—that are participating in an active Horizon 2020 initiative. The main goal is to explore how these cities identified and chose the 10 solutions they plan to replicate. Data were gathered via conversations, interviews, and the replication roadmaps prepared by each city. It should be emphasized that every city faces unique conditions regarding political backing, funding availability, technical capabilities, and stakeholder engagement—circumstances that apply universally when introducing innovative, efficient measures. Municipalities throughout Europe and other regions may encounter comparable challenges, so this article also presents the experiences of these five Fellow Cities as they advance toward PED implementation.

Keywords Replication, Fellow, Energy, Mobility, Cities

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Introduction

Urban centers serve as primary hubs for strategies to reduce climate impact across sectors such as energy supply, transportation, construction, manufacturing, and farming [1]. Despite covering just 2% of the planet's surface, cities account for around 40% of global energy use, roughly 70% of greenhouse gas releases, and approximately two-thirds of worldwide energy needs [2-4]. Today, about 55% of the global population resides in cities, a figure projected to rise to 68% by 2050 [5, 6]. The vital function of urban areas in sustainability transformations is also highlighted in Sustainable Development Goal 11, which seeks to create inclusive, secure, resilient, and sustainable cities. The United Nations introduced the New Urban Agenda [4], while the European Union adopted the 2016 Pact of Amsterdam to tackle social issues and integrate urban perspectives into policy-making. Moreover, the European Green Deal specifically mentions cities as key to achieving the EU's goals for climate neutrality and a circular economy [3].

That said, addressing climate challenges is not solely the duty of municipal governments; it also depends on residents acting in various roles—as users, producers, consumers, and property owners. Coordinated citizen actions can significantly influence neighborhoods, organizations, and households, thereby accelerating climate action, stimulating economic activity, and protecting the natural environment [1, 3].

Transforming the existing building inventory, transport networks, industrial operations, and city infrastructure will certainly require substantial funding and a holistic strategy spanning multiple domains, including residential housing, mobility, energy networks, jobs, education, and other municipal services. Such changes promise improved quality of life, new economic prospects, and broader prosperity [3]. Data indicate that the fastest urban growth will occur in low- and lower-middle-income nations, so urban renewal efforts must prioritize disadvantaged populations and vulnerable communities in both cities and rural areas [6].

Positive Energy Districts (PEDs)

The growing concept of Positive Energy Districts (PEDs) promotes more mindful practices and calls for broad, creative involvement methods along with collaborative creation techniques [7, 8]. According to the Smart Energy Transition (SET) Plan Action 3.2, JPI Urban Europe [9], and the EERA Joint Program on Smart Cities [10], PEDs are characterized as: “Energy-efficient and energy-flexible urban zones or clusters of interconnected buildings that achieve net zero greenhouse gas emissions and generate an annual surplus of renewable energy at the local or regional level. PEDs involve the integration of diverse systems and infrastructures, along with interactions among buildings, occupants, and wider energy, transport, and ICT networks, all while ensuring reliable energy access and high living standards in harmony with social, economic, and ecological sustainability” [8]. The European Energy Research Alliance (EERA) identifies three types: PED autonomous, PED dynamic, and PED virtual [11, 12].

Alongside PEDs, Positive Energy Buildings (also known as Plus Energy Buildings, or PEBs) play an essential role in combating climate change. These are high-efficiency structures that generate more energy than they use. However, defining PEBs remains challenging due to issues such as renewable energy sources, temporal boundaries, emissions accounting, and building categories. Like PEDs, PEBs lack a clear universal definition, resulting in limited technical options and viable business frameworks to support their rollout [13].

Literature review

The majority of current PED initiatives are pioneering trials conducted on a limited scale. To meet demanding climate targets, a central issue is determining which solutions can be expanded significantly and transferred to other locations [14]. The Smart City Information System (SCIS) defines PED replication as the ability to transfer or adapt outcomes from a demonstration site to different geographic contexts with varying constraints [15]. Essentially, a successful pilot PED in one area can be applied to others—locally or internationally—provided the surrounding conditions are appropriately adjusted. Replication might also involve adopting the governance methods or stakeholder collaboration frameworks from the original project.

From 2014 to 2019, the European Commission’s Horizon 2020 smart cities program (EC-H2020-SCC) supported 17 Lighthouse projects, engaging 46 Lighthouse cities that trialed nearly commercial-ready technologies in energy, mobility, and ICT at the district level, together with 71 Fellow Cities that created plans to adopt solutions from those Lighthouse sites [16]. Early projects (starting in 2014) adopted a fairly rigid, one-directional replication model in which Lighthouse cities largely guided the process with minimal input from Fellows. Later initiatives shifted toward more interactive and adaptive methods by: (1) including Fellow Cities from the outset [17–23]; and (2) facilitating knowledge sharing via workshops, focused online sessions, and collaborative events [24–27]. Even so, several barriers can hinder broader replication: (1) weak alignment between the technology and local stakeholder priorities; (2) reliance on routine practices and narrow short-term perspectives [28]; (3) highly specific local conditions; (4) regulatory constraints; and (5) insufficient political dedication to urban change [29]. In response, Calzada [16] proposes a City-to-City Learning Program grounded in social innovation, which accounts for diverse urban actors (whether Lighthouse or Fellow) and stresses multidirectional, networked, adaptive, iterative, and inclusive learning within city networks [30–32]. Similar views appear in Bartels [33] and Calzada and Cobo [34], who argue that social innovation helps reinforce profound change and supports learning pathways in smart urban governance.

van Summeren *et al.* [35] argue that joint production, use, storage, handling, and exchange of energy are vital for socio-technical shifts. Yet in practice, many activities remain disconnected and fail to advance energy transitions. Limited evidence exists on the mechanics of replication or on the viewpoints of the involved parties. Their research on community-based Virtual Power Plants (cVPP) shows that straightforward copying is rarely effective; instead, success lies in blending processes that promote wider adoption [35]. Overall, detailed practical insights into replication remain scarce, and most discussions stay theoretical [36, 37]. There is especially little documentation of how replication unfolds in real settings or what drives the actors involved [36–38]. Grassroots efforts, in particular, tend to focus on solving immediate local needs rather than pursuing expansion, spread, or systemic overhaul [39–41]. Rodriguez-Calvo *et al.* [42] investigated scaling and replication potential for smart grid applications, using scalability and replicability analysis (SRA) to predict outcomes when applying solutions at larger scales or in new settings. Hearn [43] assessed how PEDs could alleviate energy poverty. García-Fuentes *et al.* [44] evaluated the capacity of 41 European cities to adopt the REMOURBAN sustainable regeneration approach. Pulselli *et al.* [5] conducted roadshows across 10 cities inside and outside Europe as part of the EU City-zen project to kickstart energy shifts, using expert-led co-working sessions, participatory workshops, and visual tools on energy planning, urban form, and carbon tracking to make the process engaging, adaptable, and inclusive [5]. Talmar *et al.* [45] built on Calzada [16] by introducing embedded replication potential—a project’s inherent ability to scale locally or transfer to other contexts—and developed a checklist tool to evaluate this potential in smart city initiatives. Sista and De Giovanni [46] identified four main factors influencing scalability in urban logistics: financial, technological, stakeholder, and legal/regulatory. Paalosmaa and Shafie-Khah [47] analyzed mobility options for replication in Vaasa within the IRIS project, identifying vehicle-to-grid and second-life battery systems as highly suitable given the city’s climate ambitions. Building energy optimization continues to attract attention; Baghoolizadeh *et al.* [48] demonstrated 17%–34% reductions in electricity expenses through optimized solar shading and PV tilt angles, especially valuable in locations farther from the equator. Rasool *et al.* [49] proposed a techno-reliability framework that integrates reliability limits into the design and operation of hybrid renewable systems. Reinert *et al.* [50] outlined an approach for optimizing and evaluating sector-integrated national energy systems via dynamic Life Cycle Assessment (LCA).

Purpose of the paper

This article builds on prior work concerning the five municipalities—Maia (Portugal), Reykjavik (Iceland), Kifissia (Greece), Kladno (Czech Republic), and Lviv (Ukraine)—involved in the ongoing Horizon 2020 project titled Sustainable Energy Positive and Zero Carbon Communities (SPARCS) [51]. The SPARCS initiative includes two Lighthouse cities (Espoo and Leipzig) and five Fellow Cities. Lighthouse cities, selected only once, serve as demonstration models in fields like building retrofits for efficiency, renewable integration, electric transport, and ICT applications [52]. Fellow Cities, which often need additional technical support to reach Lighthouse status, gain valuable experience that may position them to become future Lighthouses.

The present study extends an earlier analysis [53] that evaluated the overall energy profiles, local obstacles, and readiness of these five cities to implement Positive Energy Districts. Here, the focus shifts to detailing the 10 PED-related solutions selected for replication across the cities, along with the collaborative co-creation procedures that guided their selection. This is the first publication to outline the replication activities of these particular five cities, while illustrating each one’s unique approach to co-creation and decision-making. Table 1 provides a summary profile of each city.

Table 1. Overview of the Fellow Cities: Maia, Reykjavik, Kladno, Kifissia, and Lviv (adapted and updated from [53]).

City	Maia	Reykjavik	Kladno	Kifissia	Lviv
Climate type (Köppen–Geiger classification)	Warm and temperate (Csb)	Marine West Coast Climate (Cfc)	Warm and temperate (Cfb)	Mediterranean climate (Cfa)	Humid continental (Dfb)

Proportion of energy demand met by renewable sources (RES)	26.5%*	100	5%	-	-
Proportion of electricity demand met by RES	45%	100	4.75%	-	-
Types of renewable energy utilized	Hydro, wind, solar	Hydro, geothermal	Solar, partial hydro, wind	Solar (water heating)	-
Other energy sources	Natural gas, oil	None	Coal, natural gas	Coal, natural gas, oil	Natural gas (heating)

Note: The percentage of renewable energy used in Maia is influenced by the national electricity generation (and import) infrastructure so it can vary over time. The current value provided is an estimate. Kifissia currently has no renewable energy production, but public PV systems are being introduced through the SPARCS energy community. Lviv does not produce renewable energy locally; it is part of the national Ukrainian energy grid, and specific data for Lviv is unavailable. However, Lviv uses natural gas for heating.

Materials and Methods

This section describes the series of steps that enabled the cities to understand their unique characteristics better and make informed decisions about suitable solutions for creating Positive Energy Districts (PEDs). This work was carried out over two years and includes efforts from the City Vision 2050 initiative, as well as an analysis using the Morgenstadt framework, developed by the Fraunhofer Institute for Applied Research (Figure 1).

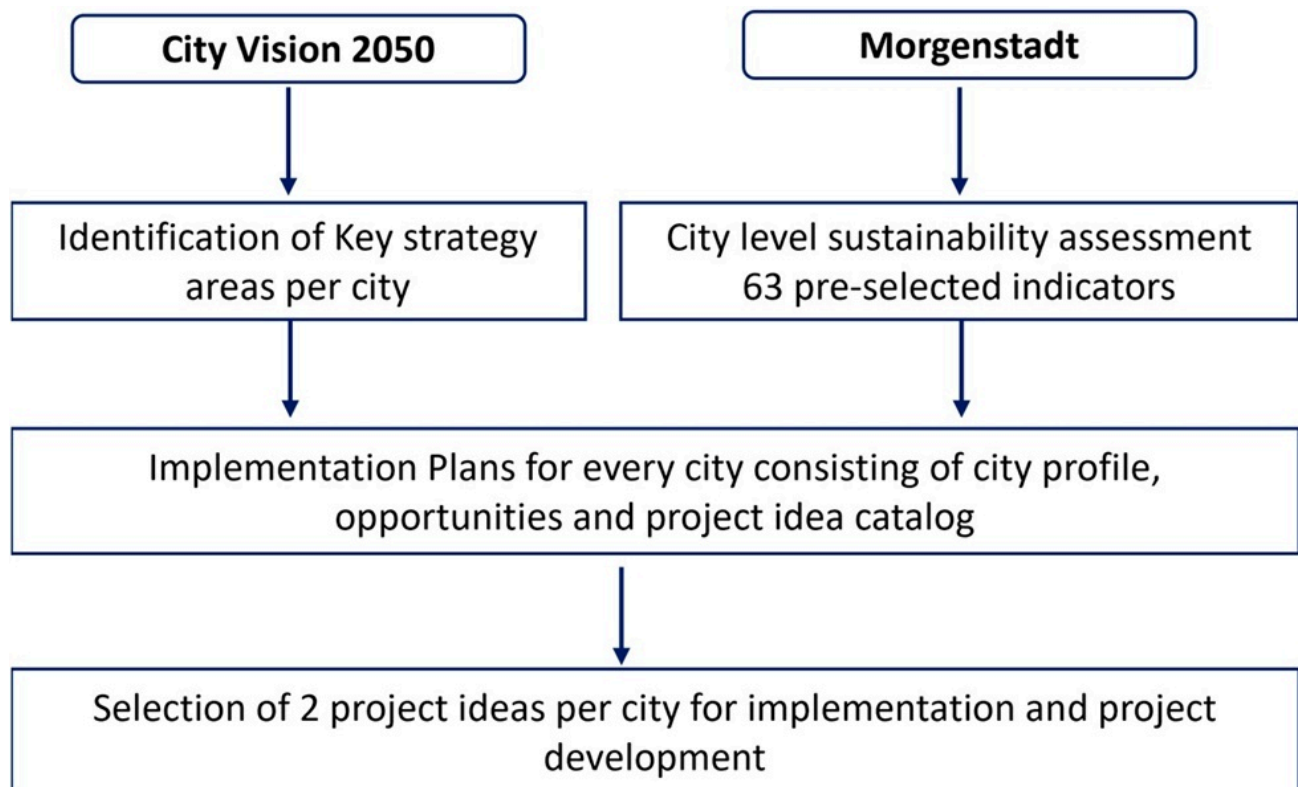


Figure 1. Method used to determine the number of solutions per city.

City vision 2050

The City Vision 2050 initiative focuses on critical strategic domains, particularly energy systems and transportation/mobility, while also encompassing interconnected sectors. The process actively involves political decision-makers, key stakeholders, residents, and community groups in jointly shaping a feasible, forward-looking urban vision [37]. At its core, such a vision seeks to answer: What kind of future do we want for our city? It represents the foundational stage for driving meaningful change and is generally led by elected officials, grounded in inclusive and participatory engagement methods.

Between September and November 2020, dedicated vision-building workshops took place in the five participating cities—Maia, Reykjavik, Kifissia, Kladno, and Lviv—plus the two Lighthouse cities. Each location (including the Lighthouse ones) received comprehensive instructions regarding timeline planning, creation of a dedicated working group, selection of priority thematic areas, evaluation of the present situation, development of inclusive participation mechanisms, and implementation of the vision workshops themselves. Workshop length varied between one and two days depending on local preferences. All sessions were conducted in the respective native languages of the cities. Given the pandemic-related constraints at the time, each city decided whether virtual or face-to-face meetings were more appropriate. The visions developed are intended to be periodically revisited and refined both during the project lifecycle and in the years that follow.

Application of the morgenstadt framework within SPARCS

Originally developed in 2011 by the Fraunhofer Institute for Industrial Engineering (IAO) together with ten other Fraunhofer institutes, over ten city administrations, and several industrial partners as part of a major research effort, the Morgenstadt framework provides a structured approach to sustainable urban transformation. Central to it is the City Lab Methodology, which is continuously refined to better match diverse urban contexts. A detailed account of the methodology can be found in von Radecki [54].

The framework has been successfully applied in various urban settings across Europe, Asia, and South America—for example, in Lisbon (Portugal) [55], Coimbatore (India) [56], and Joinville (Brazil) [57]. Its analytical structure is built on three main layers:

- Key performance indicators (quantitative evaluation);
- Action fields (qualitative evaluation);
- Impact factors (qualitative evaluation).

Through this multi-level assessment, a detailed snapshot of the city's current state is created, revealing both promising opportunities and existing obstacles. It directly answers the question: How sustainable is the city at present? The process also clarifies which municipal data are actually available and yields valuable insights into current priorities, ongoing initiatives, and future potential.

Impact factors capture the unique local conditions—cultural norms, economic structures, climatic realities, and other drivers or constraints—that influence sustainability efforts in each place. This layer allows the overall model to be tailored to each city's specific profile.

Because the SPARCS project specifically targets energy transitions and closely linked mobility solutions, only the most pertinent indicators and action fields were retained from the full Morgenstadt model. Replication leaders from each city reviewed and commented on the proposed selections, followed by a meticulous filtering process to confirm data availability. At the same time, benchmark values for the indicators were validated against global reference sources and adjusted when necessary. The customization of the framework involved intensive desk research combined with multiple

expert workshops; this phase ran from September 2019 (shortly after project kick-off) until early 2021, once all required data had been gathered. An overview of the resulting tailored framework used in SPARCS is presented in [Table 2](#).

Table 2. Two levels of analysis in the Morgenstadt framework.

Level	Description	Examples
Level 1: Indicator assessment	This level evaluates the current status of urban systems through quantitative analysis. From an initial pool of over 100 Morgenstadt indicators [54], 63 were selected for use in SPARCS. Categories for these indicators included: Economy & Governance, Urban Resilience, Zero Emissions, Innovation Leadership, Budget & Finance, Mobility, ICT, and Energy.	• Total city energy consumption (GWh/year) per capita • Proportion of public transport in total traffic • Bicycle path length (km) per 100,000 people
Level 2: Action field assessment	This level involves direct yes/no questions posed to cities regarding their performance in areas such as ICT, Governance, Mobility, Energy, Building Transformation, and Political Dynamics. A total of 35 action fields, comprising more than 100 questions, were defined to assess the city's sustainability efforts and its strategy for addressing challenges while leveraging opportunities. A simple scoring system was used to evaluate the responses.	• Does the city have a long-term strategic vision? (y/n) • Are long-term sustainability goals, such as a 50% reduction in CO2 by 2040, established? (y/n) • Does the city adopt higher building performance standards for its buildings than the minimum required? (y/n)

The information compiled throughout this procedure provided a solid grasp of each city's existing sustainability performance level, which, in turn, served as the basis for crafting a customized profile for each municipality. Throughout, the methodology remained attentive to the particular local factors influencing outcomes—such as social and cultural patterns and the city's physical and environmental setting.

Every piece of insight derived from this stage proved vital in setting the groundwork for the collaborative co-creation meetings that followed with principal stakeholders (covered in the next part). The full sequence of the evaluation steps is illustrated in [Figure 2](#).

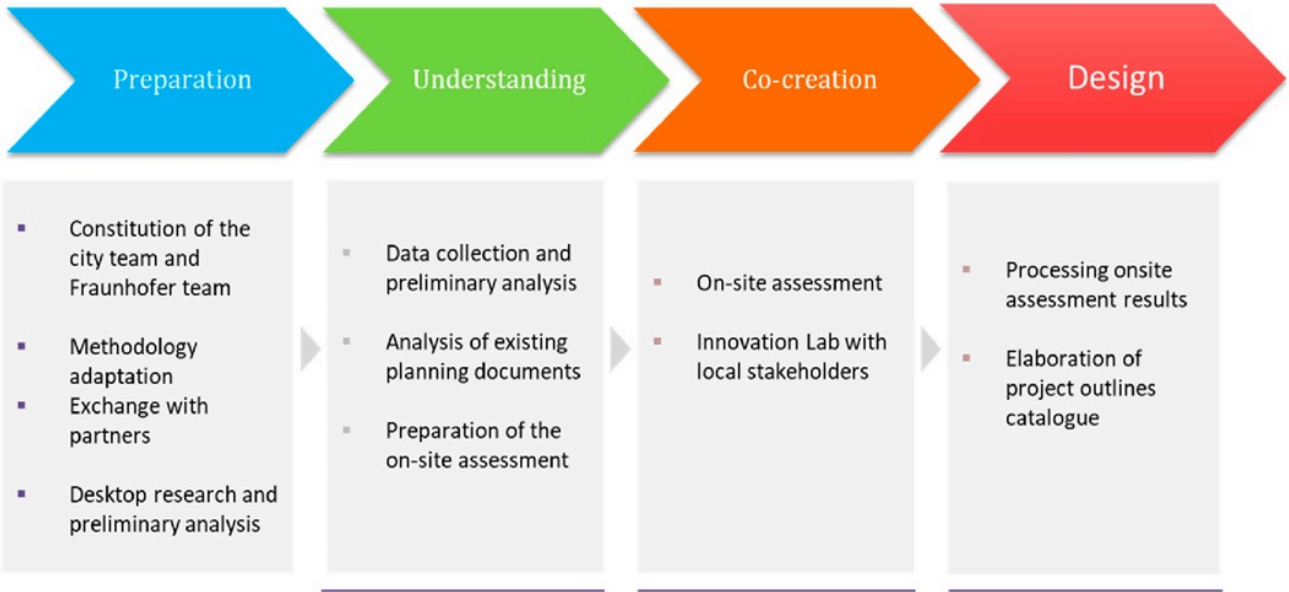


Figure 2. The 4-step City Lab process in SPARCS.

1. The initial understanding stage involved gathering and examining key strategic documents related to the energy and mobility domains. Additionally, the cities supplied the predefined indicators and action areas. Any missing or incomplete data was flagged, shared, and reviewed together with the respective city teams. This process laid the groundwork for developing each city's profile.
2. The co-creation stage focused on conducting remote assessments (due to pandemic-related restrictions) instead of in-person site visits. The primary goal during this phase was the collaborative generation of project concepts, achieved through joint working sessions with local specialists. Because of the online setting, discussions took place using Microsoft Teams and supplementary digital tools, including interactive mapping platforms to pinpoint potential implementation sites, PowerPoint slides for sketching out project proposals, and video footage or documentaries that enabled virtual exploration and familiarization with each city's context. Under the guidance of the Fraunhofer research group, every participating city organized interviews with a broad range of important local actors. It was essential to engage a diverse mix of individuals and organizations to ensure comprehensive coverage of all pertinent topics. Participants included representatives from various municipal departments, academic institutions, citizen groups, private-sector firms, public utilities, service providers, and other relevant entities. The digital tools facilitated rapid idea generation and refinement during the sessions. Ultimately, the outcomes proved just as effective as those achieved in previous live city lab initiatives. The approach proved highly successful, yielding over 10 project proposals per city. A subset of these ideas was then examined more thoroughly and refined during a dedicated innovation workshop, where stakeholders collectively reviewed, validated, and advanced the selected concepts.
3. All information gathered through the interviews and workshop discussions was systematically organized and structured to produce detailed Implementation Plans for each city [58-62]. These plans outline specific project proposals inspired by the experiences of the Lighthouse cities.

Within the design stage, the various project concepts underwent a screening and prioritization process to identify those suitable for in-depth development. The ideas proposed in each city were evaluated using a set of defined criteria (Table 3).

Table 3. Criteria for project selection.

Criteria	Description
Stakeholder involvement	Represents the potential for stakeholder interest or approval, as expressed during interviews.
Regulatory requirements	Identifies whether existing regulations need modification or whether new regulations should be introduced to facilitate project implementation.
Financial feasibility	Availability of funding, whether from public or private sources, to support the project.
Political backing	The degree of political interest and support that can be mobilized to promote and sustain the project.
Alignment with city goals	The degree to which the project aligns with the city's broader objectives and strategic agenda.
Implementation feasibility	The project's complexity and the level of effort required for successful implementation.
Lighthouse project potential	The possibility of the project serving as a model for future initiatives, with potential for wide-scale expansion.

This paper does not aim to present a comprehensive sustainability evaluation for all five participating cities. For an in-depth examination of each city and the complete collection of project concepts, the reader is referred to the dedicated reports [58–62]. Nevertheless, the following section offers a concise summary of the evaluation outcomes. It emphasizes the project proposals that emerged from the combined application of the City Vision approach and the Morgenstadt framework.

Results and Discussion

Over the initial 24 months of the project, the five Fellow Cities engaged in intensive activities to identify and assess solutions that advance their energy transition goals while remaining consistent with SPARCS's broader aims. These efforts were intended to enable effective deployment and eventual replication of Positive Energy District (PED) concepts.

The City Vision 2050 workshops played a central role in clarifying the most important focus areas for each city. An overview of the principal priority domains identified for each location during these sessions is presented in [Table 4](#) [63].

Table 4. Main strategy areas identified in the city vision 2050 (adapted and improved from [53]).

Strategy area	Maia	Reykjavik	Kladno	Kifissia	Lviv
Spatial development	✓	✓	✓		✓
Mobility	✓	✓	✓	✓	✓
Efficient buildings and materials	✓		✓	✓	✓
Green Energy	✓		✓	✓	✓
Digital networks and e-services	✓		✓		
Citizen education and participation	✓	✓	✓	✓	✓
Circular economy (Waste management, etc.)	✓	✓		✓	
Nature-based solutions	✓		✓		

The City Lab methodology outlined earlier enabled a deeper insight into each city's context and generated a range of promising intervention concepts: 35 for Maia, 26 for Reykjavik, 28 for Kladno, 29 for Kifissia, and 8 for Lviv. All proposed solutions align with principles of sustainable urban development and continue to inform the cities' long-term planning processes. However, to carry out the in-depth project elaboration activities stipulated in the SPARCS grant agreement, a rigorous prioritization exercise was required, ultimately limiting implementation efforts to two selected initiatives per city.

Maia

The sustainability review highlighted that Maia is already pursuing multiple Smart City measures to advance its energy transition, most notably through the establishment of the Maia Net Zero Carbon City Living Lab, which seeks to achieve decarbonization by combining diverse technological and systemic solutions. The city also benefits from several well-defined strategic frameworks, including the 2013 Sustainability Strategy, the 2016 Action Plan for Urban Regeneration, and the 2020 Climate Adaptation Action Plan, all of which address broad themes such as public engagement and spatial development. Indicator data indicated a comparatively high rate of residential property ownership, a favorable condition for rolling out large-scale energy-efficiency upgrades. In terms of final energy use, industry accounts for 42% and transport for 38%. Renewables currently cover 45% of electricity consumption. The local authority actively promotes rooftop solar installations, particularly as part of building renovation projects. In the mobility domain, private cars dominate travel (74% of trips), whereas public transport is mainly utilized for commuting to school or work.

Due to pandemic constraints, the field assessment took place remotely in November 2020 and May 2021. Discussions involved municipal leaders, industrial players, small and medium enterprises, and representatives from the priority sectors identified in the City Vision Workshop. Through collaborative ideation sessions involving around 30 specialists, the group formulated 35 candidate project concepts. In May 2021, the application of the project screening tool reduced this list to the following five shortlisted proposals:

1. Enhancement of public transport attractiveness and performance
2. Development and integration of new eco-friendly residential districts
3. Demonstration of a smart grid and virtual power plant within an urban district, incorporating an energy community model
4. Comprehensive digitalization of municipal services and infrastructure
5. Intelligent recovery and reuse of waste heat streams

Reykjavik

Reykjavik's primary guiding documents are the Reykjavik Green Deal and the 2021–2025 Climate Action Plan. Additional supporting policies include the Reykjavik Municipal Master Plan 2040, formally adopted by the city council and the National Planning Agency in January 2022, which sets the spatial and developmental roadmap for the coming twenty years. More recently, the city's inclusion in the EU Mission for 100 Climate-Neutral and Smart Cities further strengthens its commitment to innovative climate solutions.

The remote field assessment occurred in September 2020. Twenty-five structured interviews were conducted with participants from the public administration, technology firms, service providers, academia, and logistics organizations. In place of physical site visits, the team relied on video materials, documentary footage, Google Earth explorations, virtual meetings, and interactive workshops. This process yielded 26 initial project concepts, which were subsequently refined to

ten priority ideas during the concluding workshop in April 2021. A final prioritization vote was conducted at the workshop's close. The ten concepts shortlisted at that stage included:

1. Mobility Hub development
2. Expansion of the electric vehicle charging infrastructure
3. Creation of Green Blocks
4. Launch of a "Reykjavik turns green" / smart mobility application
5. Demonstration projects showcasing energy-efficient buildings
6. Establishment of Reykjavik Environmental Zones
7. Pilot deployment of a smart grid at a Mobility Hub location
8. Implementation of Park-and-Ride facilities
9. Introduction of autonomous shuttle services
10. Promotion of organized car-pooling schemes

Kladno

Kladno's strategic planning rests on three cornerstone documents: the 2021 Sustainable Energy and Climate Action Plan (SECAP Kladno), the 2022 Sustainable Urban Mobility Plan (SUMP Kladno), and the 2021 Sustainable Development Strategy extending to 2050. Like Maia, the city has a very high homeownership rate (83% among residents aged 25+). Renewable sources currently supply only 4.75% of electricity demand, and public transport usage remains extremely limited (averaging four trips per person annually, far below typical global benchmarks of 200–400 trips).

The virtual assessment, conducted in April 2021, brought together 40 stakeholders who collectively generated 30 project proposals. Kladno organized dedicated thematic workshops covering circular economy, smart city and digitalization, public service innovation, water management, and Positive Energy Districts. An additional business-oriented roundtable involved external actors such as banks and financing bodies, offering valuable market realism during the early selection phase. All ideas were designed to reinforce the objectives of the city's SECAP. Through a subsequent evaluation with 35 municipal and industrial representatives, the initial 30 concepts were condensed to eight:

- Comprehensive building retrofitting combined with photovoltaic integration
- Waste-to-energy solutions
- Intelligent parking management systems
- Mobility hubs and enhanced Kladno station areas
- Expansion of electric vehicle charging and shared e-mobility services
- Smart regulatory frameworks

- Deployment of smart metering in municipal buildings
- Development of an urban data platform with associated smart applications

Kifissia

Kifissia supports its climate-neutrality ambitions through instruments such as its Sustainable Urban Mobility Plan, Sustainable Energy Action Plan, electric vehicle charging strategy, and waste management framework. Recent legislative updates facilitate improvements in building energy performance, the adoption of geothermal energy, the formation of energy communities, and the deployment of photovoltaics. Notably, the municipality owns less than 1% of the local building stock, underscoring the need for collaboration with private property owners. Households primarily rely on oil or natural gas for heating and electricity for cooling. Solar thermal systems are common for domestic hot water, though financing obstacles frequently hinder broader uptake. No district heating network currently exists. Private cars account for 72% of trips, walking for 12%, and cycling for 4%.

Owing to COVID-19 restrictions, the Kifissia assessment was conducted entirely online in February and March 2021, resulting in 29 project proposals. Ten targeted interviews were also arranged with staff from the environment and waste departments and with the deputy mayor.

At the concluding innovation workshop, municipal officials, residents, engineers, mobility specialists, and urban planners convened. Time limitations meant only six of the 29 ideas could be examined in depth during the session. The selected proposals were:

- Introduction of a bike-sharing scheme
- Deployment of a fully electric municipal bus fleet
- Implementation of superblock concepts
- Establishment of local energy communities
- Construction of a waste-to-energy facility
- Energy-efficient renovation of privately owned residences

Lviv

The assessment showed that Lviv is a major center of the IT sector, accounting for 20.3% of the local economy. Key urban challenges include poor air quality, severe traffic congestion, scarcity of green and open spaces, and pressure on land and water resources. The establishment of Ukraine's Ministry of Digital Transformation in 2019 markedly accelerated the integration of digital tools into public administration and e-governance. In 2018, the city committed, via memorandum, to achieving a 100% renewable energy share in its energy mix by 2050. The 2020 "Green City" Strategic Plan further prioritizes actions in solid waste management, water protection, transport, building energy use, and land stewardship. Around 95% of housing consists of privately owned apartments. The municipality has introduced various energy-saving measures, including individual thermal metering and weather-responsive heating controls. A portion of the public transport fleet is electrified, and roughly half of the residents rely on public transport daily.

The Lviv field assessment was conducted online due to pandemic measures, yielding 9 project concepts. Several proposals required adaptation in response to the evolving national situation.

The nine ideas initially developed were:

1. City-wide spatial energy planning
2. Smart metering infrastructure and data exchange mechanisms
3. Automated home energy monitoring systems
4. Participatory Positive Energy District framework
5. Large-scale thermal retrofitting of buildings
6. Integration of renewable energy sources in commercial and industrial facilities
7. Optimization and enhancement of public transport services
8. Development of urban rail/city train services
9. Extension and modernization of tram and trolleybus networks

Guided by project goals and pragmatic considerations, each Fellow City ultimately chose two initiatives suitable for detailed development and implementation within the SPARCS framework. Priority was given to concepts that enjoyed clear stakeholder support, credible political endorsement, realistic funding prospects, and could commence within a three-year horizon. Alignment with existing municipal strategies remained essential, while the selections also aimed to showcase the tangible local impact achievable through participation in a large-scale European initiative. The final two projects chosen per city are summarized in [Table 5](#).

Table 5. Finalized project concepts for further development (details in the implementation plans [\[58-62\]](#)).

City	Project concept	Description
Maia	Smart Grid and VPP Pilot at City District with Energy Community	Maia aims to gain experience in smart grids and positive-energy blocks by implementing a PED within a virtual boundary and exploring the feasibility of creating a Renewable Energy Community (REC) in a social neighborhood. The city plans to install and test various Building Integrated Photovoltaic (BIPV) technologies, including traditional BIPV and an innovative approach that integrates solar cells into building fenestration. Given the low cost and potential of photovoltaics (PV), Maia is also exploring new financing mechanisms for PV installations in municipal buildings. These experiments will generate valuable data for further research on enhancing energy flexibility and local generation, as well as strategies for reducing overall energy consumption and identifying replication strategies for the region.
	City Digital Transformation	Maia envisions creating a cross-sector platform to collect, process, and integrate urban data, thereby improving citizen awareness and facilitating strategic decision-making. The city is already collecting data from multiple sources (e.g., air quality, meteorology, energy consumption, street parking) and collaborating with stakeholders (e.g., Mobi.e, e-Redes, Waze, National Bureau of Statistics) to prepare for studies on energy consumption flexibility.
Reykjavik	Mobility Hub	This project aims to eliminate barriers that currently prevent more people from using public transportation. It will create a coordinated infrastructure for multiple transport modes to ease commuting.

	Green Housing Initiative	With evidence that 90% of driving trips are within 3 km, this project focuses on addressing the lack of spaces for social interaction within neighborhoods. It will start with neighborhoods that rely heavily on cars and lack bike paths, promoting eco-friendly streets and creating spaces for community engagement.
Kladno	Clean Energy from a Photovoltaic System with a Business Model	By 2030, Kladno plans to install new rooftop solar panels that will generate 59,410 MWh/year. Hybrid photovoltaic-thermal collectors will also be considered. A key challenge will be ensuring that most of the electricity generated is used within the buildings, with a sufficient battery storage system. Excess electricity can be exported to the grid, sold to other areas, or used for heating through heat pumps.
	Supporting Clean Individual Mobility	Currently, private vehicle use dominates Kladno, and eco-friendly transport is uncommon. The city will introduce a car-sharing system, invest in additional charging stations (currently only five), and promote the use of bicycles, which were partially tested.
Kifissia	Bike Sharing System and Smart Sensors	Kifissia aims to reduce private car use by introducing a bike-sharing system. The city has 14 km of bike lanes, which will be extended and improved. Additionally, air quality monitoring sensors will be installed, providing real-time notifications to citizens when air quality drops, encouraging them to avoid using bikes on polluted days.
	Energy Community	Kifissia is developing an Energy Community with the participation of citizens and municipal staff. The project includes the creation of a photovoltaic park, where members can benefit from the energy generated through virtual net metering.
Lviv	Spatial Energy Plan	Lviv is developing a Geographic Information System (GIS) to collect, analyze, and visualize data on energy potential, supply, and consumption within the city. This tool will serve as a beta version of a digital twin for Lviv's energy infrastructure, helping developers develop algorithms for data analysis and design innovative energy solutions.
	Data-Driven Sustainable Mobility Plan	This software will model traffic flows and calculate CO ₂ emissions from transportation. It will support the justification of mobility solutions and inform the development of sustainable transportation strategies in Lviv.

Research findings indicate that numerous Positive Energy District (PED) projects remain in their initial stages, lacking dependable benchmarks or reference cases, as noted in several prior studies [12, 64, 65]. It is widely recognized that PEDs require a comprehensive grasp of each city's strategies and available resources [66]. Furthermore, cities are inherently distinct [12, 67], with significant differences in governance structures, stakeholder dynamics, and support frameworks [3]. As observed in the initial analysis of the five cities [53], it would be unrealistic to anticipate that every city will resolve all its local issues within the scope of the project. Nevertheless, earlier research consistently identifies governance, technology, funding, and community engagement as the primary challenges cities face [7, 64, 65, 68, 69].

This study examined the early replication phase across the five Fellow Cities—Maia, Reykjavik, Kladno, Kifissia, and Lviv—drawing on ongoing efforts in the two Lighthouse Cities, Espoo and Leipzig. Over the past two years, these five cities engaged in in-depth discussions to identify the most suitable solutions for their municipalities. This extensive co-creation process revealed insights that might otherwise have stayed concealed. The present paper builds on an earlier study that assessed local conditions in these five cities, covering knowledge deficiencies (including smart mobility and e-governance) and challenges across governance, technological, financial, and social domains [53].

The City Vision 2050 serves as an initial catalyst for advancing urban transformation and will undergo ongoing updates, functioning as a foundational reference. Through this vision, the cities identified priority strategic areas for future action (Table 4). Mobility emerged as a critical focus across all five cities, while green energy was prioritized by all except Reykjavik, which already leads in renewable energy adoption. Other prominent areas included energy-efficient buildings, spatial planning, and digital services.

Supported by City Vision 2050 and the City Lab approach, local stakeholders—including utility providers and transport operators—collaborated to evaluate potential solutions based on regulatory feasibility, funding prospects, political backing, alignment with municipal strategies, and current stakeholder involvement levels. This process enabled the identification of projects suitable for implementation within three years. The City Lab methodology also yielded important insights into local drivers, obstacles, and opportunities, leading to a collection of viable solutions aligned with the broader project goals. Due to pandemic-related restrictions, onsite evaluations were conducted virtually, leading to extended online discussions and the need for repeated clarifications of instructions. This occasionally contributed to participant fatigue or reduced motivation. Despite these challenges, the cities made strong efforts to complete the necessary steps to select optimal solutions.

To advance the chosen projects, designated partners held detailed exchanges with SCC1 initiatives better to understand replication processes and the associated tools and methods. These insights were consolidated into a practical toolkit that outlines the entire procedure and the key questions to address to develop robust project concepts and progress toward realization. This also inspired the concept of assigning a dedicated advisor to guide each city through the process, offering recommendations and sharing relevant experiences, particularly in the early phases. Nevertheless, the five cities retained autonomy in selecting the two projects they wished to prioritize and develop further.

Notably, none of the Fellow Cities selected a full PED as one of their top two priorities. Instead, they favored broader city-wide initiatives in green mobility (e.g., Reykjavik, Kladno, and Kifissia) or more targeted projects with varying degrees of relevance to PED deployment, such as community or decentralized energy initiatives (selected by all cities). However, three cities (Kladno, Maia, and Lviv) opted to advance their PED concepts in collaboration with local technical partners. This suggests that PEDs are viewed as highly complex, long-term endeavors that demand sustained local cooperation. It also underscores the value of delivering smaller, quicker successes to capture the interest of politicians and stakeholders. At the same time, the PED concept retains sufficient appeal for cities to allocate additional resources to its design. This highlights the pivotal role of technical support partners as key drivers of PED development, suggesting that cities must tailor solutions to match available expertise and capacity rather than pursuing theoretically ideal options that lack local personnel or skills. Additionally, PEDs may not have been prioritized immediately due to their conceptual complexity, limited awareness of their benefits among decision-makers, perceived technical risks (e.g., achieving a genuine energy-positive balance), and a preference for projects promising stronger returns on investment.

It is also clear that cities tend to favor projects already showing momentum with local technical partners. Preliminary findings from PED feasibility studies in Kladno and Maia indicate that while positive energy balances are achievable in specific building configurations, other economic metrics often lead municipalities to prefer larger-scale building portfolios that may not collectively achieve a net positive renewable energy balance.

The two selected projects per city will now undergo detailed planning and refinement in partnership with a designated project partner. The objective is to help the Fellow Cities transition from drafting Implementation Plans [58–62] to actual implementation. This development process encompasses four stages: 1. preliminary scoping to orient the cities; 2. market engagement to explore technologies and financing possibilities; 3. in-depth planning to define the final scope and business model; and 4. investment mobilization to engage stakeholders and assess return on investment.

As van der Heijden [14] emphasizes, the central issue is how to scale solutions effectively. This study addresses that question through the application of City Vision and City Lab methodologies. The five cities benefited from ongoing consortium support—essential for replication—such as early project involvement [17–23] and regular collaborative

interactions to prevent isolation [24–27]. Given the project's emphasis on energy and mobility, areas like social innovation [33] were not explored as potential future directions.

Nevertheless, this paper addresses key gaps in the existing literature, namely: 1. the scarcity of detailed, evidence-based insights on the topic [36, 37]; 2. the predominantly theoretical nature of replication discussions; and 3. the limited documentation of practical replication processes and stakeholder perspectives [36–38]. By presenting a concrete, actionable pathway for replication—supported by City Vision and City Lab approaches, as well as hands-on project development—this work offers a practical response to these shortcomings.

Conclusion

This paper offers concrete evidence on initiating replication processes in smart cities. Although each city's circumstances differ, all five Fellow Cities demonstrate a strong commitment to climate neutrality and are actively pursuing the implementation of their two selected solutions. The collaborative efforts enabled a thorough understanding of local contexts and facilitated the adaptation of solutions inspired by the Lighthouse Cities (Espoo and Leipzig) to align with each city's vision.

The city profiles developed through the City Labs provided a robust scientific foundation, clearly outlining principal challenges and opportunities in the five cities. Subsequent co-creation workshops with key stakeholders allowed for the tailoring of context-specific solutions, kickstarting significant urban transformation and fostering synergies with existing and planned municipal initiatives.

It is anticipated that this paper will serve as a valuable guide for other cities embarking on their PED journeys. While full sustainability evaluations of the project ideas were beyond the scope of this work, key highlights from each city's proposals have been summarized. Future studies will examine the progression of these ten solutions into fully realized projects and assess the potential for these cities to evolve into leading Lighthouse examples.

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Conflict of interest

None

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Ethics statement

None

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