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Towards Net-Zero Settlements: Barriers, Enablers and Case Studies' Lessons Learnt from the Annex 83

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Abstract

Decarbonisation of urban areas is essential to reaching climate neutrality, as cities house half the global population and account for over 70% of carbon emissions. However, applying innovative approaches, such as establishing positive energy districts (PEDs), remains challenging due to stakeholder engagement and funding constraints, largely driven by knowledge gaps and a lack of best practices. This study examines barriers, facilitators and lessons learnt from six case studies in Europe, Canada and Singapore through a mixed-methods approach, including stakeholder interviews, grey literature analysis and a semi-structured review. Findings highlight district heating networks, heat pumps and photovoltaics as key technologies, with regional variations. While Mediterranean regions prioritise solar energy, northern climates employ a diverse range of solutions, including geothermal and seasonal storage. Political commitment and funding enable progress, whereas regulatory gaps and stakeholder misalignment hinder it. The study underscores the need for sharing best practices to enable PED implementation.

Keywords: buildings; positive energy districts; district heating/cooling; renewable energy sources; systemic enablers; energy and climate policy

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1. Introduction

The global average surface temperature has reached 1.2 °C in 2023 [1]. Consequently, extreme climate events are expected to occur, as outlined in the International Energy Agency (IEA) World Energy Outlook 2023. The risk of disruption in the energy sector is ever-present, facing inflation and elevated fuel costs. Although clean energy investment has increased by 40% since 2020, further efforts are needed. Cities can contribute to these efforts as they are home to 50% of the global population and are responsible for more than 70% of annual global greenhouse gas (GHG) emissions [2]. In fact, as outlined in the report Empowering Cities for a Net Zero Future, the IEA highlights that "Smart cities represent an important opportunity to reduce energy consumption while meeting service demand, improving grid stability and improving the quality of life for all" [3].

Case studies across Europe and Canada, both countries actively implementing measures to achieve climate neutrality, differ in their respective regulatory, financial and social environments. In the EU alone, 75% of citizens live in cities, although cities take up only 4% of the land. Thus, the Cities Mission in the EU is to deliver 100 climate-neutral and smart cities by 2030 [4]. In Canada, there is a variety of climate ambitions among the provinces, yet cities are taking steps towards decarbonisation. However, most cities target achieving climate neutrality in 2050 [5], which is less ambitious than the 2030 target of European cities.

Both European and Canadian cities are pushing towards reducing their GHG emissions by banning natural gas (e.g., Vancouver, Montreal [5], Amsterdam [6]), especially in new constructions and increasing the energy performance of new housing. The reduction also implies offering residential building retrofit programs (e.g., Toronto, Edmonton), implementing district energy systems (e.g., Edmonton, Toronto, Markham [5], Évora [7]) and/or deploying renewable energy sources (RESs) to decarbonise the energy supply (e.g., Halifax, Colchester, municipalities in Nova Scotia [5], Valencia [8], Valladolid [9], Stockholm [10], Amsterdam [6], or Trondheim [11]). In the transport sector, both a change in modal transport (especially active mobility or low emission zones, like Vancouver, Toronto [5], Stockholm [10] and Amsterdam [12]) and electrifying vehicle fleets are key, as in most cities, transport represents at least 25% of the GHG emissions [13]. Globally, the IEA sees as key climate actions to reach the targets: pushing towards clean electrification, energy efficiency and low- or zero-carbon fuels [2]. Singapore is aligned with these actions, with the additional objective of becoming climate-resilient. The strategy adopts a cross-sectoral approach that includes water management, economic growth and green infrastructure, while prioritising increased energy efficiency, reduced energy consumption and the expanded deployment of renewable energy technologies. Where necessary, carbon capture technologies will also be employed [14].

The energy transition at the urban district level requires a perspective that combines technical and socioeconomic aspects, considering the multilevel interactions between the built environment, energy infrastructure, mobility networks, governance institutions and diverse social actors. The effectiveness of such interventions depends on the alignment of regulatory frameworks, financial instruments, institutional capacity and social acceptance, which together constitute the conditions for sustainable implementation. The urgency imposed by short-term climate mitigation goals demands accelerated, integrated and evidence-based interventions, minimising maladaptive or fragmented outcomes.

Consequently, comparative empirical analyses in diverse urban contexts are essential to identify patterns of success and failure, elucidate context-dependent barriers and facilitators and highlight the design of transferable and adaptive strategies. Such analyses ensure that district-level energy interventions are not only technically feasible but also socially legitimate and institutionally implementable, thus contributing substantially to achieving global decarbonisation goals. However, much of the current literature relies on a limited number of cases or focuses primarily on modelling and energy balances. For example, Bruckner et al. analysed energy balances in four cases across different climates [15], but did not examine barriers or enabling conditions. Other studies focus on specific geographic contexts (e.g., Greece) [16] or restrict the evidence base to peer-reviewed publications when analysing success factors for positive energy districts (PEDs) [17]. Siakas et al. reviewed 61 PED projects using the JPI Urban Europe Booklet (2020) and reported drivers, challenges, enablers and ethical considerations [17]. While prior work indicates that pathways to high renewable energy production depend strongly on location and climate [15], the available evidence is often insufficient to explain which enabling conditions made those technical outcomes achievable in practice.

Research Motivation

Bridging the gap between ambitious urban climate targets and their effective implementation at the district scale remains a critical challenge. This study systematically examines the technologies, barriers and enabling factors underpinning the transition of urban districts to positive energy districts and near-zero energy districts. By combining a comprehensive literature review with in-depth interviews across six case studies, the research captures the complex socio-technical and institutional interactions that shape technological choices and project outcomes. Beyond conventional energy performance metrics, the study identifies critical enabling conditions, including governance structures, stakeholder collaboration, community engagement and regulatory and financial frameworks, which determine the success and scalability of district-level initiatives. These findings offer transferable, actionable insights for policy design and large-scale replication, addressing a gap largely overlooked in previous studies and advancing the state of the art in district-level energy transition research.

This article interviews several case studies whose climate targets are summarised in Table 1. Even if climate actions are similar between cities and regions, cities differ in the enabling factors that will allow them to achieve their goals in aspects such as access to finance, expertise and governance, to name only a few [5]. District-based approaches, such as net zero energy buildings (NZEBs), zero energy buildings (ZEBs), PEDs [18], renewable energy communities (RECs), or zero-carbon settlements [19] can help push forward the actions as they are innovation niches that combine multiple actors, creating an ecosystem of trust and ownership of environmentally friendly values [20].

Table 1. Climate targets of interviewed case studies' cities and regions.

City/Region	Climate Target	Source
Okotoks	Achieving carbon neutrality by 2050, while increasing community resilience and quality of life	[21]
Åland Islands	Climate neutral by 2035, with 100% of electricity consumption from fossil-free energy sources	[22]
Singapore	Reduce emissions to around 60 $MtCO_2e$ by 2030 after peaking earlier and achieve net-zero emissions by 2050	[14]
Amsterdam	100% climate-neutral, circular and climate-adaptive city by 2050, with an intermediate 60% CO_2 reduction by 2030 compared to 1990	[6]
Évora	Reduce municipal GHG emissions by 20% per capita by 2020, relative to 2009 levels	[7]
Trondheim	Reduce GHG emissions by 80% by 2030 and transition towards a greener and more circular city	[11]

This study synthesises evidence from the International Energy Agency's Energy in Buildings and Communities (IEA EBC) Annex 83 knowledge base [23] to identify barriers, enablers and recurring technology choices in district-based net-zero initiatives. The primary focus is on PEDs, while also considering adjacent typologies (e.g., net zero building, ZEB and high solar fraction district heating) where practices related to energy efficiency, RES integration and flexibility assets overlap.

This study combines a semi-structured literature search with a review of grey literature to identify case studies, followed by six case study interviews, to assess the factors affecting the success of nearly zero energy initiatives. The latter ones are analysed through structured interviews, categorising the information in terms of technologies, stakeholders involved, goals and context-information with the aim to extract and to examine the factors influencing the choice of specific technologies. Overall, the research aims to answer the following research questions:

- Which are the most frequently reported technologies applied in energy transition in urban areas for district-based approaches?
- What are the most frequently reported barriers and enablers in the urban environment hindering or supporting this transition?

Lessons learnt are explored and so are recommendations for ensuring replicability of innovative urban settlements, emphasising the role of overcoming barriers and community renewable energy ownership as an enabler for district solutions.

2. Materials and Methods

The study starts by reviewing the scientific literature using Scopus [24] and Web of Science [25] databases, using R in RStudio [Version 2023.06.1; Build 524; Boston, USA]. The following strings of search terms were applied to the title field of both databases on 20 November 2023, adapted to the respective syntax:

- Scopus: TITLE (positive PRE/2 energy PRE/2 (district OR neighborhood OR block OR precinct OR settlement OR community OR building))
- Web of Science: TI = (positive NEAR/2 energy NEAR/2 (district OR neighborhood OR block OR precinct OR settlement OR community OR building))

The selection of keywords is based on past research efforts on district-scale energy and emission reduction, such as by Brozovsky et al. 2021 [26] and Bjelland et al. 2024 [27], adapted to fit the specific objective of positive energy. The results were limited to literature in English, the authors' only common language. Furthermore, a grey literature review is performed, categorising the findings into types of urban action and types of technologies applied. The literature is further explored for both existing and simulated case studies, including guidelines, proposed frameworks, metrics and tools. From the grey literature, 39 case studies are collected, identifying which technologies are being implemented and context-information (such as population density and climate). Climate zones are organised using the Köppen–Geiger climate zones classification [28].

Six interview case studies distributed across different countries—Finland, Norway, Canada, Portugal, Singapore and the Netherlands—are analysed. These cases were selected purposively to span diverse contexts (e.g., climate zones, urban settings and enabling environments) and to ensure access to key stakeholders for interviews. The cases also represent different but related typologies, including PED, REC, net zero energy building, or ZEB initiatives.

Although Annex 83 focuses primarily on PEDs, there is substantial methodological and practical overlap across these typologies in terms of energy efficiency measures, renewable energy integration and the deployment of flexible assets. Therefore, the study uses the broader category of district-based net-zero initiatives to investigate technology choices and implementation barriers, while recognising that system boundaries and performance metrics may not be directly comparable across typologies.

Technologies are identified and categorised using keywords, such as photovoltaics (PV), district heating (DH) networks, heat pumps (HPs) and electric mobility (EM), among others (see Table 1). Structured interviews were conducted to obtain information across five domains: (i) energy efficiency, (ii) renewable energy technologies (RET), (iii) energy flexibility, (iv) green and smart mobility and (v) citizen engagement within six case studies:

- **Case 1 (C1): Åland Smart Energy Islands, Finland.** A public–private partnership in the Finnish archipelago, conceived as a living laboratory to test innovative technologies and progress toward 100% RES.

- **Case 2 (C2): Trondheim, Norway.** The ZEB Laboratory at the Norwegian University of Science and Technology (NTNU), designed as a zero emission building (ZEB).
- **Case 3 (C3): Okotoks, Canada.** The Drake Landing Solar Community, designed to achieve a high solar fraction using seasonal thermal energy storage.
- **Case 4 (C4): Singapore.** The School of Design and Environment (SDE4) at the National University of Singapore, designed as a net-zero energy building and reported to achieve net-positive performance through hybrid cooling design and adaptative comfort control [29].
- **Case 5 (C5): Amsterdam, The Netherlands.** A district comprising two building blocks in the Buiksloterham area (former harbour/industrial zone), developed as a positive energy district (PED).
- **Case 6 (C6): Évora, Portugal.** A district comprising three demonstration areas, developed as positive energy districts (PEDs).

Additional information is summarized in Table 2 for reference and to provide context-specific indicators.

Table 2. Contextual descriptors and energy indicators for case studies C1–C6.

Case	C1-Åland	C2-Trondheim	C3-Okotoks	C4-Singapore	C5-Amsterdam	C6-Évora
Objective	PED	ZEB	High solar fraction	Net zero	PED	PED
Objective achieved?	Not yet	Yes	Yes	Yes	Not yet	Not yet
Irradiation	1078.1	849.35	1428.0	1810.1	1785.1	1778.6
Building typologies	Mix-use	Office University lab	Residential	University	Mix-use	Mix-use
Heating needs (MWh/yr)	NA	54.0	760.0	NA	537.0	NA
Electricity needs (MWh/yr)	328,600.0	40.97	21.0	470.7	565.0	5035.0
Wind energy (MWh/yr)	56,200.0	NA	NA	NA	NA	NA
PV energy (MWh/yr)	1000.0	102.0	NA	619.3	165.0	NA
Other energy carriers (MWh/yr)	NA	NA	ST: 706.0	NA	NA	NA

Notes: NA means not available data. Cooling is not included (except electricity consumption for hybrid cooling in Singapore). Okotoks only includes electricity consumption from pumps and heating demand (excluding domestic hot water). Amsterdam only includes the Republica preliminary data from 9 months, which is extrapolated to have one year. Furthermore, total electricity consumption includes electricity use for heat pumps and EV chargers. For ZEB lab gross floor area is 1700 m^2, and it is considered to transform data into MWh/yr, with electricity usage of 24.1 kWh/m^2 and heat pump consumption of 8.8 kWh/m^2 with a coefficient of performance of 3.6.

The interview guide comprised standardised questions aimed at identifying implementation choices and constraints, including the rationale for case selection, the principal barriers to implementation, the energy efficiency, RET chosen and flexibility measures currently deployed, the expected evolution of the heat supply mix and anticipated challenges (e.g., waste-heat recovery and electrified mobility). Interview insights were captured through notes and video recordings.

For each case study and technology domain, interview responses were systematically mapped into four analytical categories: technology descriptors (including acronyms), barriers, enablers and co-benefits. Coding was done by one researcher using the interview notes. A second researcher then checked the coding and any differences were discussed and resolved. To validate the results, interviewers were asked to review the keyword mapping for their case and confirm that it reflected the interview correctly. Reported frequencies therefore, indicate how often topics appeared in the coded interview material, not how common they are across all district-based net-zero initiatives. For example, the interviews include six case studies (referred to in the text as n = 6), while the grey literature comprises 39 case studies (n = 39). Thus, the same process is applied with the grey-literature case studies.

In addition, contextual variables describing local conditions—climatic characteristics and demographic and socio-economic indicators (e.g., gross domestic product and population) from open data sources to support comparative interpretation. Data gathered comprise: Gross Domestic Product (GDP) in million USD (constant prices/PPP, base year 2015) [30], population in 2019, population density (inhabitants per square kilometre) in 2019 [22,31] and irradiation. Irradiation is obtained from PVGIS (yearly horizontal irradiation in kWh/m^2), retrieving the information from each centroid of the district case study using the Python API [32]. These data were used to explore potential relationships between innovation uptake, technology adoption and socio-economic conditions.

The interview materials were converted into a keyword-indexed data set using a predefined coding scheme (see Appendix A, Tables A1–A3). Descriptive synthesis was performed through cross-tabulation of coded categories across cases and technology domains. Pivot-based aggregation (Microsoft® Excel® for Microsoft 365) and custom scripts in Python 3.11.13 (libraries: Pandas 2.3.2 and Plotly 6.3.0) were used to compute category frequencies and generate visual summaries. This approach enabled the identification of recurring barrier–enabler patterns across the full sample, comprising 39 case studies from grey literature and 6 cases derived from interviews. An overview of the methodological workflow is provided in Figure 1.

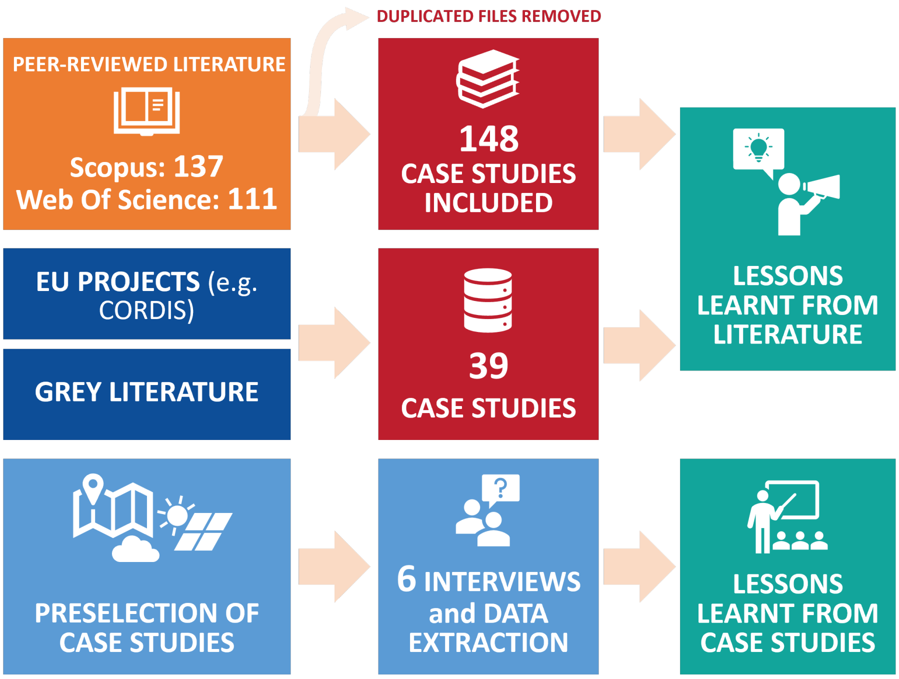

Figure 1. Illustration of methods followed in the literature search and analysis.

3. Results

3.1. Literature Review of Scientific Literature

The findings of the scientific literature analysis indicate that numerous studies have been conducted on PEDs. The importance of the keywords chosen for performing scientific literature analysis, which have been previously introduced, has increased significantly in recent years, with most research work being conducted in Europe. The main outcomes highlight that, overall, the research focuses not only on achieving the PED balance in individual case studies, but also on identifying overarching takeaways as a guide for further development. A total of 137 documents were downloaded from Scopus and 111 from Web of Science. 148 documents remained after duplicate documents were removed. The graph of scientific production, Figure 2, shows a significant increase in research on PEDs, particularly since 2021, with data still incomplete for the year 2023. The reason for the strong increase in publications is presumably also due to the start of the IEA EBC Annex 83 in 2020 [23]. In fact, the main affiliations, displayed in Figure 3, are associated with entities involved in the aforementioned project, such [23] as VTT Technical Research Centre in Finland, Technische Universitat Wien in Austria or the Center for Energy, Environment and Technology (CIEMAT) from Spain.

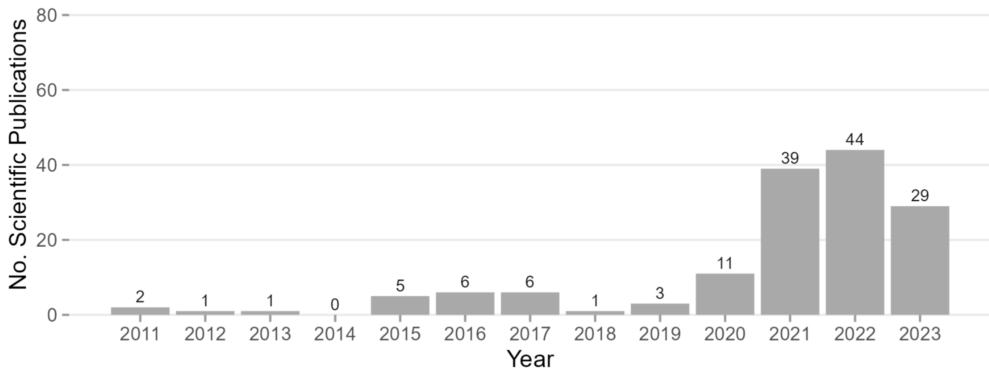

Figure 2. Scientific production of the 148 non-duplicate scientific documents over the years, identified in the literature search of Scopus and WebofScience.

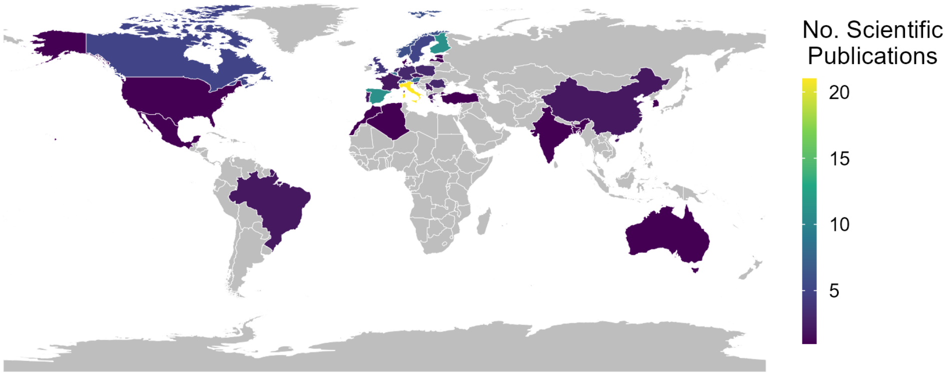

Figure 3. Scientific production and the location of the contributors, identified in the literature search of Scopus and WebofScience.

The content of all accessible documents was reviewed following a preliminary assessment. It was observed that PED research encompasses numerous practical applications of the framework and its principles. Of the 148 studies, more than 40% directly covered actual case studies. More than 10% of the studies were reviews of case studies, methodologies and other related topics, leaving approximately half of all documents that contribute to the development of methods, definitions, frameworks, regulations and similar concepts. Figure 4 shows the scientific reviews performed from 2016 to 2023. The publication of reviews was especially high since 2021, which implies that their content remains largely up-to-date. The move away from the single building scale to the district scale poses additional technical, economic, environmental and social challenges.

The rising interest in PEDs is accompanied by the effort to expand the scope of building-oriented analysis to communities and districts, as highlighted in the results of the literature review presented in Table 3. The research on the topic strives to provide comprehensive guidelines intended to support the transition towards carbon-neutral cities by including all key pillars of sustainability [33]. However, the literature review findings highlight that other factors influencing the operation of PEDs should be considered in addition to mathematical energy and environmental balances [34]. First, scientific works strive to encompass the energy demand for urban transportation and waste disposal [35] as well as the energy needed in outdoor and public spaces [36] beyond the heating, cooling and electricity demand of buildings. Compared to analyses focused on the single-building level, the interactions between buildings pose significant challenges from the technical [37,38], economic [39], and environmental [40], as well as the social [41], point of view. However, these challenges may also turn out to be opportunities [20].

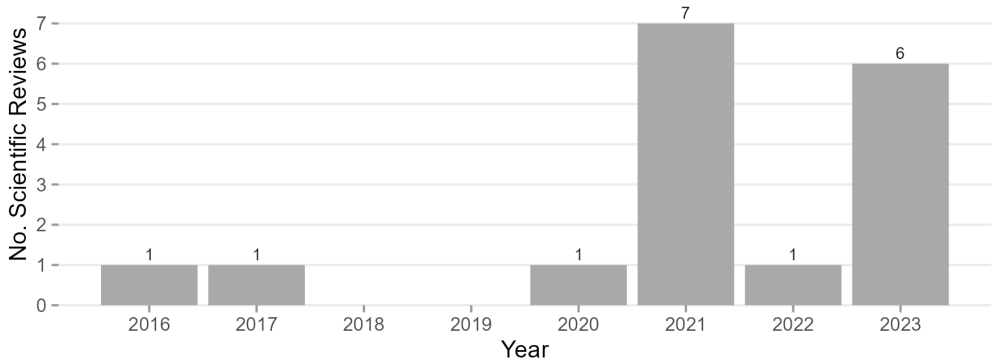

Figure 4. Reviews identified in the literature search of Scopus and WebofScience.

Table 3. Influential literature on positive energy districts (PEDs) and related carbon-neutral district frameworks.

Reference	Main Topic
Laitinen et al. (2021) [42]	Analysis of techno-economic factors affecting the achievement of energy self-sufficiency in districts and communities.
Samadzadegan et al. (2021) [43]	Proposal of a framework for the design of carbon-neutral districts.
Ala-Juusela, Crosbie, and Hukkalainen (2016) [44]	Development of metrics and a tool, including an "energy positivity label," to assess the extent to which candidate areas meet the PED target.
Marrasso et al. (2023) [45]	Analysis of a PED in an industrial area in southern Italy, using simulated and measured energy-consumption data.
Kim et al. (2019) [46]	Performance assessment of an eco-friendly town in South Korea.
Andresen et al. (2022) [47]	Assessment of energy-refurbishment measures and renewable-based plant deployment to achieve a positive energy balance in existing districts.
Erdinç (2023) [48]	Analysis of residential communities supplied by multiple renewable-based energy plants.

3.2. Grey Literature Results (39 Case Studies)

In Annex 83, a grey literature review was conducted, collecting 39 case studies from around Europe and Canada. The collected case data were retrieved from available databases (e.g., in Europe's Cordis database) or the public website of the project. From the website, keywords for each technology are identified, mapped and classified on each case study accordingly. Frequency counts in the analysed corpus (n = 39 grey literature; n = 6 interviews) are therefore analysed (not as statistical prevalence).

Figure 5 illustrates the distribution of mapped energy technologies across the grey-literature case studies (n = 39), by Köppen–Geiger climate classification and population density (as described in Section 2). From this literature review, PV and HPs are the most widely adopted technologies to achieve PED-related concepts, appearing across various climate zones and population densities. Population density influences technology selection, with some technologies (e.g., DH networks) appearing more frequently in denser areas, while decentralised solutions (e.g., PV and HPs) are spread across different population levels. In some cases, especially in northern European regions, the use of wind for energy production is also found.

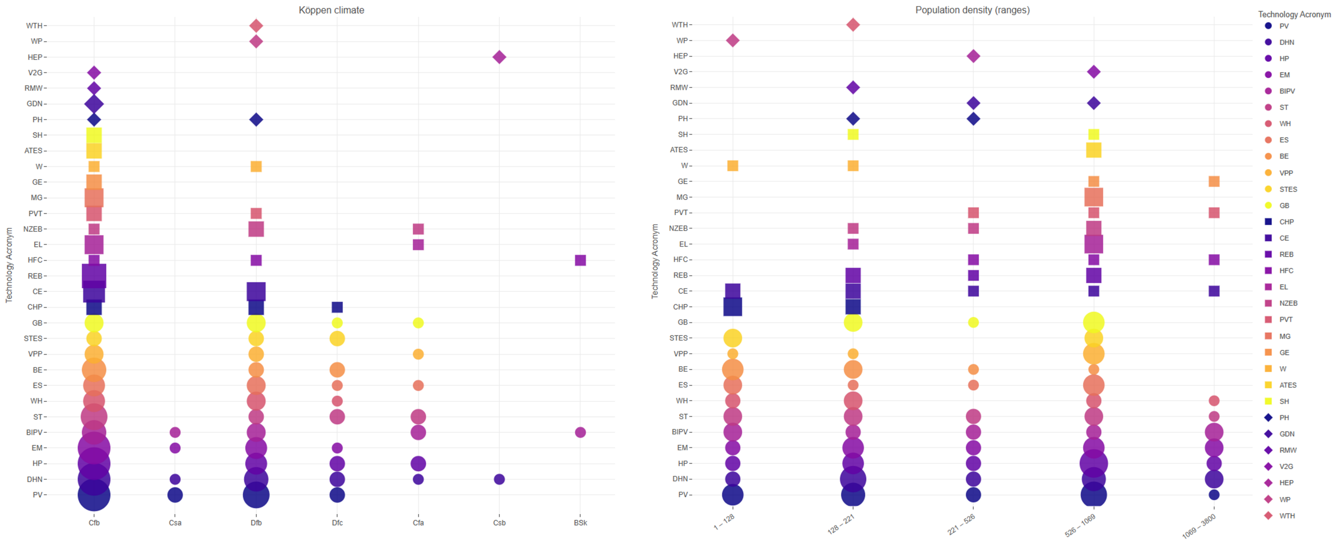

Figure 5. Grey-literature case studies (n = 39): distribution of mapped energy technologies by Köppen–Geiger climate classification and population density.

Dfb and Cfb climates (compared to Csa or BSk climates—see characteristics in Table 4) show the highest diversity across supply, storage, networks, and flexibility technologies. It could indicate that a heating-dominated context requires system integration across sectors. Thermal networks and "district" solutions concentrate in mid- to high-density ranges. DH networks (and associated system components, such as combined heat and power—CHP—and thermal storage) appears more often in denser bins, while low-density bins are dominated by decentralised assets (PV and HP). Technologies such as seasonal thermal energy storage (STES) or Aquifer thermal energy storage (ATES) are largely visible in colder climates and in non-low-density settings, suggesting that they are pursued where space-heating demand is substantial and district infrastructure is viable. Items like virtual power plants (VPP) or vehicle-to-grid (V2G) show up mainly in mid-/high-density areas, consistent with grid constraints and the higher value of flexibility in urban contexts. However, as the sample is unevenly distributed across types of climates and densities, these patterns should be interpreted as indicative and would benefit from normalisation by the number of cases per climate and density category.

The 10 most repeated technologies are PV, HPs, DH networks, electric mobility, building-integrated PV, solar thermal, electric storage, waste heat use, bioenergy, and VPPs.

Table 4. Climate types for winter (W) and summer (S) and key characteristics [28].

Type	Name	Temperature (W/S)	Precipitation
Dfb	Humid Continental	Cold/warm	No dry season
Cfb	Temperate Oceanic	Mild/warm	No dry season
Csa	Mediterranean	Mild/hot and dry	Summer drought, rainy winter
BSk	Cold Semi-arid	Cold/warm (dry)	Semi-arid steppe

3.3. Interview Results (6 Case Studies) and Literature

Semi-structured interviews are performed covering the six case studies. For clarity, the six case studies are referenced using identifiers C1–C6, corresponding to the cases listed in Section 2.

According to the results obtained from the interviews, PV, HPs, and DHN are the most widely used technologies across the interviewed case studies (Table 5). In contrast with the grey literature review of case studies, these technologies (PV, HPs) are widespread across climates and densities, except in case C6. DH networks appear in C1 (Dfb, 18.3 inh/km²), C3 (Dfb, 1753.3 inh/km²), and C5 (Cfb, 864 inh/km²), indicating that DH networks deployment in this sample is not exclusively associated with dense urban form. The differences with the grey literature could indicate that with the necessary budget, policies or ambition these technologies are implemented.

Table 5. Technology-related information across case studies (C1–C6).

Information	C1—Åland	C2—Trondheim	C3—Okotoks	C4—Singapore	C5—Amsterdam	C6—Évora
Climate	Dfb	Dfc	Dfb	Af	Cfb	Csa
GDP	1389	14,395	60,747	349,820	209,154	33,308
Pop. density	18.3	44.0	1753.3	7	864	43
Energy efficiency	–	ZEB	–	CE	NZEB	CE, NZEB
RES	BE, GE, PV, ST, W	PV	ST, PV *	PV	PV	BIPV, PV
Energy infrastructure	DHN	–	DHN	–	DHN	–
Energy storage	ES, HFC *	PCM	STES	–	ES, ATES	ES
Energy System components	CHP, EL, HP	HP	GB, HP *	HP, EL	HP	EL
Mobility	EM *, V2G *	–	–	–	–	EM
Smart technology components	FLEX *	–	–	–	FLEX	FLEX, PLA

Note: Asterisks (*) indicate future technologies that have not yet been installed but are included in the assessment. Singapore's HP is an air conditioning system that considers hybrid cooling with adaptive comfort.

Smart technologies are also a component added in half of the cases, where flexibility measures are employed to exchange energy with the power grid more efficiently, and data platforms are utilised. Efficient lighting (EL), NZEBs, electric mobility (EM), circular economy (CE) principles, and electric storage (ES) are also considered. The ten most frequently reported technologies in the interview case studies (n = 6) are summarised in Figure 6.

The Drake Landing Solar Community, Okotoks (C3), was implemented as a high-profile solar thermal DHN demonstration with a STES to store energy in summer and provide space heating for 52 detached homes in winter [49]. The project was a research project and had a successful implementation for 17 years, achieving a high solar contribution during winter. The large funding (7 million Canadian dollars) that has made possible its implementation was largely supported by public-sector funding. Homeowners pay around USD 60/month for solar-based space heating [50]. According to a survey performed in [51], respondents would have paid a premium above the market price of their home to support the system.

In the Singapore case (C4), reducing the cooling load was crucial to achieving the net concept. A hybrid cooling approach, based on a single-pass fresh-air system and adaptive comfort, was described as one of the innovative design features supporting Singapore's alternative to conventional air-conditioning systems. The interviewee also noted that the concept was extended from SDE4 (Building 4) to SDE1 and SDE3 (Buildings 1 and 3). In addition, efficient artificial lighting (classified as EL in Table 5) and a high-efficiency chilled-water microgrid supplied by the university were implemented, alongside PV electricity generation, enabling energy-positive operation that has been certified for two years.

The Amsterdam case (C5) was developed under an EU-funded project and supported through cooperation between private companies (responsible for battery management), a real estate owner (Republica), and the EU project partners. Amsterdam selected Republica as the pilot site for an energy community managed by a real estate owner, combining an energy-efficient building with PV generation and battery storage. The strategy focused on reducing energy demand as much as possible in order to achieve positive energy performance. In addition, the case assessed the possibility of cooperatively joining a wind energy community to offset part of its electricity consumption. In these interview cases, cold climates (Dfb/Dfc) include more heating-related infrastructure and storage elements, whereas the warm climate (Af) shows a stronger emphasis on passive measures (reduce setpoint temperatures, hybrid cooling, etc.).

The Évora (C6) case selects these technologies in response to clearly defined heritage, territorial, and technical constraints. Its status as a World Heritage city limits the deployment of invasive solutions, leading to the prioritization of integrated and digital technologies compatible with architectural preservation. The existence of three PEDs with distinct urban typologies and consumption profiles justifies the adoption of tailored solutions for historic buildings, rural residential areas, and industrial infrastructures. Moreover, the predominantly electrified local energy system, grid injection limitations, and the objective of achieving energy positivity drive the selection of distributed generation, self-consumption, storage, and flexibility algorithms, supported by previously deployed infrastructures and citizen engagement mechanisms.

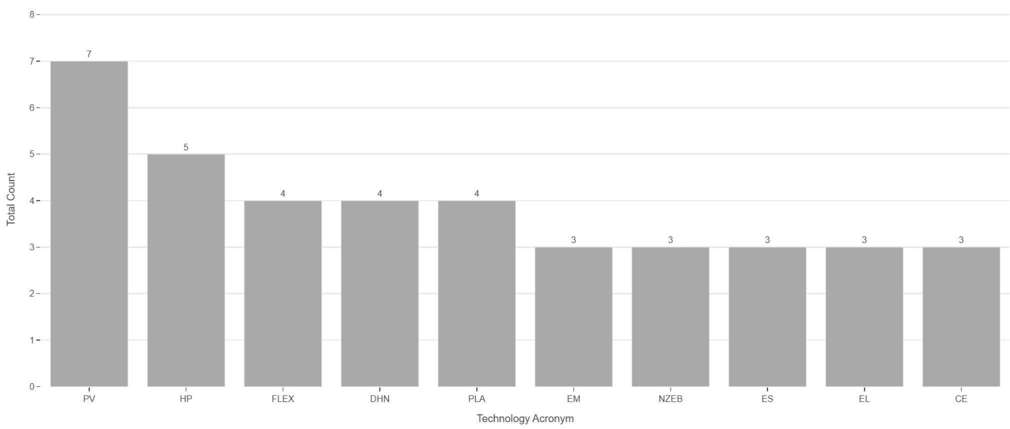

Figure 6. Interview results (n = 6): most frequently reported technologies applied in the coded interview material.

Within the six-case sample, wind-based electricity generation is reported only for Åland (C1), consistent with its "energy island" living-lab orientation. Similar island contexts in Europe also rely on wind as a core renewable resource. On Samsø (Denmark), surplus wind generation is exported and accounted for as compensating residual transport-sector emissions. Tilos (Greece) combines wind with PV and battery storage through a hybrid power station designed to cover a large share of local electricity demand. El Hierro (Spain) integrates wind with pumped-hydro storage, while retaining conventional diesel generation to ensure supply security during periods of low renewable availability [52].

All interview cases (n = 6) highlighted a barrier: the "Complexity of actors/not all in the same agenda". Four out of the six cases also highlighted "Political commitment to innovation" and "Regulation hinders implementation". Half of the cases see as barriers the "Limited budget constraints", "Access to diverse funding sources" and "Infrastructure inadequacies". Two cases faced "Community opposition or scepticism", whereas the other two experienced "effective community engagement". Two saw "public-private partnerships" as a key enabler. The ten most frequently reported barriers in the interview case studies (n = 6) are summarised in Figure 7.

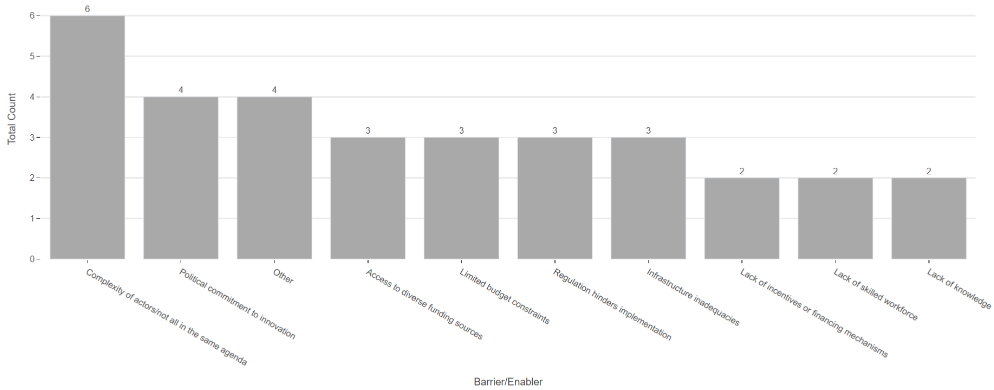

Figure 7. Interview results (n = 6): Most frequently reported barriers in the coded interview material.

4. Discussion

4.1. Which Are the Most Frequently Reported Technologies Applied in Energy Transition in Urban Areas for District-Based Approaches?

Given the heterogeneity of the analysed initiatives (PED/REC/NZEB/ZEB) and the differences in system boundaries and reporting practices, it is premature to infer definitive technology barrier or technology climate relationships. Accordingly, this section reports technologies that are frequently described within the described grey-literature corpus (n = 39) and in the interview corpus (n = 6), rather than implying universal patterns or direct cross-case comparability.

The grey-literature cases suggest that initiatives in Central European and northern climates tend to be more innovative in terms of the portfolio of technologies applied, with a wide variety of energy sources, grids (including microgrids and DHN), energy efficiency, flexibility and (in some cases) green and smart mobility components. Circularity measures are focused on aspects such as rainwater collection, rather than energy generation. In temperate oceanic cases (Cfb), DH network and thermal storage appear more frequently than in the warm-climate cases represented in the dataset. The Dfb climate also has a significant variety of technologies applied, particularly in heating and energy storage solutions, such as heat pumps, seasonal thermal storage, or geothermal boreholes. In Mediterranean cases, the adoption of diverse technologies is lower, focusing mainly on solar and electrification (via electric mobility) with flexibility measures (batteries or peer-to-peer energy management). The literature also indicates that no single technology can cost-effectively provide all flexibility services in high-renewable district energy systems; robust solutions typically rely on combining multiple technologies and strategies across different needs (from fast balancing to seasonal storage) [53].

The interview cases reflect similar qualitative tendencies, while remaining context-specific. For example, the Singapore case appears to focus on reducing energy consumption to the lowest possible level and then implementing PV and hybrid cooling to meet the needs. In the Amsterdam case, the roles of batteries and flexibility are particularly relevant, as they are facing grid capacity restrictions, congestion issues and the need for efficient and fast battery power delivery in short durations. These observations are reported as stakeholder perceptions and implementation choices within the interview sample, and should not be interpreted as performance ranking across typologies.

4.2. What Are the Most Frequently Reported Barriers and Enablers in the Urban Environment Supporting or Hindering This Transition?

Across the interview cases, barriers, complexity of actors and processes are highlighted by all the cases, showcasing differing agendas and priorities. When RES are collectively owned, the distinction between individual ownership and diverse cooperative ownership introduces complexities, potentially leading to management and decision-making challenges. Regulation was frequently cited as a barrier across several interview cases (e.g., Trondheim, Amsterdam, Évora) [20]. Laws often hinder implementation by creating compliance difficulties or lacking flexibility, such as Évora's restrictions in the heritage landscape or Évora's need to reduce net metering possibilities in contrast with making storing electric energy profitable. In the case of Okotoks, the absence of binding contracts to stay connected to the DHN poses a challenge to maintain the sustainability landscape of the district (e.g., people disconnecting and switching back to gas), which is also a risk for investors (undermining the financial viability). In fact, according to the latest news Okotoks project should be dismantled and people switched to natural gas; interviewee mentioned it was a research project with no long-term viability.

Access to diverse funding sources is seen as an enabler in cases like Åland, Singapore and Okotoks, but limited budget constraints or the lack of incentives are noted barriers too. Interviewees also identified infrastructure limitations (e.g., grid constraints and space limitations) as recurring challenges (e.g., Åland, Évora, Trondheim, Amsterdam). Political commitment to innovation was described as an enabler in cases such as Åland, Okotoks and Singapore, whereas resistance to change was repeatedly reported as a barrier (e.g., Trondheim, Åland). The lack of knowledge of citizens (in Amsterdam) and a skilled workforce is a major issue in Trondheim, Okotoks and Singapore, signalling the need for education and training around innovative technologies. This is particularly important for Amsterdam and Évora to engage citizens in reducing peaks, for example, by limiting the times when laundry or charging electric vehicles can happen. Interviewees further reported technology-specific constraints, including the high energy consumption of buildings (Évora), insufficient grid robustness or limited space for renewables (Amsterdam) and the novelty and operational challenges of high-solar-fraction district heating in Okotoks.

In Åland, the island context, low population density, and limited grid interconnection increase the need for local balancing and flexibility solutions. This, in turn, raises coordination requirements among multiple actors (public authorities, utilities, technology providers, and local communities), which can slow decision-making. In this case, stakeholder alignment through the public–private partnership (PPP), together with a stable financing and ownership model, functions as a necessary condition for implementation because they determine whether investments can proceed and be operated over time. Contextual factors, such as island geography, low density, and grid limitations, act as modifiers that shape which flexibility and infrastructure options are feasible and how urgent they become (e.g., wind energy deployment, heat pumps, and options linked to maritime transport using hydrogen). The interviewee also described Åland as a long-standing research-oriented initiative, which has supported the testing of innovative technologies and participation in R&D projects. However, one of the main stakeholders in the PPP has recently entered bankruptcy, which introduces uncertainty regarding future delivery and long-term targets. Recent reporting nevertheless indicates that the initiative remains active, including continued wind turbine installation [54].

Barriers in the Évora case interact in a reinforcing manner rather than acting independently. Heritage and regulatory constraints represent necessary conditions, as they directly determine the feasibility and timing of technology deployment and increase stakeholder complexity, leading to permitting delays and business model uncertainty. Contextual factors, such as urban density, governance arrangements, grid constraints, and social engagement, act as modifiers that shape the intensity of these barriers across different PEDs. Together, these interactions influence the selection, scale, and implementation speed of PED solutions under varying spatial and governance conditions.

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In Okotoks, the project was successful for 17 years, but component issues and increasing maintenance needs from 2020 onwards made operating costs exceed the revenue collected from households, resulting in persistent annual losses that were not financially sustainable. Decommissioning was therefore initiated, with households transitioned off the district system during 2024 and system decommissioning planned to conclude by the end of 2025 [49]. The interviewee also described a structural implementation constraint: households were not required to remain connected, which limited the project's ability to stabilise demand over the long term. Thus, rising operation costs, requirements and reinvestment needs, combined with the absence of a binding connection/retention mechanism, increased demand and revenue uncertainty, weakened the business case, and contributed to the project's long-term viability risk. This illustrates that implementation outcomes can be time-dependent and that governance/contract design and long-term operation capacity can be necessary conditions for shared district infrastructure to persist beyond the demonstration phase.

In Singapore, barriers interact primarily through organisational capacity and coordination. The interviewee emphasised a lack of skilled workforce and limited training focused on integrating innovative solutions to achieve the intended building performance. This interacts with cross-departmental silos, creating actor complexity and weak coordination across departments, which can slow implementation. Political commitment to innovation was described as an important enabler, as the project was designed as a living laboratory to showcase tropical design and engage students. Access to diverse funding sources was also described as an enabler, supporting implementation and providing a degree of autonomy. Contextual factors, such as the hot-humid climate and the resulting importance of cooling performance, act as modifiers that increase the value of the innovative adaptive comfort and hybrid cooling. The ambition to achieve net positivity also led to reducing the energy consumption as much as possible and installing PV.

In Amsterdam, barriers interact through a chain that links infrastructure constraints to market and governance challenges. Grid congestion and capacity limits increase the value of flexibility and storage, but the ability to deploy these solutions depends on regulatory and market conditions that determine whether flexibility can be monetised and included in a viable business case. In a multi-owner redevelopment context, stakeholder complexity further increases coordination effort and can slow permitting and decision-making. Nevertheless, the real estate owner and developer were highly motivated to make the project work, yet this was not sufficient to ensure a smooth process. Technical delivery issues were also reported: the battery system did not perform as expected and experienced multiple technical problems, which contributed to the business-case challenges. The regulatory clarity and a bankable business model function as necessary conditions because they determine whether flexibility and storage investments can proceed and generate returns. Furthermore, EU funding was described as an enabler that improved the financial viability of the initiative. Contextual factors, such as high urban density, space constraints, and the severity of grid congestion, act as modifiers that intensify the need for flexibility and shape feasible system designs, including options to increase renewable generation (e.g., PV or participation in offshore wind arrangements) to support PED ambitions.

In Trondheim, limited central planning and weak municipal commitment, together with political resistance, reduced political support and incentives. Combined with high investment costs and the lack of established business models, this required new contractual arrangements, as part of the research project. Limited knowledge and skills, infrastructure compatibility issues, and the need to adapt solutions to different user needs increased implementation complexity and contributed to performance gaps that had to be managed within the campus boundaries. In this case, clear governance and defined roles, viable financing and business models, and sufficient technical capacity function as necessary conditions. Contextual factors, including the cold climate (heating relevance), the ambition to achieve ZEB, and the single-building setting within a larger campus, reduce stakeholder conflict but increase the importance of robust technical delivery, including a highly insulated building with low embodied emissions, efficient heating solutions, PV integration, and coordination with the overall campus.

As a result, the authors conclude that a transition towards climate-neutral cities that involves innovative settlements such as PEDs requires an integrated approach. Aligning stakeholders, as well as promoting community support, is necessary to ensure engagement and that all parties share the same agenda. Interview cases underline the importance that strong partnerships need to be built to bridge the gap between research, market applications and community needs via forums, PPP (Åland) or multi-stakeholder platforms (such as in Amsterdam). For citizen engagement, interviewees argued that traditional awareness campaigns are often insufficient. Promoting behavioural change and engaging active participants requires co-creation, along with strategies to involve hard-to-reach communities, so that a sense of shared ownership and private investments can be unlocked. Évora, for instance, employed participatory processes to ensure citizens' participation and meetings were held between different stakeholders to facilitate debates and social acceptance. Testing, developing and scaling solutions that are very innovative (such as PEDs or peer-to-peer trading) should be accompanied by a supportive regulatory framework, or, in its absence, urban sandboxes can play a crucial role to test in a controlled environment and to showcase the benefits.

Lastly, in the grey literature and especially for PEDs, a high upfront cost is required, highlighting the need to diversify funding mechanisms and financing instruments. Half of the interviewed cases have had financial help from external funds, driving the innovative settlements. For RECs in the literature review, it is seen that incentives to promote collective self-consumption (feed-in tariffs in Italy and tax bonuses in Spain) have helped in some countries. PV implementation can be the first step towards building financial capacity in households to later invest in HPs or electric vehicles. Financing gaps are also evident at the country level in Europe. As noted in [55], financial innovations (e.g., green guarantees, involvement of public and multilateral banks) are needed to reduce risks and incentivise investment. Multistakeholder investments, such as the ones observed in PEDs, help distribute these risks among actors; however, the co-creation of robust business models that deliver win–win outcomes for all parties involved remains essential and should be a key objective for cities. Finally, the interview cases provide additional detail on capacity-building needs along the stakeholder chain. For instance, Okotoks highlighted the importance that DH networks were and are not common in North America and radiant heating was seen as too much of a novelty, so they had to discard it and go with traditional air emitter systems. The Amsterdam case also highlights the importance of space constraints for renewable energy projects and identifies information technologies as a hurdle for accelerating the energy transition, especially with the lack of a robust grid. Furthermore, Amsterdam sees another hurdle that may discourage developers from implementing advanced energy management systems and large-capacity ES: the lack of support for innovative energy storage systems. Thus, even if the ES is integrated into the system, it currently cannot be included in the business case due to failing the frequency containment reserve test, making it ineligible for frequency regulation services and preventing a viable return on investment.

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4.3. Limitations and Further Work

Although some lessons learned have been extracted, the study has its limitations. For instance, the article did not assess any social outcomes, including housing affordability and social acceptance. Prior research highlights that green infrastructure (re)development can create distributional risks and should be assessed through a just-transition lens, including measures to protect affordable housing (often defined as housing costs below 30% of tenant income) [56].

The capacity of technologies implemented in each case study is not reported and the number of case studies per climate zone or population density category is relatively small.However, sample size of interviewed experts, even if relatively small, is not uncommon in the literature on expert surveys (14 interviews with experts in [57], 23 experts in live voting [58]). This method is useful for exploring experiences and knowledge in the field. Certain climate zones (like Dfb) have more data points than others, which may bias interpretation of observed patterns. In addition, no normalisation by the number of cases per climate and density category or qualitative comparative analysis were performed. The technologies listed represent the actions deployed or recorded by the case study, but that does not represent all options available for that climate type. Therefore, the results should be interpreted as descriptive evidence of what is reported in the analysed sources, rather than as causal inference about necessary or sufficient conditions.

Further case studies should be reported in future studies with similar structured data. Nevertheless, our study remains ongoing, with plans to expand the analysis in the future by incorporating additional case studies and analyses, such as through collaboration with the COST-ACTION 19126 PEDEU-NET PED database [59]. Furthermore, some aspects revealed further need for research, such as the coverage of urban transportation and waste management, as well as a focus on outdoor and public spaces in future cases. Finally, the literature search was conducted on 20 November 2023; therefore, more recent publications may report additional case studies that are not captured in this review.

5. Conclusions

The energy transition towards climate-neutral cities necessitates a holistic approach, in which lessons learned from other case studies are required to avoid making the same mistakes and improve the local ecosystem. This will allow sharing good practices, reducing risks and facilitating and unlocking private investments. Drawing on the IEA EBC Annex 83 grey-literature set (n = 39) and six interview case studies (n = 6), this paper synthesises lessons learnt to support policymakers and practitioners in designing and replicating district-based net-zero initiatives. The main conclusions are:

- PV and HPs, followed by DHNs, were most frequently reported as enabling technologies across the analysed cases (grey-literature corpus and interviews). Storage becomes a dominant solution when grid capacity constraints and/or seasonal winter–summer imbalances limit direct renewable integration, increasing the relevance of both thermal and electrical storage. Observed climate- and density-related patterns should be interpreted as indicative only, given the uneven distribution of cases and the heterogeneity of system boundaries.
- Interview cases showed that political commitment, access to funding and stakeholder coordination are associated with progress on project implementation, whereas regulatory uncertainty and fragmented actor agendas delay the progress of the projects. Long-term lifecycle of innovative projects and risks should also be accounted for when designing such innovative projects, to ensure long-term reliability and financing. Bankable business models and supportive regulatory conditions are therefore central to long-term delivery.

- Across the interview cases, contextual modifiers such as climate, urban density, grid constraints, and planning restrictions influence which technical options are feasible and which barriers become dominant. The most recurrent necessary conditions included substantial funding availability (often linked to R&D programmes), strong stakeholder coordination, and political commitment.
- Practical implication: Cities seeking replication should prioritise governance alignment and bankable business models early, then tailor technology choices to local climate, density and grid conditions.Social acceptance and potential social risks, including housing affordability considerations, should be incorporated as part of the broader assessment of implementation conditions.
- Limitations and future work: A unified performance comparison (e.g., Life Cycle Cost of Energy -LCOE, payback, CO_2 per investment) was not feasible due to inconsistent cost data; future Annex 83 updates would benefit from standardised reporting templates that support improved comparability (including normalisation) and include social and affordability indicators as optional add-ons.

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Institutional Review Board Statement: During the development of these activities, the potential ethical implications were assessed and monitored. Based on the minimal-risk nature of the study and the fact that the interviews addressed professional and organizational practices (and not sensitive personal data), it was concluded that no further approval by an external Ethics Committee/IRB was required, only follow-up our institutional procedures and applicable regulations. The information processed and reported in the manuscript was handled in accordance with applicable data protection requirements (including the GDPR). The data collected focused on non-personal and non-sensitive information, such as project-level barriers, enabling factors, governance approaches, and the implementation of policies or internal practices. Participation was entirely voluntary. Interviewees were informed in advance about the purpose of the study, how the information would be used (including scientific publication), and their right to decline to answer any question or withdraw at any time. Informed consent was obtained via email confirmation and/or verbally at the start of each interview.

Informed Consent Statement: Informed consent for participation was obtained from all subjects involved in the study.

Data Availability Statement: Anonymised data available upon request.

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readability of the text. The authors have reviewed and edited the output and take full responsibility for the content of this publication.

Conflicts of Interest: Authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

RES	Renewable energy source
ZEB	Zero emission building
NZEB	Nearly zero-energy building
PH	Passive house
CE	Circular economy
PV	Photovoltaic
BIPV	Building-integrated photovoltaic
ST	Solar thermal
W	Wind
BE	Bioenergy (fuels from biomass)
GE	Geothermal energy
DHN	District heating network
ES	Electrical energy storage (battery)
HFC	Hydrogen fuel cell
PCM	Phase-change material
STES	Seasonal thermal energy storage
ATES	Aquifer thermal energy storage
CHP	Combined heat and power
EL	Efficient external lighting
HP	Heat pump
GB	Geothermal borehole
EM	Electric mobility
V2G	Vehicle-to-grid
FLEX	Flexibility to grids (demand response, etc.)
PLA	Information and Communication Technology (ICT) platform

Appendix A

Note: Additional keywords used for technology mapping are provided in the Appendix A.

Table A1. Technology categories, acronyms and descriptions.

Category	Acronym	Description
Energy Infrastructure	DHN	District Heating Network
Energy System Components	HP	Heat Pump
Energy System Components	CHP	Combined Heat and Power
Energy System Components	EL	Efficient External Lighting
Renewable Energy Devices	ST	Solar Thermal Collectors
Renewable Energy Devices	PV	Photovoltaic Module (private building)
Renewable Energy Devices	PVI	Photovoltaic Module (community infrastructures)
Renewable Energy Devices	PVT	Hybrid Collectors
Renewable Energy Devices	BIPV	Building Integrated Photovoltaic
Renewable Energy Devices	W	Wind Power (>30 kW)
Renewable Energy Devices	MW	Micro Wind Power (<30 kW)
Renewable Energy Devices	BE	Bioenergy (fuels from biomass); includes solid biofuels, biogas and liquid biofuels
Renewable Energy Devices	WP	Tide, Wave, Ocean Power

Table A1. *Cont.*

Category	Acronym	Description
Renewable Energy Devices	MHEP	Micro Hydroelectric Power
Renewable Energy Devices	HEP	Hydroelectric Power
Renewable Energy Devices	RMW	Renewable Municipal Waste
Renewable Energy Devices	WH	Waste Heat
Renewable Energy Devices	GDN	Geothermal District Network
Renewable Energy Devices	GB	Geothermal Borehole
Renewable Energy Devices	GE	Geothermal Energy
Renewable Energy Devices	ATES	Aquifer Thermal Energy Storage
Smart Technology Components	MG	Microgrid
Smart Technology Components	VPP	Virtual Power Plant
Smart Technology Components	PA	Phone App for citizens
Smart Technology Components	PLA	ICT platforms
Smart Technology Components	FLEX	Flexibility to grids (demand response, etc.)
Energy Storage	ES	Electric Storage
Energy Storage	STES	Seasonal Thermal Energy Storage
Energy Storage	HFC	Hydrogen Fuel Cell
Energy Storage	TSG	Other thermal storage: water tank, PCM
Mobility	EM	Electric Mobility
Mobility	V2G	Vehicle to Grid
Other Components	WTH	Water Harvesting
Design Parameters	CE	Circular Economy Perspective
Design Parameters	SH	Social Housing
Design Parameters	ZEB	Zero Emission Building
Design Parameters	PH	Passive House
Design Parameters	NZEB	Net Zero Energy Building
Design Parameters	REB	Retrofit Efficient Buildings
Fossil Fuels	O	Oil
Fossil Fuels	NG	Natural Gas
Fossil Fuels	C	Carbon

Table A2. List of co-benefits considered in the analysis.

Co-Benefits
Climate adaptation
Climate mitigation
Local economy enhancement
Financial savings for citizens
Increase employment rate and jobs
Decrease future maintenance costs
Social cohesion (gender, minority groups)
Enhance citizen participation, connectivity and community
Improve access to information and social capacity building
Raise awareness and behavioural change
Improve air quality
Reduce noise pollution
Reduce hot spots and urban heat islands
Enhance attractiveness of the city
Promote healthier and more attractive lifestyles
Reduce ecological footprint
Greater biodiversity
Waste efficiency
Water efficiency
Food efficiency
Sustainable land use

Table A3. Identified barriers and enablers by domain and type.

Barrier/Enabler	Type	Subtype
Technological advancements	Technical enabler	Enabler
Skill development programmes	Technical enabler	Enabler
Robust infrastructure development	Technical enabler	Enabler
Technological limitations	Technical barrier	Barrier
Lack of skilled workforce	Technical barrier	Barrier
Infrastructure inadequacies	Technical barrier	Barrier
Standards and interoperability frameworks in place	Technical barrier	Barrier
Effective community engagement	Social enabler	Enabler
Building strong stakeholder relationships	Social enabler	Enabler
Transparent and inclusive decision-making	Social enabler	Enabler
Community opposition or scepticism	Social barrier	Barrier
Complexity of actors/misaligned agendas	Social barrier	Barrier
Stakeholder conflicts of interest	Social barrier	Barrier
Poor communication between stakeholders	Social barrier	Barrier
Lack of acceptance	Social barrier	Barrier
Lack of knowledge	Social barrier	Barrier
Supportive policy frameworks	Regulatory enabler	Enabler
Flexible regulations for innovation	Regulatory enabler	Enabler
Incentives for sustainable practices	Regulatory enabler	Enabler
Regulation hinders implementation	Regulatory barrier	Barrier
Complex permitting processes	Regulatory barrier	Barrier
Lack of flexibility in existing laws (e.g., procurement, self-consumption regulation)	Regulatory barrier	Barrier
Political commitment to innovation	Political enabler	Enabler
Strong advocacy for change	Political enabler	Enabler
Consistent political leadership	Political enabler	Enabler
Lack of political or city governance	Political barrier	Barrier
Political resistance to change	Political barrier	Barrier
Lack of political will or support	Political barrier	Barrier
Changes in leadership affecting continuity	Political barrier	Barrier
Streamlined decision-making processes	Organisational enabler	Enabler
Internal support and alignment	Organisational enabler	Enabler
Collaborative organisational culture	Organisational enabler	Enabler
Resistance from within existing organisations	Organisational barrier	Barrier
Lack of coordination among departments	Organisational barrier	Barrier
Access to diverse funding sources	Financing enabler	Enabler
Innovative financing models	Financing enabler	Enabler
Public–private partnerships	Financing enabler	Enabler
Limited budget constraints	Financial barrier	Barrier
Uncertain return on investment	Financial barrier	Barrier
Inadequate funding mechanisms	Financial barrier	Barrier
High risks	Financial barrier	Barrier
Lack of incentives or financing mechanisms	Financial barrier	Barrier
Other		Barrier

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