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Research paper

Understanding novel district concepts: A structured exploration of interdisciplinary clustering in urban energy systems

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ABSTRACT

Recently, there has been a surge of interest in novel concepts for jointly operating devices in urban areas in clusters, motivated by their potential to support decarbonization, enhance power system flexibility, and promote energy justice. Such clusters encompass multiple devices or buildings but operate on a smaller scale than cities. Examples include Renewable Energy Communities and Positive Energy Districts. These Novel District Concepts (NDCs) integrate interdisciplinary urban planning and social sciences terminology into the energy domain. However, these concepts' precise definitions and practical implementation lack consistency, leading to conceptual ambiguities in the literature.

The present paper reviews clustering approaches from both the energy domain and the urban planning and social sciences disciplines to analyze rules for defining device clusters. The findings reveal that while numerous papers claim novelty using Novel District Concepts terminology, many rely on established energy-domain methodologies, such as clustering techniques structured around electricity grid hierarchies. In contrast, clustering approaches from urban planning and social sciences, which employ spatial and social criteria, remain underutilized and lack systematic evaluation for energy system applications.

The present paper's key contribution lies in systematically identifying and differentiating clustering rules, establishing a robust foundation for subsequent cluster-based research, and ensuring methodological consistency. By integrating concepts from urban planning and social sciences with established energy-domain approaches, this paper delineates clear boundaries and grounds them contextually. The present paper's structured methodology provides a comprehensive workflow for distinguishing diverse clustering rules, mitigating the risk of misapplied terminology, and facilitating future evaluations of their applicability to specific energy-system tasks.

1. Introduction

Terms such as Positive Energy Districts (PEDs) and Renewable Energy Communities (RECs) have recently attracted significant attention in the context of urban energy systems (Sassenou et al., 2024; Natanian et al., 2024; Haji Bashi et al., 2023). District-level concepts also play a central role in sustainable urban development initiatives worldwide, as illustrated by projects in Morocco (Echlouchi et al., 2022) and China (Xu et al., 2024). They are further relevant in the United States, Canada, and New Zealand, as reported by Barabino et al. (2023). These Novel District Concepts (NDCs) are predominantly applied in energy-related applications that are inherently tied to devices that produce, consume, store, transmit, or convert energy (Galenzowski et al., 2023a; Haji Bashi et al., 2023). Examples of such devices include photovoltaic systems, battery energy storage systems, electric vehicles, combined heat and power plants, wind turbines, heat pumps, chillers, and thermal energy storage systems (Haji Bashi et al., 2023). In addition to these controllable devices, the urban energy system includes non-controllable residual consumers, such as devices in residential units, offices, and workshops (Galenzowski et al., 2023b). NDCs are associated with a range of anticipated benefits (Caferra et al., 2024; Haji Bashi et al., 2023). Climate action benefits include decarbonization, the achievement of renewable energy targets, and an increase in public acceptance of the energy transition. Technical benefits encompass enhanced power system flexibility, self-sufficiency, and decreased dependence on national grids. Additionally, social benefits include promoting energy justice, fostering job creation, and facilitating investment and energy cost reduction (Haji Bashi et al., 2023).

Due to their interdisciplinary nature, PEDs and RECs are applied across legal, economic, and governance contexts (European Parliament, Council of the European Union, 2019, 2018; Hinterberger et al., 2020).

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Abbreviations

CEC	Citizen Energy Community
EMD	Electricity Market Design
GIS	Geographic Information System
IRIS	Ilots Regroupés pour l'Information Statistique
JPI	Joint Programming Initiative
LV	Low-Voltage
MV	Medium-Voltage
NDC	Novel District Concept
PCC	Point of Common Coupling
PED	Positive Energy District
PV	Photovoltaic
REC	Renewable Energy Community
RED	Renewable Energy Directive
ZCC	Zero Carbon Community
ZEC	Zero Energy Community

The foundational grounding in legislation is presented in Section 1.1. The present paper, however, adopts a technical energy system perspective, focusing on the operational role of NDCs in clustering devices and subsystems within urban environments to enable joint operation and control. These clusters represent an intermediate scale between entire cities and individual devices or buildings (Sassenou et al., 2024; Bauwens et al., 2022). The intermediate scale of the clusters addresses the limitations of single-building approaches by considering building interdependencies and enabling solutions involving multiple stakeholders, such as grid operators and energy producers (Sassenou et al., 2024). It balances the operational complexity of larger urban units while facilitating cross-sector integration, democratic energy planning, and the inclusion of local resources in broader energy strategies. To ensure operational coherence and to achieve the intended benefits, it is essential to define system boundaries consistently and systematically (Albert-Seifried et al., 2022). The legislative context is examined, focusing on this cluster- and boundary-oriented technical perspective, in Section 1.1. As highlighted by Casamassima et al. (2022), an essential aspect of concepts, such as PEDs and RECs, is their interdisciplinary nature, which involves incorporating insights from social sciences to enhance community engagement and foster integrated energy solutions (Bielig et al., 2022) and urban planning (Natanian et al., 2024). In contrast to the extensively studied social impact of technology, the implications of interdisciplinary approaches, encompassing social sciences and urban planning, for the energy system as a technical system remain insufficiently explored. The implementation of NDCs continues to face challenges due to inconsistencies in definitions and the absence of systematic methodologies for establishing operational boundaries, as demonstrated by Sassenou et al. (2024) in the context of PEDs and RECs.

To address these challenges, the present paper makes three main contributions. (1) It develops a methodological workflow for categorizing clustering approaches across energy, urban planning, and social sciences. (2) It identifies and analyzes inconsistencies in interdisciplinary terminology. (3) It also proposes a framework for consistent and scalable cluster definitions, supporting the integration of technical, social, and spatial perspectives in urban energy systems. A detailed discussion of these contributions is provided in Section 1.3.

1.1. Related work

The challenges discussed in the introduction, particularly the lack of consistent definitions and systematic approaches to operational boundary-setting, are also evident in the literature discussed in the following:

The terminology surrounding Renewable Energy Communities and Positive Energy Districts has been strongly shaped by the European Union's key legislative and research frameworks. Relevant are the Electricity Market Design (EMD) Directive 2019/944 (European Parliament, Council of the European Union, 2019), which introduced Citizen Energy Communities (CECs), the Renewable Energy Directive (RED) 2018/2001 (European Parliament, Council of the European Union, 2018), which established Renewable Energy Communities, and the Joint Programming Initiative (JPI) Urban Europe (Hinterberger et al., 2020; Bossi et al., 2020; Gollner et al., 2020), which defined Positive Energy Districts. Directive 2019/944 outlines CECs as legal entities established through voluntary participation and collective control, capable of providing a broad range of energy services, but it does not specify proximity requirements or operational limits. In contrast, Directive 2018/2001 defines Renewable Energy Communities similarly, but it explicitly requires proximity to the renewable energy projects involved while refraining from providing a clear definition of system boundaries. The JPI Urban Europe introduces PEDs as spatially integrated, energy-efficient, and energy-flexible urban areas or groups of connected buildings, emphasizing the importance of well-defined boundaries. However, JPI Urban Europe acknowledges the complexity of boundary definitions and the necessity of further concretization through collaboration with local stakeholders, as guidelines remain under development (Hinterberger et al., 2020).

Beyond the European context, similar community concepts have also been discussed in the United States. For example, Zero Energy Communities (ZEC) were introduced by the U.S. Department of Energy and the National Renewable Energy Laboratory as established concepts (Moghaddasi et al., 2021). Yet, the number of official government documents on these communities is limited. The initial definition dates back to 2015, describing a ZEC as an energy-efficient community where, on a source energy basis, the actual annual delivered energy is less than or equal to the on-site renewable exported energy (Peterson et al., 2015). Similarly, in China, the idea of Zero Carbon Communities (ZCC) appears in policy and research, with pilot initiatives such as the 2021 Shenzhen Implementation Programme and the 2022 national Guide to Building and Evaluating Zero-Carbon Community. More recent standards, including Shenzhen's T/SZS4049-2022 and the 2023 draft Technical Standards for Zero-Carbon Buildings, signal a move toward stronger regulatory support, though a unified national framework is still missing (Zhou et al., 2025). Other countries, such as Nigeria, are pushing community renewable energy through local projects (Kaze et al., 2025). Recent studies highlight the potential of decentralized and citizen-led models to reduce energy poverty and support sustainability. However, legislation and government support structures are still under development (Kaze et al., 2025).

Since the legislative context does not sufficiently clarify boundary-related aspects when viewed through a cluster- and boundary-oriented technical system's perspective, the following section examines relevant research that specifically addresses this dimension.

Albert-Seifried et al. (2022) reviewed key challenges associated with PEDs, including defining boundaries to group devices into districts. They identified five boundary types: physical, political, economic, social, and legal. These boundaries should consider factors such as renewable energy potential, land use patterns, urban built forms, and infrastructure layout. While they described these general criteria, the authors acknowledge a lack of concrete guidance for deriving boundaries. As a result, systematic methods for clustering or partitioning cities into PEDs remain absent, particularly concerning the systematic scaling of such approaches across entire urban areas.

European research projects, such as Cities4PEDs, presented by Schneider (2023), play a leading role in advancing the definition of PED concepts. The authors classified balance boundaries into three types: spatial, temporal, and functional. Spatial boundaries need to be defined such that they do not hinder neighboring districts from achieving the PED status in the future. However, they pointed out that, in practice, determining these boundaries becomes challenging and imprecise, particularly when a more nuanced distinction between different energy services is required. Additionally, the authors emphasize the lack of a uniform definition for system boundaries, complicating their practical implementation.

Sassenou et al. (2024) systematically reviewed the challenges associated with the deployment of PEDs. Their paper highlighted ambiguities in definitions, the absence of holistic design methodologies, and the limited integration of social and environmental dimensions. Their review revealed a lack of interdisciplinary solutions and emphasized the need for clearer boundary definitions and flexible concepts to operationalize PEDs effectively across diverse urban contexts.

Regarding RECs, Bauwens et al. (2022) reviewed the meaning of community in the context of energy systems. They identified that a community can refer to a group jointly investing in energy projects, such as wind turbines, while emphasizing economic and social perspectives. Additionally, the concept of community as a physical place facilitating peer-to-peer energy trading and community-based energy markets is becoming increasingly prominent in the literature. However, despite covering various aspects, the review lacks a systematic examination of the definition of boundaries for these communities.

Haji Bashi et al. (2023) provided a comprehensive review of various RECs, explicitly addressing grid topology as a basis for defining physical boundaries within energy systems. They noted that energy communities can conflict with the natural monopoly of transmission and distribution system asset ownership, requiring regulatory interventions to address these challenges. However, the paper lacks a systematic analysis of the conceptual origins of RECs, particularly regarding the relative influence of energy-domain methodologies versus social sciences and urban planning concepts. Furthermore, a structured evaluation of the practical application of these boundaries is lacking in existing literature.

Bielig et al. (2022) provided a systematic review of the social impacts associated with energy communities in Europe, focusing on constructs such as community empowerment, social capital, energy democracy, and energy justice. They identified a lack of rigorous quantitative evidence and emphasized the need for experimental and longitudinal studies to substantiate assumed social benefits. While they critically highlighted the lack of rigorous quantitative evidence for social benefits, the paper did not address the technical selection of devices for their joint operation within a district. The paper focuses on the social aspects of RECs but lacks an evaluation regarding the relevance of social sciences methodologies to technical energy systems.

1.2. Problem description and research gaps

The present paper identifies several key aspects of the problem and corresponding research gaps. The current body of research lacks a clear, operational definition of spatial boundaries for NDCs, creating ambiguity in practical implementations.

Moreover, the literature falls short in addressing standardization for scalability. Literature on optimization, control, and design in urban energy systems frequently references device clusters but lacks rigorous discussion on scaling these methods beyond single local areas to nationwide application. Standardization of device cluster selection is essential for embedding NDCs in legislation alongside existing well-defined legal rights, for example, in the legal form of RECs or CECs.

Additionally, a comprehensive inventory of clustering rules used in current publications is missing. In particular, a systematic examination of existing literature to identify the diverse set of rules applied to form device clusters is currently absent, impeding further quantification and analytical efforts.

Furthermore, a methodological workflow for analyzing interdisciplinary terminology alignment is missing. More specifically, there is insufficient discussion on whether the interdisciplinary terminology of NDCs aligns with the actual selection processes for device clusters. Specifically, it remains unexamined whether devices are grouped strictly by energy system boundaries or if boundaries from other disciplines, such as urban planning and social sciences, are considered.

Finally, baseline definitions and benchmarking for urban planning and social sciences boundary selection for energy-related applications are absent. The absence of clear definitions for truly urban planning and social science-based clustering methods prevents rigorous analysis of their potential benefits for energy system operation. There is a need to establish baseline definitions and benchmarks by reviewing existing clustering methods and literature on urban planning and social science in various countries.

1.3. Contribution

We respond to the shortcomings presented in Section 1.2 by clarifying key conceptual distinctions, establishing methodological coherence, and enhancing the practical applicability of NDCs in urban energy systems through the following core contributions:

- Development of a systematic methodological workflow for analyzing literature that employs NDC terminology, specifically focusing on the clustering rules used to define spatial and technical boundaries.
- Specification and distinction of the device-cluster-oriented perspective of NDCs, in contrast to perspectives that focus on legal structures, investment models, or community-oriented benefits.
- Compilation and categorization of clustering approaches from both the energy domain and urban planning or social sciences, enabling a comparative assessment of their applicability and integration potential.
- Identification and critical evaluation of inconsistencies in the use of interdisciplinary terminology, demonstrating the need for explicit, standardized criteria when applying clustering concepts in energy-related applications.

In doing so, it lays the foundation for classifying and comparing existing work across disciplinary domains and proposes a coherent methodological workflow for analyzing and delineating NDC in future research and implementation.

1.4. Structure of the paper

The paper is structured as follows: The methodology in Section 2 outlines the prerequisites for concepts to be included in the review and defines how NDCs are interpreted in the present paper. It also details the approach used to identify and analyze clustering methodologies. The results, presented in Section 3, classify the existing clustering approaches in the energy domain and review urban planning and social sciences methodologies, providing a foundation for examining interdisciplinary approaches. Section 4 critically evaluates the findings, addressing terminology inconsistencies and offering recommendations for future research. Section 5 summarizes the contributions and key insights.

2. Methodology

This section outlines the methodology employed in the present paper, with Fig. 1 illustrating the key steps undertaken. The analytical workflow for evaluating existing papers on NDC is depicted as a top-to-bottom process in Fig. 1. At the top, a filtering step (represented by a trapezoid) establishes the selection criteria for identifying relevant literature (see also Section 2.1 and Section 2.2). The primary division within this workflow arises from the categorization of the clustering concepts applied. Literature that utilizes energy-related clustering concepts flows through the green pathway on the right, whereas literature employing urban planning and social sciences clustering concepts is represented by the blue pathway on the left. Additionally, two side

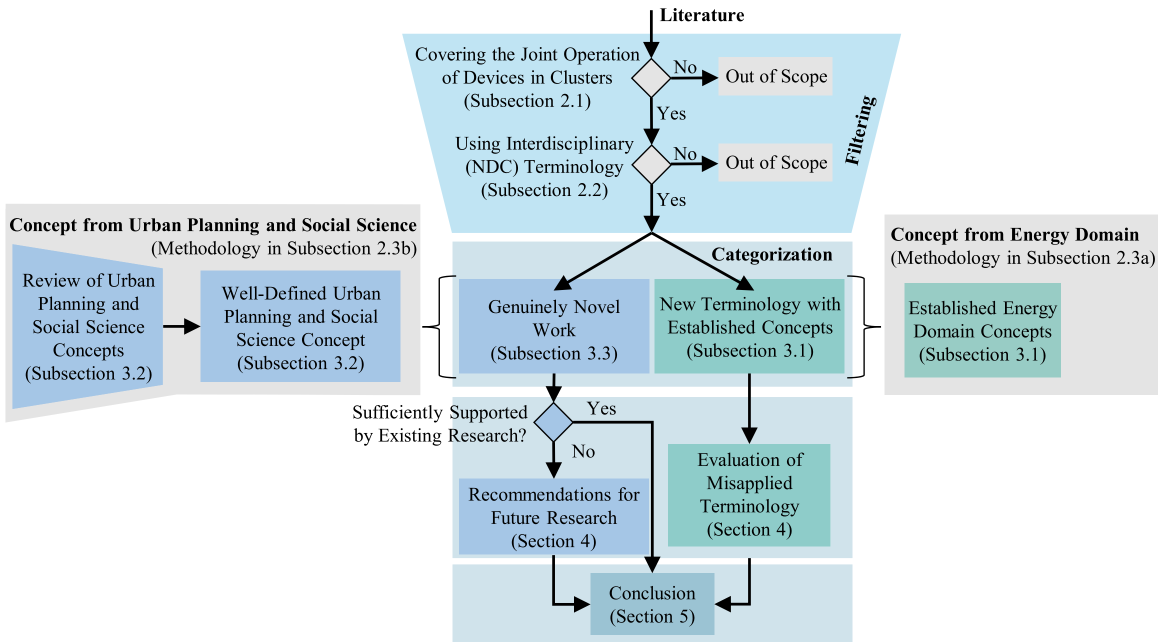


Fig. 1. Methodological approach of the present paper: A top-to-bottom workflow categorizes and evaluates existing NDC. Literature is filtered (inverted trapezoid) to include studies on joint device operation (Section 2.1) and using interdisciplinary NDC terminology (Section 2.2). Clustering concepts were defined outside the main workflow: energy-related concepts in Section 3.1 (methodology in Section 2.3a) and urban planning and social sciences concepts in Section 3.2 (methodology in Section 2.3b). Based on this categorization, energy-domain concepts are elaborated in Section 3.1 and evaluated regarding the alignment of terminology and clustering concepts in Section 4. Urban planning and social sciences concepts are presented in Section 3.2, and the question of whether NDCs are sufficiently supported by existing research is discussed in Section 4, before concluding in Section 5.

tasks (indicated in the gray boxes) involve defining appropriate clustering rules for these concepts on a meta-level outside the main analytical workflow. The subsequent steps of the analysis are carried out in the results sections (Sections 3.1 to 3.3), followed by a discussion that reflects on the identified categories (Sections 4.1 and 4.2) and a comprehensive conclusion synthesizing all findings (Section 5).

Certain aspects of the workflow depicted in Fig. 1 necessitate additional elaboration in dedicated Section 2.1, Section 2.2, and Section 2.3 of this methodology section. One such aspect is establishing clear selection criteria, as detailed in Section 2.1. Additionally, Section 2.2 provides a precise definition of NDCs, ensuring conceptual clarity and focus throughout the paper. Section 2.3 explains how clustering concepts are identified, classified, and analyzed across disciplines. Further methodological aspects, including proposing future research directions, refining terminology, and drawing conclusions, are straightforward and integrated into the main sections of the paper, aligning with the corresponding analytical findings.

2.1. Selection criteria for analyzed concepts

The present paper considers concepts that are comparable to district-related energy systems (see also Section 1). Energy-related applications are inherently linked to devices that produce, consume, store, transmit, or convert energy (Galenzowski et al., 2023a; Haji Bashi et al., 2023). Examples of such devices include photovoltaic systems, battery storage, electric vehicles, combined heat and power plants, wind turbines, heat pumps, chillers, and thermal storage units (Haji Bashi et al., 2023). The key characteristic underlying the comparability of district-related energy systems, and thus the prerequisite for including literature in the present analysis, is the joint operation of multiple devices that form subgroups within a superordinate administrative entity such as a city, representing an intermediate scale of analysis (Sassenou et al., 2024; Bauwens et al., 2022). Building on this understanding of intermediate granularity, the present analysis focuses exclusively on the joint operation in energy devices. It deliberately excludes broader REC, CEC, or PED objectives, for example, related to investment, governance, or social impact. Accordingly, device clusters are a core concept of the analysis and are defined as follows:

> **Device cluster:** A device cluster is characterized as a collection of multiple energy-related devices (consumer, producer, or storage unit) that are collaboratively managed and constitute a subunit of a superordinate entity, such as a city.[1]

As illustrated in Fig. 2, relevant concepts must operate at an intermediate granularity, representing the scale between individual devices and an entire city. The focus lies on grouping these devices into

[1] To improve the readability, device clusters are hereafter called clusters.

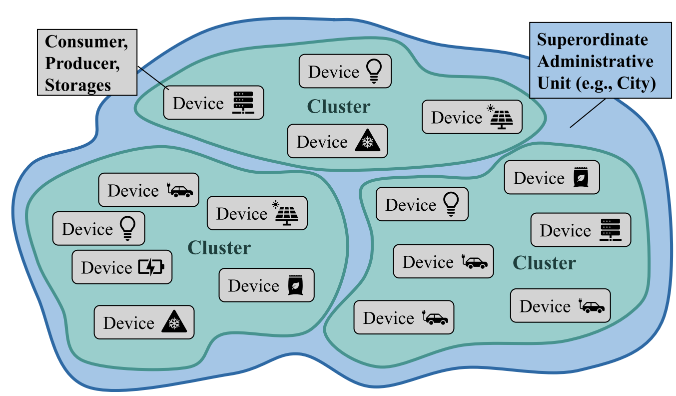


Fig. 2. To be considered in this paper, papers must focus on an intermediate granularity level between a single device and a superordinate administrative unit. Because energy-related applications link to devices rather than intermediate entities like buildings (see Section 2.1), only devices are considered.

units for joint operation, enabling sustainable energy systems, localized renewable energy production, enhanced citizen engagement, reduced procurement costs, and improved energy reliability and quality (Ahmed et al., 2024). From a conceptual perspective, the real-world system may exhibit varying intermediate topographies. For instance, some buildings may utilize dedicated building management systems that aggregate data from individual devices and present an abstracted, aggregated interface to the cluster. From the cluster's perspective, these systems are seen as devices with potentially different or limited boundary conditions. For simplification purposes, optional intermediate layers are not depicted in Fig. 2.

In any approach to grouping devices, it is essential to determine the specific cluster to which each device belongs. This requires the establishment of clearly defined boundaries between the clusters based on a set of rules. These rules can vary depending on the domain or context, but are crucial for ensuring the coherence and functionality of the grouping. The present paper focuses on NDCs, whose definitions and specific characteristics are described in Section 2.2. Grouped and jointly operated devices inside cities are a fundamental prerequisite for defining district-related concepts in the energy context, making this criterion essential for inclusion in the review.

2.2. Definition of Novel District Concepts (NDCs)

The term Novel District Concepts (NDCs) in the present paper refers to approaches that integrate at least one aspect of urban planning or social sciences into the energy domain. These concepts are characterized by the fact that they incorporate at least one term from urban planning or social sciences into their name. Natanian et al. (2024) and Haji Bashi et al. (2023) provided an overview of 22 such concepts, with the most prominent examples being *Positive Energy Districts*, community energy, and *Renewable Energy Communities*. We observe that all the discussed concepts merge energy-related terminology with at least one term originating from urban planning or social sciences. For instance, terms are drawn from the energy domain (e.g., *energy*, *net-zero*, *renewable*), urban planning (e.g., *district*, *neighborhood*, *block*), and social sciences (e.g., *community*, *citizen*, and *consumer*). A detailed overview illustrating the popularity and interdisciplinary characteristics of the concepts from Natanian et al. (2024) and Haji Bashi et al. (2023) is presented in Table A.4 in Appendix. The present paper does not aim to comprehensively quantify the prevalence of all NDCs. Rather, Table A.4 highlights exemplary works to illustrate the interdisciplinary nature of the adopted NDC definition. The interdisciplinary nature is summarized and visualized in Fig. 3.

Moreover, we do not aim to evaluate the overlapping terminologies themselves but rather to investigate the fields from which these terms originate and their implications for energy systems. Terms such as districts, neighborhoods, and communities, commonly used in urban planning and social sciences, often refer to geographic regions, administrative divisions, or social groupings. For example, a district may denote an administrative division,[2] whereas a neighborhood typically describes a city area inhabited by people with shared characteristics (for further definitions of the terms, see Appendix A.2).

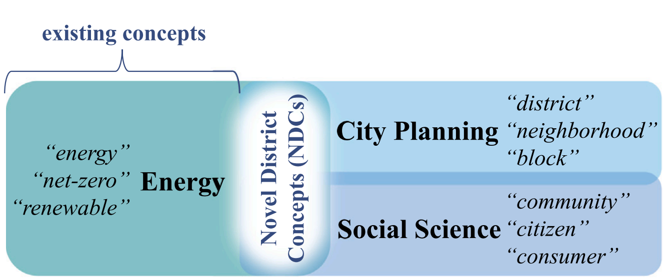


Fig. 3. The novelty in the definition of NDCs consists of applying terminology originating from urban planning or social sciences in the energy context. For instance, a PED combines *positive energy* (an energy-domain concept) with *district* (an urban planning concept). See also Table A.4 in Appendix.

Consequently, we refine the literature selection to include only works that address concepts aligning with this interdisciplinary definition for further analysis. This initial selection is based solely on the terminology of the concepts, although the applied clustering approach is not necessarily from the same domain.

2.3. Identification of clustering concepts through literature review

A key contribution of the present paper is the identification of clustering concepts derived from exemplary papers in the literature. The aim is to highlight the diversity of approaches and to present preliminary findings rather than conducting an exhaustive review of all available literature. The two primary groups of clustering approaches are those based on established energy concepts and those rooted in urban planning and social sciences.

(a) Established energy concepts are well-known in the energy field and form the foundation of the present analysis. The aim is to create a comprehensive list of these concepts, categorize the reviewed papers, and highlight the variety of clustering rules applied in the energy domain. A significant issue in the current literature is the tendency to apply various clustering rules from the energy domain while claiming them to represent NDCs. To address this, the present paper emphasizes the importance of documenting all possible variations in the clustering rules in the energy domain to provide clarity and coherence. Various clusters and reviewed papers are presented in Section 3.1.

***(b)* Urban planning and social sciences approaches** are less explored in the energy context. Thus, the first step is to research and define these concepts and then discuss how they appear in the reviewed papers. These methods are straightforward to apply because many countries have well-defined administrative districts that can serve as boundaries for clustering. Moreover, large publicly available Geographic Information System (GIS) datasets established by governmental or administrative bodies provide reliable and standardized data. These datasets, which are available across numerous countries, enable a rapid and consistent definition of district boundaries. Additionally, these approaches offer significant advantages for defining clusters because they are based on publicly available or readily observable spatial and social data, ensuring accessibility and ease of application. By contrast, energy-focused methods often depend on inaccessible, fragmented, or outdated data, such as grid topology, which requires coordination among multiple stakeholders and lacks transparency for broader audiences. To leverage the advantages of urban planning and social sciences approaches, we review state-defined clustering methodologies and their associated rules, complemented by scientific definitions. These concepts provide a practical and scalable foundation for defining district boundaries. By integrating state-defined methodologies with scientific insights, the paper establishes a robust basis for interdisciplinary clustering, reviewed and described in Section 3.2.

This paper establishes the groundwork for categorizing reviewed papers into distinct groups based on boundary origin from energy, urban

[2] In the context of urban planning and social sciences, as discussed in Sections 2.3 and 3.2, the term **district** is used to refer to a geographically delineated area defined by an interdisciplinary origin. Among the available interdisciplinary terminology, the geographical aspect is best reflected by the term district (see Section 3.1). All devices located within this area form a cluster according to interdisciplinary rules. The only exception to this use of district is in the review of established energy concepts (Section 3.1), where the term *district* is used exclusively as a citation of terminology from the presented literature.

planning, and social sciences. By integrating these established concepts, the present paper provides a holistic and practical methodology for analyzing and defining NDC concepts, as outlined in Fig. 1. In this context, the idea of misapplication (see Fig. 1) needs clarification. We do not imply that terminology must be identical across domains or that general definitions are questioned. Instead, terminology should reflect the origin of the grouping logic: energy-domain terms are appropriate for clusters defined by energy system boundaries, whereas interdisciplinary terms are more suitable for clusters based on urban planning or social sciences. The key point is not whether a term is correct in itself, but whether it makes clear after which logic the devices were grouped. Based on the defined NDC terminology in Section 2.2 and the origin of clustering rules, the evaluation distinguishes:

Misapplied Terminology: Use of NDC terminology (as defined in Section 2.2) for clusters derived solely from *established energy system* boundaries.

Genuinely Novel Work: Use of NDC terminology (as defined in Section 2.2) for clusters derived from interdisciplinary *urban planning* or *social science* boundaries.

Bias in the rating of misapplied terminology is not expected, since the definition of NDC terminology (Section 2.2) and boundary rules (Sections 3.1 and 3.2) are unambiguous. Potential uncertainty arises only in works where the rules for cluster creation are not explicitly described in the reviewed literature, which limits the available input.

3. Results

This section presents the clustering approaches identified in the literature, categorized into three distinct sections. Section 3.1 focuses on established energy-domain concepts, directly integrating relevant literature to highlight the diversity of clustering rules within the field. Section 3.2 reviews and defines clustering approaches derived from urban planning and social sciences, providing a comprehensive foundation for interdisciplinary methodologies. Finally, Section 3.3 examines interdisciplinary research integrating urban planning and social sciences concepts into the energy domain. Together, these sections provide a systematic analysis of the clustering approaches across disciplines.

3.1. Review of established energy system concepts and literature adopting novel terminology

In this section, we investigate the typical grouping of devices into clusters within the energy domain. Additionally, it analyzes existing papers that reference the terminology of NDCs (see Section 2.2), but rely on energy-domain clustering rules to select the included devices. To highlight which NDCs terminology is used by the authors of these papers, the terminology extracted from the papers is highlighted in the following in *italic*. The purpose of these terms is only to highlight the utilization of NDC terminology and not to explain them in detail; for details, the original publications should be consulted. The present analysis focuses on the actual processes underlying cluster formation, often requiring a detailed examination to reveal the criteria used for selecting specific devices. Many of these papers lack transparency and clarity regarding the selection criteria, necessitating a meticulous review to discern the rules actually applied.

Table 1 provides an overview of the identified energy-domain clustering concepts detailed in the subsequent paragraph. To enhance clarity, these concepts are illustrated using examples in the Figures Figs. 4, 6, and 7. The displayed clusters are fictional, emphasizing the general applicability of concepts rather than specific locations. To demonstrate applicability within the same urban context, all figures depict the same city area (left part of the figures) with corresponding detailed clustering views (right part of the figures). The selected area measures 2.3 km in width and 1.3 km in height. The figures were generated using QGIS 3.30.1, with data from OpenStreetMap,[3] GlobalMLBuildingFootprints,[4] and Google Satellite imagery.[5] The following sections present the nine clustering approaches identified in the present paper as commonly used in the energy domain.

(a) Below the same MV/LV transformer substation An approach widely recognized within the energy community is to cluster devices below a single Medium-Voltage (MV) to Low-Voltage (LV) transformer (MV/LV transformer) as shown in Fig. 4a. It is described as having the MV/LV connection point as the point of common coupling, specifically mentioning the below-a-single-transformer aspect or referring to all devices sharing a single low-voltage grid as one cluster. For example, Terrier et al. (2024) focused on identifying different district types in Switzerland. They referred to *local energy community*, *energy hubs*, or *district*, even though they used the MV/LV transformer to cluster devices in their paper. Middelhauve et al. (2022) presented a novel algorithm for the optimal *district* design as *renewable energy hubs*. While referring to *districts*, they considered all devices below a single MV/LV transformer. Kharboutli et al. (2022) examined *district* energy system models, focusing on economics, ecology, system serviceability, and resilience. They highlighted the need for multi-criteria optimization to balance conflicting objectives of *districts* for a holistic assessment while, in fact, considering the cluster of all buildings at the connection point at the MV/LV transformer. Lang et al. (2023) examined power system architectures at the *district level*, using the term station area to describe the zone supplied by a single MV/LV transformer. Their case study focuses on devices connected to the low-voltage side of a 630 kVA transformer, aligning the district concept with the local distribution level. Dynge et al. (2021) examined a local electricity market in a *neighborhood*. Their results are based on devices connected to a single MV/LV transformer. Clustering at the MV/LV transformer level is not only performed in numerous scientific papers but also finds applications in laws such as the German EnWG, §14a (Bundesrepublik Deutschland, 2025) on grid relief measures that specify them for devices connected to the low-voltage grid. Moreover, the voltage control of distributed energy resources is realized at this low-voltage grid level (Demirel et al., 2025).

(b) Private grid areas This approach considers all devices connected to a privately operated grid as one cluster. The boundary is defined by at least one connection point to the public grid. District concepts that apply this clustering focus on larger private grid areas such as college campuses, industrial sites, or large residential building complexes (see Fig. 4b). Unlike single-family buildings, campuses meet the scale and complexity expected of a district in urban planning and social sciences. However, they are a special case, considering the freedom from using a privately operated grid. Araújo et al. (2023) examined the increase of Photovoltaic (PV) and self-consumption for a *local energy community*, using the campus of the School of Technology and Management of the Polytechnic Institute of Viana do Castelo. Blumberga et al. (2024) conducted a simulation of production and consumption for a *positive energy district*, using buildings belonging to the Riga Technical University campus and, therefore, a closed campus private grid area. According to the private grid area approach, a larger large-scale industrial complex (see the purple area in Fig. 4b) would be considered as a cluster, but also each single-family home with its grid connection point.

(c) Same cell manager If the grid is structured in a cellular way, the grid inside a cell is managed by a specific entity with a unique connection point to the distribution grid. Those entities act as sub-grid-managers that are not private (see Fig. 4c). *Community* microgrids

[3] http://tile.openstreetmap.org/{z}/{x}/{y}.png (accessible as QGIS layer source, not via a web browser).

[4] https://github.com/microsoft/GlobalMLBuildingFootprints

[5] https://mt1.google.com/vt/lyrs=s&x=\{x\}&y=\{y\}&z=\{z\} (accessible as QGIS layer source, not via a web browser).

Table 1
Key clustering approaches relevant in the energy domain, highlighting their primary boundary-defining criteria, scale of coverage (in terms of area or number of devices), and representative papers from the literature. A *private grid area* is a grid section owned and operated by a private actor with at least one connection to the public grid. A *cell manager* operates a defined grid cell that integrates multiple private areas below a single point of common coupling (PCC). A *sub-balance group* denotes a subgroup within an electricity market balance group collectively managed by a coordinator, such as a virtual power plant operator. The concepts are explained in depth in the corresponding paragraphs.

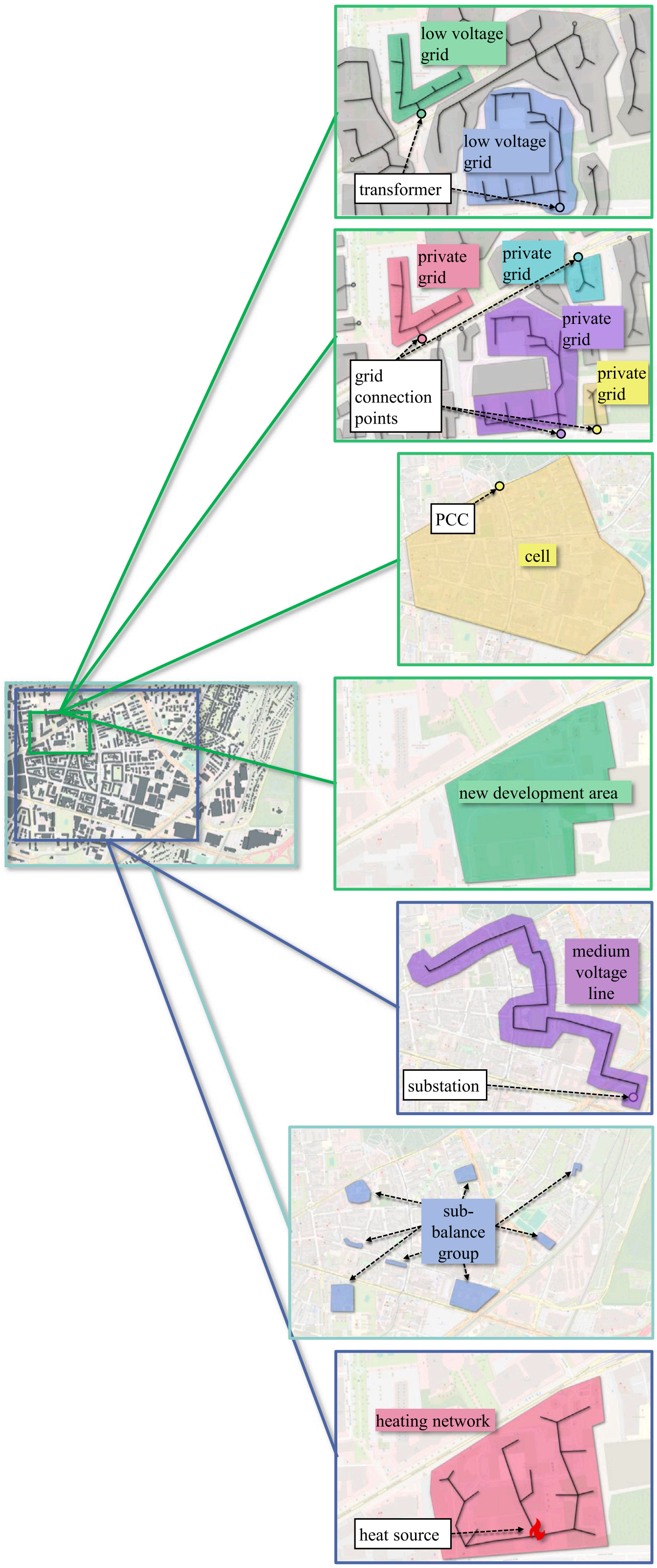
Clustering concept		Boundary definition criterion	Scale	References
(a)	Below the same MV/LV transformer substation	Devices below a single MV/LV transformer within a shared low-voltage grid.	Small	Terrier et al. (2024), Middelhauve et al. (2022), Kharboutli et al. (2022), Lang et al. (2023), Dynge et al. (2021)
(b)	Private grid areas	Privately operated grid areas, with defined connection points to the public grid.	Small	Araújo et al. (2023), Blumberga et al. (2024)
(c)	Same cell manager	Managed by a single entity or community microgrid.	Medium	Cornélusse et al. (2019), Coelho et al. (2025), Ottenburger et al. (2024)
(d)	Belonging to a newly or commonly developed area	Assets constructed during the same period or as part of a joint development project.	Medium	Cheng et al. (2025), De Rosa et al. (2024)
(e)	Shared medium-voltage line	Devices sharing the same medium-voltage line.	Medium to Large	Kermani et al. (2022), De Barros et al. (2024), Liu and Ledwich (2021)
(f)	Sub-balance group	Managed under a single energy market balance group.	Medium to Large	Reis et al. (2020), Sauerbrey et al. (2024), Van Summeren et al. (2020)
(g)	Common heating or cooling grid	Devices sharing a local heating or cooling grid.	Small to Medium	Wakui et al. (2021)
(h)	Motivation to participate or data availability	Chosen based on data availability or owner participation.	Small to Medium	Guarino et al. (2023)
(i)	No information on clustering	No clear or systematic clustering criteria.	Varies	Chuat et al. (2024)

are essential concepts of forming a cell with a single connection point - called the Point of Common Coupling (PCC) - to the superordinate grid (Salehi et al., 2022). Depending on their focus, they lie between a private grid area and a managed cell. According to Cornélusse et al. (2019), *community* microgrids consist of all devices connected to a local bus. The authors neither formulated the requirement that this bus is equivalent to an MV/LV transformer nor explicitly stated that the grid parts below this bus must be privately owned. They differentiate the grid below the bus from the public grid, but this does not mean that the grid is owned by a single building owner or a private company. Instead, it is a grid owned by a unique entity that belongs to the community, forming a cell that lies below the public grid and forms its grid area (Cornélusse et al., 2019). Coelho et al. (2025) simulated *community* microgrid operation. Their clusters are derived at a PCC, clearly delimiting the microgrid boundaries without aligning to a specific voltage level or ownership structure (Coelho et al., 2025). Ottenburger et al. (2024) examined the development of device clusters for microgrid design, employing a structured approach that incorporated both technical criteria and social dimensions, such as socioeconomic and housing conditions to address community vulnerabilities. Clusters were formed at two levels of aggregation: initially, subclusters were defined based on medium voltage circuit boundaries (devices sharing the same medium voltage line), and ultimately, final clusters were established as microgrids, representing physically distinct grid sections capable of operating independently. The paper avoids mislabeling microgrids by precisely defining their boundaries and clearly documenting the social rules and technical principles used to derive them, fostering transparency and scalability in cluster-based energy system design (Ottenburger et al., 2024).

(d) Belonging to a newly or commonly developed area Assets within a newly or commonly developed area share a similar construction time frame, enabling the adoption of unified energy concepts and suggesting comparable energy efficiency and consumption profiles (see Fig. 4d). Unlike private grid areas, these regions encompass multiple grid connection points or low-voltage grids. For instance, Cheng et al. (2025) presented a co-simulation concept for district heating in a *new residential area* in Germany. De Rosa et al. (2024) presented an integrated planning methodology for new decarbonized urban districts that combines energy management in buildings, electric vehicle charging infrastructure, and electricity distribution network design, demonstrated through a large-scale case study in a commonly developed area of the *new district* in Madrid.

(e) Shared medium-voltage line This approach clusters all devices connected to the same medium-voltage line by considering the cable originating from the major substations and all devices connected to one cable coming out of the substation (see Fig. 4e). This cable can originate from a bus in the substation, or from a single corresponding HV/MV transformer. Kermani et al. (2022) enhanced MV/LV transformer designs for *energy communities*, which in this publication are understood as aggregations of assets connected at a shared medium-voltage line. De Barros et al. (2024) targeted a *regional* improvement of the power quality in a distribution grid. Liu and Ledwich (2021) presented an algorithm for grid-friendly control of *communities* either referring to devices connected to the same voltage level or devices connected to the same medium-voltage network. Distribution system operators tend to know the power flows through a line at the substation but may not know what happens between assets further along the line.

(f) Shared sub-balance group This clustering approach is defined by a single entity, such as a Virtual Power Plant (VPP) operator or a local small-scale energy supplier, responsible for managing energy market transactions and ensuring balance for the entire group (see Fig. 4f). While VPPs can encompass large geographical areas, this work focuses on smaller, localized VPPs that align with the definition of an intermediate scale, situated between individual devices and entire cities, as detailed in Section 2.1. Reis et al. (2020) proposed a multi-agent system to model an energy community, interconnected primarily through a common coordinator agent rather than strictly by grid boundaries. In their approach, clusters comprise residential and non-residential agents geographically co-located, whose demand flexibility is collectively optimized by the coordinator agent (Reis et al., 2020). Sauerbrey et al. (2024) defined a *district* as a group of spatially related buildings that pursue a joint energy supply and consumption. Their work introduced the role of a district energy manager, who centrally manages forecasting, optimization, and flexibility within this group, effectively coordinating energy supply and demand across sectors such as electricity, heat, and mobility through a modular district energy management system. Van Summeren et al. (2020) examined



(a) Below the same MV/LV transformer substation.
A low-voltage grid served by a single MV/LV transformer is illustrated in green with another example shown in blue. Additional clusters across the city are represented in gray, highlighting the broader applicability of the concept.

(b) Private grid areas.
Depicts privately operated grid areas with boundaries at grid connection points to the public grid. Examples include single-family homes (light-blue and yellow), larger apartment complexes (red), and industrial grid areas (purple). Gray-shaded regions indicate neighboring clusters.

(c) Same cell manager.
Pictured is a cell managed by a designated entity that operates the internal grid and maintains a single connection point (PCC) to the higher-level distribution network. In contrast to private grid areas, the cell is not owned by a single actor but is collectively managed by an entity representing the community.

(d) Belonging to a newly or commonly developed area.
Depicted is an area in which assets were constructed within the same development phase or as part of a coordinated project. The defining criteria of this clustering type are the shared construction time frame and the resulting uniformity in building standards and technologies, which suggest comparable energy efficiency and consumption profiles.

(e) Shared medium voltage line.
The figure shows a cluster defined by all devices connected to the same medium-voltage line originating from a substation. This type of clustering is characterized by the shared physical cable that links multiple assets to the grid, independent of ownership or end-use.

(f) Shared sub-balance group.
The schematic illustrates a cluster defined by a common balancing responsibility, typically coordinated by an entity such as a Virtual Power Plant (VPP) operator or a local energy supplier. In this approach, the boundary is defined by a shared sub-balance group, where energy market transactions, forecasting, and flexibility management are coordinated collectively.

(g) Common heating or cooling grid.
This clustering method is based on the interconnection of assets through a shared district heating or cooling network. The cluster boundary is defined by the spatial extent of the thermal grid rather than electrical topology or ownership.

Fig. 4. Conceptual illustration of identified energy-domain clustering concepts (a) – (g) within a consistent urban context. Left panels show the same city area, right panels the corresponding detailed clustering views. The fictional examples demonstrate the general applicability of the clustering rules described in Table 1, independent of specific locations.

Fig. 5. Examples of existing district definitions from publicly available GIS datasets. The maps showcase administrative boundaries for selected cities – IRIS in Strasbourg (France) on the left, Buurten in Amsterdam (Netherlands) in the middle, and Census Blocks in New York (United States) on the right – highlighting the accessibility and standardization of spatial data for district-level analysis.

three VPPs in Ireland, Belgium, and the Netherlands, focusing on their goals, structures, and challenges. The so-called *community-based* VPPs (cVPPs) integrate diverse renewable energy resources, such as solar panels, batteries, and heat pumps. They promote local energy independence, democratize energy use, and help participants align with energy market rules. In doing so, they address the challenges of integrating community-driven models into established energy systems (Van Summeren et al., 2020).

(g) Common heating or cooling grid The terminology for a district is well established when referring to local heating networks (see Fig. 4g). Wakui et al. (2021) presented a design method for distributed energy networks combining heat and power, providing an *energy supply area*.

(h) Motivation to participate or data availability Guarino et al. (2023) modeled the consumption and generation of a *positive energy district*. All the selected buildings were used for public purposes. From the aerial image, it is evident that they are not contiguous, with no clearly visible outer boundaries. It is not explicitly stated by Guarino et al. (2023); however, based on these facts, it is reasonable to assume that the buildings were chosen based on the respective owners' willingness and availability to participate in the research.

(i) No information on clustering Chuat et al. (2024) discussed the solution space of possible configurations of devices for *districts* operated as energy hubs by performing a sensitivity analysis of the different configurations and price parameters. However, they do not discuss how the 15 buildings in their analysis were systematically selected and how a whole city could be clustered in a similar manner. Even laws such as the German GEIG (Bundesrepublik Deutschland, 2021) use the term *district* (Quartier in German). While the GEIG primarily regulates the installation of charging infrastructure in new buildings, it allows certain requirements, such as the mandated number of charging stations, to be fulfilled collectively at the *district* level. However, the law does not provide a precise and strict definition of what constitutes a *district*, leaving its interpretation open-ended despite its central role in fulfilling these obligations.

Summary of existing energy system concepts In conclusion, this section underscores the diversity of clustering approaches within the energy domain, highlighting methods such as MV/LV transformer areas, shared medium-voltage lines, and private grid areas as well-defined boundaries. Examples of less-structured clustering are also discussed as approaches based on motivation and data availability or undefined criteria. These findings demonstrate the range and complexity of the methods used to cluster devices for energy applications, offering valuable insights into existing practices.

3.2. Review of established clustering approaches in urban planning and social sciences

Urban planning and social sciences offer established approaches for subdividing cities into clusters, which are often developed for statistical evaluations or census data collection. These approaches focus on clustering populations because social aspects are inherently tied to people. In the context of energy-related applications, these methods can be adapted to group all devices associated with individuals in a cluster, or to focus on clustering buildings and their related devices. Many countries, including France, the Netherlands, the United States, Australia, and England, have well-defined concepts for city subdivisions, particularly for administrative or statistical purposes. Fig. 5 exemplarily shows the GIS boundaries of those concepts for the Ilots Regroupés pour l'Information Statistique (IRIS) in Strasbourg[6] on the left, Buurten in Amsterdam[7] in the middle, and Census Blocks in New York[8] on the right, displayed on a base layer from OpenStreetMap.[9] The following paragraphs and Table 2 provide an overview of these established concepts and their potential relevance to interdisciplinary applications.

(a) IRIS Units in France The National Institute of Statistics and Economic Studies (Insee) in France uses the IRIS clusters for social sciences and urban planning purposes. IRIS stands for "Ilots Regroupés pour l'Information Statistique" or "grouped block for statistical information". IRISs are used for detailed spatial analysis and the statistical collection of population and social data at the local level to support targeted urban planning, public services, and policy decisions. They comprise building blocks of 1,800 to 5,000 inhabitants that are homogeneous in terms of settlement type. Major disruptions in the urban fabric, such as major roads, railways, and waterways, were defined to mark the borders of each IRIS. In total, approximately 16 thousand IRIS clusters existed throughout France in 2016 (Institut national de la statistique et des études économiques (Insee), 2016).

(b) Buurten in the Netherlands The Centraal Bureau voor de Statistiek (CBS) in the Netherlands uses a similar concept with the Buurten for statistical purposes. Buurten, the Dutch word for neighborhoods, is defined as contiguous buildings or development areas (e.g., a similar year of construction or building type). Interruptions, such as roads, railroads, and waterways, are defined as delineating factors. They consist of 250 to 2,500 inhabitants. According to Statistiek, Centraal Bureau voor de (2024) the whole Netherlands, was clustered in around 18 thousand Buurten in 2024 (Centraal Bureau voor de Statistiek (CBS), 2023).

(c) Census Blocks in the United States In the United States, the Census Block is the smallest unit used by the United States Census Bureau (USCB) to collect detailed demographic data. Census Blocks

[6] IRIS GIS source for Fig. 5: https://data.geopf.fr/wfs/ows?SERVICE=WFS&VERSION=2.0.0&REQUEST=GetCapabilities|layername=STATISTICALUNITS.IRISGE:iris_ge (accessible as QGIS layer source, not via a web browser).

[7] Buurten GIS source for Fig. 5:https://geodata.cbs.nl/files/Wijkenbuurtkaart/WijkBuurtkaart_2020_v3.zip.

[8] Census Blocks GIS source for Fig. 5:https://hub.arcgis.com/datasets/d795eaa6ee7a40bdb2efeb2d001bf823_0/about.

[9] http://tile.openstreetmap.org/{z}/{x}/{y}.png (accessible as QGIS layer source, not via a web browser).

Table 2
Summary of clustering approaches in the urban planning and social sciences domain across different countries.

Country	Local concept	Inhabitant range	Total n clusters	Clustering characteristics	Source
(a) France	IRIS Unit	1,800–5,000	16,100	• Connecting: Homogeneous settlement type • Delineating: Major disruptions in the urban fabric, e.g., major roads, railways, waterways	Institut national de la statistique et des études économiques (Insee) (2016), Statistiek, Centraal Bureau voor de (2024)
(b) Netherlands	Buurt	250–2,500	18,310	• Connecting: Contiguous buildings/development • Delineating: Roads, railroads and waterways	Centraal Bureau voor de Statistiek (CBS) (2023)
(c) United States	Census Block	2,500–8,000	8,180,866	• Connecting: Similar housing and socioeconomic • Delineating: Easily observable features like roads, railroads, and streams	U.S. Department of Commerce et al. (1994), US Census Bureau (2022)
(d) Australia	Mesh Block	ca. 75-150 (30–60 dwellings)	368,286	• Connecting: Homogeneous land use • Delineating: Topographic, or landscape like water bodies, roads, rail, open space, mountains, or escarpments	Australian Bureau of Statistics (2021)
(e) England	Output Area	100–625	171,372	• Connecting: Social homogeneity based on the tenure of household and dwelling type • Delineating: Obvious boundaries like major roads	Office for National Statistics (2022)
Additional Definition					
(f) Urban planning				• Autonomous: Subsystem within a city • Connecting: Internal binding factors • Delineating: External boundary factors	Neppl et al. (2016)

cover populations of 2,500 to 8,000 people, with an average population of 4,000. Within their boundaries, Census Blocks have similar housing styles and socioeconomic characteristics. Boundaries are drawn along physical and cultural markers such as streets, railways, waterways, and other legal divisions. Census Blocks assist in precise spatial data collection for urban planning, public services, and policy analyses. According to US Census Bureau (2022), in 2020, approximately eight million Census Blocks were recorded across the United States (U.S. Department of Commerce et al., 1994).

(d) Mesh Blocks in Australia The Australian Bureau of Statistics (ABS) uses the Mesh Block as the smallest geographical unit for census and statistical purposes. Mesh Blocks cover a range of 30 to 60 dwellings, corresponding to 75 to 150 inhabitants per block. Homogeneous land use is a key factor contributing to the internal coherence of a Mesh Block. To the outside, they are delineated by topographic or landscape features such as water bodies, roads, rail, open space, mountains, or escarpments. In 2021, there were approximately 368 thousand Mesh Blocks across Australia (Australian Bureau of Statistics, 2021).

(e) Output areas in England In England, the Office for National Statistics (ONS) uses Output Areas as the primary unit for structuring population and demographic data. Each Output Area includes between 100 and 625 inhabitants. Output Areas aim to ensure social and demographic homogeneity within boundaries drawn along prominent physical features, such as major roads. Output Areas are fundamental for standardized data gathering, supporting local government planning, and resource allocation. As of 2022, there were approximately 171 thousand Output Areas across England (Office for National Statistics, 2022).

(f) Urban planning definition An extensive definition of urban districts was provided by Neppl et al. (2016). According to them, districts are relatively autonomous subsystems within cities, serving as functional centers and identifiable places of assembly and identity. Internally, districts exhibit cohesion through uniform building designs, homogeneous social structures, coordinated building orientations, architectural consistency, and shared social constructs among residents. Externally, they are delineated by natural boundaries (e.g., rivers or topography), hard boundaries (e.g., train tracks or major roads), and soft boundaries, including differences in architectural style, social composition, and building orientation between adjacent districts (Neppl et al., 2016).

Summary of urban planning and social sciences clustering concepts As presented in Section 3.2 and Table 2, the present paper shows that various countries have well-defined methodologies to cluster buildings for urban planning and social sciences. In summary, these concepts have the common definition of districts:

- Relatively independent *subsystems* within a city
- Visible *delimiting factor* and *boundaries* to the *outside* that are major disruptions in the city fabric like:
  - Roads
  - Railroads
  - Streams and bodies of water
  - Mountains or escarpments
- *Homogenous* attributes and connecting factors on the *inside* that are similar, like:
  - Type of housing
  - Year of construction
  - Functional purpose
  - Socioeconomic characteristic
  - Architectural consistency

For illustration, Fig. 6 shows a district defined according to these rules. While this type of clustering seems ambiguous and challenging for engineers in the energy domain, the widespread use of urban planning approaches in numerous countries shows that it is feasible for experts in the domain. It is essential to note that some countries, such as Germany, lack GIS data for statistical evaluation based on urban planning or social science methodologies, as their statistical evaluation relies on an orthogonal grid system (Statistische Ämter des Bundes und der Länder, 2025). Nevertheless, the clearly defined urban planning and social science methodologies enable straightforward, large-scale application, as proven in other countries. The suitability and transferability of these approaches are further evidenced by the successful implementation of block-based methodologies in German cities such as Berlin Senatsverwaltung für Stadtentwicklung, Bauen und Wohnen Berlin (2024) and Rostock (Hanse- und Universitätsstadt Rostock – Kataster-, Vermessungs- und Liegenschaftsamt, 2022).

The subsequent section addresses whether social sciences and urban planning clustering approaches have been widely adopted in the energy domain.

Fig. 6. Conceptual example for clustering: **urban planning and social sciences common definition.** Following the Urban planning and social sciences common definition, the cluster is delineated by major external boundaries (roads, tram line, and a green strip) that disrupt the urban fabric, while the inside is characterized by homogeneous attributes such as consistent building types and functional coherence. Across countries, districts share these joint characteristics (see Table 2), which enable their use as a common basis for clustering.

Table 3
Literature on energy-related applications based on urban planning and social sciences domain clusters. While work applying those clustering rules to answer a specific problem exists, a comprehensive meta-analysis could not be found.

Country	Paper's focus	Reference
France	Evaluate the suitability of urban areas for district heating or cooling networks	Patureau et al. (2021)
United States	Model the energy use of building and transport	Reiter and Marique (2012)
England	Energy demand modeling	Urquizo et al. (2017)
Wales	Comprehensive dataset for demand profiles in Wales	Knight et al. (2016)
France	Identifying the smallest possible areas allowing self-consumption	Fillaut (2015)

3.3. Literature review of integrating urban planning and social sciences into energy systems

Only a small subset of papers on NDCs in the energy domain (as outlined in Section 2.2) genuinely apply interdisciplinary clustering approaches, such as IRIS units, Buurten, Census Blocks, Output Areas, or other urban planning and social sciences approaches (see Section 3.2). The present section highlights selected publications that exemplify the integration of these interdisciplinary concepts into energy systems (see Table 3 for an overview).

Patureau et al. (2021) conducted an evaluation of the suitability of urban areas for district heating or cooling on an IRIS basis. They found that suitability can be well characterized on an IRIS basis. However, multiple suitable IRIS need to be aggregated to obtain a viable size for a district heating or cooling network. While Patureau et al. (2021) used IRIS level data, the resulting cluster was based on the existing energy-domain cluster principle of a shared heating or cooling grid, as presented in Section 3.1.

Reiter and Marique (2012) modeled the energy use of building and transport on a city scale. They used Census Block data to determine transport demand. While Reiter and Marique (2012) used Census Block data, they aggregated it to the whole-city level. Hence, an analysis of the Census Block concept is missing.

Urquizo et al. (2017) modeled energy demand based on Lower Layer Super Output Areas (LLSOAs). LLSOAs aggregate multiple Output Areas. Their paper emphasized the hierarchical possibilities in urban planning and social sciences to aggregate data at varying granularity, ranging from the smallest Output Areas over LLSOAs and further aggregations to an entire city. When examining an entirely social sciences and urban planning clustering approach, future research should consider the different aggregation levels in these domains. Urquizo et al. (2017) focused on energy consumption modeling, identifying the LLSOAs as relevant clusters for policy decisions. However, further analysis of the underlying technical energy system, such as grids or actual devices, and power flows, is lacking.

Knight et al. (2016) presented half-hourly demand profiles on an Output Area detail level. These profiles were generated for 10,048 Output Areas in Wales. A limitation is that the profiles only present building demand, not those of industry or transport; consequently, there are no comprehensive consumption profiles. While providing a large dataset for further research, an investigation of the local operation strategies of devices, as well as the investigation of the influences on the grids, is missing.

Fillaut (2015) aimed to identify the smallest possible areas that achieve local self-sufficiency. The authors used IRIS as the smallest building block in their research. Consequently, local self-consumption is defined by the number of IRIS units surrounding a larger production plant, which implies a balance between demand and production. This approach integrates statistical data on buildings with wind maps and solar radiation. While IRIS units serve as the foundational building blocks for the paper, the focus is not on processes within individual IRIS units, and a systematic review of the IRIS units themselves is lacking.

While the presented papers effectively leverage statistical and social data, key aspects remain unaddressed. Specifically, a systematic investigation of spatial units, such as IRIS or Census Blocks, within the energy system context is lacking—unlike the comprehensive analyses conducted for building or city modeling, for example, with CityGML in works like Geiger et al. (2024). Existing papers on these spatial units in the energy domain primarily focus on data aggregation at the spatial unit scale rather than examining their internal processes. Moreover, integration of technical energy systems, including grid operations and device-level strategies, is lacking. Most importantly, the present paper found literature on specific aspects of urban planning and the integration of social sciences perspectives into energy-related clustering, such as identifying demand profiles for specific regions (Knight et al., 2016) and determining the optimal size of heating or cooling networks for other areas (Patureau et al., 2021). However, our research did not uncover a comprehensive or systematic exploration of the application of these concepts to the energy domain at the meta-level.

4. Discussion – terminological misalignment and proposing future research directions

We systematically analyze the rules by which clusters are formed, focusing on exemplary papers within the field of NDCs. Numerous publications have employed the terminology of NDCs while, in reality, their device selection is based on energy-domain clustering approaches.

Through this analysis, a diverse collection of clustering concepts prevalent in the energy domain is identified, none of which aligns with the interdisciplinary definition of NDCs as outlined in Section 2.2.

According to the applied methodology and the decision step “Sufficiently Supported by Existing Research?” in the methodological workflow (see Section 2 and Fig. 1), sufficient support is not found in the literature. A comprehensive meta-level evaluation of urban planning and social sciences clustering concepts in the energy system context is absent. While the present paper does not constitute an extensive review, the absence of such papers is notable. This finding is particularly significant, as the authors specifically sought papers addressing the systematic application and evaluation of these clustering concepts at a broader level, focusing on integrating spatial units such as IRIS or Census Blocks into energy system considerations. This absence highlights a critical gap in the literature that warrants further exploration. Our findings do not allow final conclusions on why urban planning and social sciences clustering concepts are largely absent in the energy domain or how their alignment with grid operation may influence suitability (see need for study in Section 4.2). Clear hindering factors include the lack of district-level GIS data in some countries, such as Germany, where only orthogonal statistical grids exist despite the availability of suitable methodologies (Neppl et al., 2016), and the absence of policies that could create incentives or awareness of such concepts (see also the lack of clear definitions in legislation in Section 1). In any case, we do not claim that interdisciplinary methods are always the best choice. What we call for after our findings is clarity: if clusters are defined by energy-domain rules, this should be stated explicitly in scientific publications. In such cases, interdisciplinary terms should not be used, or the operation of devices must be clearly distinguished from the interdisciplinary perspective discussed in the publication. What needs to be avoided is the use of interdisciplinary terminology when clusters are in fact defined by energy-system boundaries. This use risks attributing benefits from technical cluster operation to an interdisciplinary concept.

4.1. Identified need for further research on quantifying applied clustering rules

Using NDCs for energy-focused clustering, disguised under novel terminology, is not an isolated phenomenon but a recurring issue, as evidenced by the many papers adopting this approach. The analysis demonstrates that the terminology is misapplied (as defined in Section 2.3) by numerous publications. These findings underscore the need for a more comprehensive examination of the field in a future large-scale investigation to assess the clustering approaches used across all relevant papers. A researcher following this open gap is guided by the presented methodological approach (Fig. 1), the defined terminology (Section 2.2), and the identified concepts from the energy, urban planning, and social sciences domains (Section 3). While the terminology can be used for keyword-based searches, the selection of work focusing on clustering devices, and particularly the rule by which the devices inside a cluster are selected, is hidden, implicitly, inside paragraphs. Although the present paper provides a foundational understanding by defining NDCs and exploring social science-based clustering approaches and their limited application in the energy domain, a broader and more systematic review is beyond the scope of the present paper. Such an effort would constitute a separate full-scale research endeavor, building on the groundwork laid here.

4.2. Need for studying the impact of urban planning and social sciences clustering on the energy system

We show that thorough research is lacking on the value, feasibility, and problems of clustering energy-related devices according to the increasingly popular concepts stemming from urban planning or social sciences. To evaluate the suitability of clustering approaches derived from social sciences and urban planning for energy systems, future research has to investigate the influence of the selected boundaries on the underlying energy infrastructure. Specifically, it is necessary to analyze how these boundaries affect the realization of claimed benefits, such as increased self-sufficiency and less dependence on external grids (Haji Bashi et al., 2023). A large-scale analysis across a representative number of clusters using GIS data and energy system information is required. In this analysis, suitable metrics are needed to quantify the alignment between cluster boundaries and the underlying energy infrastructure. Identifying the most appropriate metric remains uncertain and must be defined as part of future research. Such an analysis would enable the comparison of clustering approaches regarding their ability to deliver the promised advantages of NDCs. The scope of the present paper is to describe terminology and cluster formation found in the literature related to NDCs and derive insights on the misapplication of terminology and gaps requiring future research. The simulation-based and quantitative evaluation of clustering approaches derived from social sciences and urban planning for energy systems is reserved for a future publication.

4.3. Sketch of proposed steps for future research

While developing a full study setup for this identified gap must be carried out comprehensively in future research, a sketch to empirically approach the problem can be as follows:

1. Data Basis: The first step consists of collecting all required data. This includes GIS data on clustering boundaries from urban planning and social sciences (for example, in the CityGML format), as illustrated in Section 3.2 and Fig. 5. In addition, energy infrastructure data, for example, grid topology and the technical connections of energy-producing and consuming devices, can be obtained from distribution system operators and utility companies. Where access to energy infrastructure data is restricted due to privacy concerns, it is possible to synthetically generate it (Weber et al., 2024) or use open datasets (Meinecke et al., 2020).

2. Study Design: Building on the GIS and the energy infrastructure data, three scenarios are proposed for benchmarking clustering approaches: (a) urban planning and social sciences-based clusters, (b) established energy system-based clusters, and (c) operation without an additional cluster.

3. Modeling and Simulation: Assumptions regarding markets, typical operation, and different operational goals, for example, peak shaving (Terrier et al., 2024), savings in energy costs (Blumberga et al., 2024), or battery dispatch based on Model Predictive Control (De Barros et al., 2024), must be integrated in the simulation model. Additionally required is knowledge of the placement and type of devices and suitable mathematical representations (see Fan et al. (2019) or (Zhang et al., 2022)). The selection of strategies needs to represent the core operational strategies established in the literature.

4. Evaluation: The suitability of the clustering approaches needs to be evaluated through metrics, quantifying the clustering approaches' differences, and through the execution of sensitivity and uncertainty analyses. Established evaluation metrics for assessing the quality of energy system operation can be applied, such as Transformer Loading Ratio (Widagdo et al., 2024), Line Utilization Factor (Subramaniyan and Gomathi, 2023), Voltage Deviation (Ghaffari and Aly, 2024), or System Losses (Schavemaker and Sluis, 2025).

5. Validation, Transferability, and Reproducibility: The final step addresses validation, transferability, and reproducibility. For example, the identification of country-specific boundary conditions. Varying conditions can include voltage levels, regulatory frameworks for device operation, and environmental factors like weather (Psimopoulos et al., 2020).

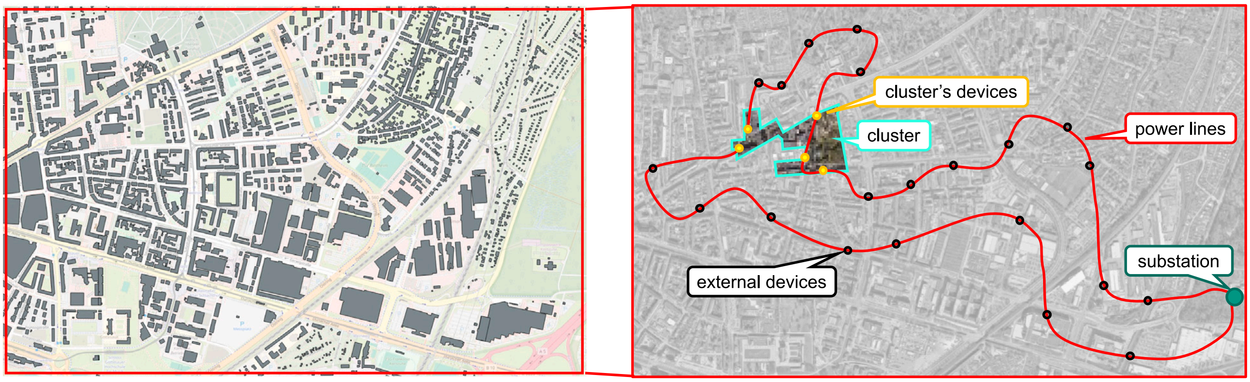


Fig. 7. Real-world example in Karlsruhe, Germany. The figure shows medium-voltage power lines extending from the substation to both the cluster's devices and external devices. Circles represent individual MV/LV transformers and their connected devices. Notably, when cluster devices exchange energy, the grid topology forces flows outside the cluster — even via the substation — underscoring the need to examine the broader infrastructure implications of such exchanges.

4.4. Illustrating potential conflicts between cluster boundaries and energy infrastructure:

To provide a preliminary insight into the potential conflicts between urban planning-based clustering and the existing energy infrastructure, a real-world NDC example from Karlsruhe, Germany, is presented in Fig. 7. In this case, the cluster boundaries are overlaid with the underlying electrical medium-voltage grid. Although the real-world example cluster is derived from the concept of willingness to participate, the illustrated problem remains the same for a dataset of urban planning and social science-based clusters.

Fig. 7 illustrates how overlaying GIS-derived, urban planning-based cluster boundaries with the underlying energy infrastructure, represented by the electrical grid, can reveal significant discrepancies. The extent of these discrepancies depends on the chosen evaluation metric. For instance, when using a metric aimed at confining all power flows within the cluster and minimizing reliance on external grid loads, the misalignment between the designated clustering boundaries and the physical infrastructure becomes pronounced. As shown in the figure, multiple lines extend beyond the cluster, supplying additional devices outside the prescribed cluster. Moreover, energy exchanges between devices within the cluster often span substantial distances — sometimes several kilometers via the substation — thereby undermining the intended benefits of self-sufficiency and localized energy usage within the delineated cluster. Such observations must be systematically quantified to evaluate the suitability of urban planning and social science-based clustering approaches. Metrics should assess the degree of overlap between district boundaries and energy infrastructure and the implications for grid efficiency, self-sufficiency, and reliance on external networks. Conducting such analyses on a large scale would provide critical insights into the practical feasibility and limitations of applying urban planning and social science-based clustering approaches in the energy domain.

While all interdisciplinary clusters are to a certain extent misaligned with the energy infrastructure, the use of district definitions based on urban planning and social sciences offers the significant advantage of methodologically adequate, nationwide, and unambiguous GIS datasets. From a policy perspective, it further provides the benefit that statistical data are collected at the same district level, enabling direct links between energy-related and social policies. Moreover, nationwide district coverage reduces the risk of bias in current PED and REC initiatives, which are often implemented in socio-economic upper-middle-class areas, reinforcing social injustice (Bielig et al., 2022). Additionally, nationwide district coverage avoids drawing boundaries solely based on a positive energy balance. This reduces the risk of a form of "gerrymandering", where boundaries are set in a way that hinders other districts from later becoming a PED (Schneider, 2023). Although the urban planning- and social sciences-based approach may initially result in many districts without a positive energy balance, it provides a systematic and unbiased representation of the national energy system, allowing for genuine change.

5. Conclusions

The present paper elaborates on emerging NDCs in the context of jointly operating devices in urban areas in clusters, looking at the applied novel terminology and its origins. It then presents the clustering concepts according to the energy domain as well as the social sciences and urban planning domains. The paper further categorizes existing papers and highlights the underlying clustering approaches used in these papers. It discusses the state of research on methodically transferring concepts from social sciences and urban planning to the energy domain. Based on these insights, the paper identifies the gaps and the need for further research.

5.1. Key findings

Numerous well-established concepts for the joint operation of devices in clusters exist in the energy domain. Examples include grouping devices that fall under the same MV/LV transformer substation, that are situated in newly or commonly developed areas, that are managed by the same cell manager, that are part of the same private grid, that share the same medium-voltage line, that belong to the same sub-balance group, or that are integrated through a common heating or cooling grid.

The majority of the reviewed NDCs papers adopt concepts from the energy domain. Among these, "Below the Same MV/LV Transformer Substation" is the most frequently applied concept. These papers often inaccurately label their approach as NDCs despite the availability of more precise terminology grounded in established energy-domain clustering methods.

A methodologically sound and consistent definition of districts can be found within the domains of urban planning and the social sciences. According to these disciplines, a district is a relatively independent subsystem within a city, defined by visible external boundaries created by major disruptions in the urban fabric, such as roads, railways, streams, water bodies, mountains, or escarpments. Internally, districts are characterized by homogeneity and shared attributes, including housing type, year of construction, functional purpose, socioeconomic features, and architectural consistency.

Several countries, including France, the Netherlands, the United States, Australia, and England, have adopted urban planning and social science-based methods to delineate districts. These definitions offer practical advantages such as open-source accessibility, in contrast to grid models, which are often proprietary or unknown to grid operators.

The easy access and broad availability simplify large-scale applications for regulations, including the formulation of policies for the operation of energy system device clusters based on these predefined districts' boundaries. This ensures a holistic comparison and improvements for all participants, fostering energy justice and avoiding the reinforcement of existing social inequalities that affect marginalized groups and vulnerable households, as emphasized by Bielig et al. (2022). However, systematic research on the impact of utilizing these urban planning and social sciences clusters on energy systems is lacking.

5.2. Outlook

We demonstrate the importance of developing a practical guide for selecting device clusters tailored to various energy-related applications, with criteria derived from urban planning, social sciences, or energy principles. It takes a key step by precisely defining and clearly delineating these concepts, ensuring clarity and preventing the misapplication of interdisciplinary terminology. Future research on NDCs should properly specify the concepts used to derive clusters of the included devices. It is crucial to discuss explicitly how these rules align with or diverge from the established energy system clustering approaches. Furthermore, researchers must evaluate whether clustering rules are theoretically scalable and applicable for dividing an entire region or country. Such large-scale applicability is a prerequisite for developing policies based on clustering methodologies.

A comprehensive large-scale investigation is required to quantify all existing papers on districts based on the clustering rules outlined in our paper. This effort would clarify the extent to which genuinely novel interdisciplinary concepts are applied or confirm whether most papers labeled NDCs predominantly rely on established energy domain approaches.

Systematic research on the impact of utilizing urban planning and social sciences clusters on energy systems needs to be conducted. This research needs to explore the overlap between urban planning districts and energy infrastructure, both of which are systems that have evolved over decades and are nearly impossible to comprehensively restructure due to their scale and complexity. In doing so, this research must investigate how clustering methods informed by urban planning and social sciences influence technical energy systems. Future research should aim to determine whether large-scale implementation of district-based energy concepts warrants incentivization. This includes evaluating whether technically focused clustering approaches, such as grouping devices below a single transformer or optimizing plants within private grids, may provide more effective solutions than urban planning-based district definitions.

In summary, we establish a systematic foundation for comparing clustering approaches, providing a framework to identify the rules and processes by which device clusters are formed to achieve energy system benefits. While NDCs claim unique advantages, such as enhanced grid stability or reduced energy flow, these benefits remain insufficiently demonstrated when compared to traditional energy-domain methods, such as grouping all devices connected to MV/LV transformers. Furthermore, many benefits often attributed to districts, such as increased investment in PV systems or participant engagement, can be achieved through alternative mechanisms such as citywide initiatives or solely financially driven energy communities. In such cases, it is transparently communicated that the operation of devices within these communities is optimized based on technically sound and widely accepted energy-domain criteria, such as balancing within a private grid area or below a single transformer. These technical optimizations occur independently of financial collaboration or other social initiatives that may define the community. Inside the social sciences and urban planning domain, where these terms originate, concepts such as community and district may hold significant value in fostering a sense of belonging or encouraging joint investment. These disciplines are responsible for evaluating these aspects.

CRediT authorship contribution statement

Johannes Galenzowski: Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Simon Waczowicz:** Writing – review & editing, Validation, Supervision. **Hüseyin K. Çakmak:** Writing – review & editing, Resources. **Erfan Tajalli-Ardekani:** Writing – review & editing. **Sebastian Beichter:** Writing – review & editing. **Ömer Ekin:** Writing – review & editing. **Ralf Mikut:** Writing – review & editing, Supervision. **Veit Hagenmeyer:** Writing – review & editing, Supervision, Funding acquisition.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used ChatGPT to assist with translation, text editing, and refining. After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

A.1. Interdisciplinary Novel District Concepts (NDCs)

Table A.4 categorizes various NDCs by their origin in energy, urban planning, and social sciences while also presenting their prevalence based on Google Scholar and Scopus search results, with bold font indicating the most prominent concepts.

A.2. Definitions from urban planning and social sciences

Definitions according to Merriam-Webster dictionary:

- **District:** a territorial division (as for administrative or electoral purposes) or an area, region, or section with a distinguishing character
- **Quarter:** a division or district of a town or city
- **Neighborhood:** a section lived in by neighbors and usually having distinguishing characteristics
- **Town/City:** a thickly settled, highly populated area
- **Community:** the people living in a particular area
- **Area:** a geographic region
- **Block:** a usually rectangular space (as in a city) enclosed by streets and occupied by or intended for buildings
- **Building:** a usually roofed and walled structure built for permanent use (as for a dwelling)

Data availability

No data was used for the research described in the article.

Table A.4
Based on terminology identified in the literature (Natanian et al., 2024; Haji Bashi et al., 2023), the present paper categorizes terms according to their origin, demonstrating that NDCs incorporate at least one term derived from urban planning and social sciences, in addition to energy-related terminology. The present paper further includes search results from Google Scholar and Scopus for district concepts. Google Scholar results are based on exact search terms for papers published between 2019 and July 18, 2024, while Scopus results account for plural forms using advanced wildcard filtering as of November 8, 2024. **Bold font** emphasizes the most prevalent concepts without any claim to completeness.

Concept	Energy	Urban planning	Social sciences	Scholar	Scopus
By Natanian et al. (2024):					
Net Zero Emission Neighborhood	Net Zero Emission	Neighborhood		2	2
Positive Energy Community	Positive Energy		Community	87	19
Sustainable Plus Energy Neighborhood	Plus Energy	Neighborhood	Sustainable	9	8
Nearly Zero Energy Neighborhood	Nearly Zero Energy	Neighborhood		8	6
Net Zero Energy Community	Net Zero Energy		Community	399	57
Low Energy District	Low Energy	District		246	19
Nearly Zero Energy District	Nearly Zero Energy	District		125	18
Net-Zero Energy District	Net-Zero Energy	District		317	27
Positive Energy Block	Positive Energy	Block		112	13
Positive Energy District (PED)	**Positive Energy**	**District**		**780**	**228**
By Haji Bashi et al. (2023):					
Community Energy System	Energy System		Community	1,780	344
Local Energy System	Energy System	Local		2,120	487
Community Energy	**Energy**		**Community**	**16,200**	**1,791**
Community Energy Project	Energy Project		Community	591	97
Citizen Energy	Energy		Citizen	2,360	177
Energy Citizenship	Energy		Citizenship	1,400	87
Citizen Power Plant	Power Plant		Citizen	14	1
Citizen Energy Community	Energy		Citizen, Community	697	90
Renewable Energy Community (REC)	**Renewable Energy**		**Community**	**2,580**	**618**
Active Customer	Customer		Active	2,910	267
Jointly Acting Renewable Self-Consumer	Renewable		Self-Consumer	8	9
Renewable Self-Consumer	Renewable		Self-Consumer	80	14

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