Building and Environment 255 (2024) 111429

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Ten questions on tools and methods for positive energy districts

Jonathan Natanian [a,*], Francesco Guarino [b], Naga Manapragada [a], Abel Magyari [c], Emanuele Naboni [d,e], Francesco De Luca [f], Salvatore Cellura [g], Alberto Brunetti [b], Andras Reith [c,h]

[a] Faculty of Architecture and Town Planning, Technion – Israel Institute of Technology, Technion City, Haifa, 3200003, Israel
[b] Department of Engineering, University of Palermo, Viale delle Scienze Edificio 9, 90145, Palermo, Italy
[c] Advanced Building and Urban Design (ABUD), Budapest, Hungary
[d] Department of Engineering and Architecture DIA, University of Parma, Parco Area delle Scienze 181A, 43124, Parma, Italy
[e] Institute of Architecture and Technology, The Royal Danish Academy of Fine Arts Schools of Architecture, Design, and Conservation, Philip de Langes Allé 10, DK-1435, København K, Denmark
[f] Academy of Architecture and Urban Studies, Department of Civil Engineering and Architecture, Tallinn University of Technology, Estonia
[g] Energy Department, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129, Torino, Italy
[h] Faculty of Engineering and Information Technology, University of Pécs, Pécs, Hungary

ARTICLE INFO

Keywords:
Positive energy districts design
Environmental performance assessment and simulation
Energy and carbon balance
Urban design
Urban environmental evaluation
Urban climate adaptation

ABSTRACT

Positive Energy Districts (PEDs) are emerging as a new symbol for sustainable urbanism and energy transition in the built environment. The pursuit of PED development is increasingly rooted in several EU policies and initiatives, sparking discourse on the interplay between governance, technological and non-technological solutions, multiple stakeholders, and the dynamics of urban and climatic contexts. As their name suggests, PEDs are characterized by surplus renewable energy generation; however, recent developments in urban environmental science emphasize the critical need for an integrated approach to achieve the key performance indicators of the UN 17 Sustainable Development Goals (SDGs). Consequently, PED designs must dynamically integrate several stakeholders. These complexities intersect with urban challenges such as urban heat islands, microclimates, nature-based solutions integration, future climatic conditions, resource availability, social vibrancy, connectivity, walkability, economic activity, and more. Current tools are fragmented, severely limiting their ability to support such a multifaceted design process. This paper describes a holistic framework for tools and methods for PED design through a set of relevant questions. Drawing upon the expertise of nine researchers with complementary practical and scientific experience in various aspects of district-scale environmental performance analysis, we offer a comprehensive overview of the scopes, methods, metrics, and toolchains for PEDs, along with available tools to integrate them into different phases of the design process. This paper highlights both the challenges and opportunities ahead, emphasizing the cutting-edge methods and tools necessary to achieve robust, resilient, and data-driven processes for PED designs in a dynamic, multi-scale, and multi-disciplinary urban environment.

1. Introduction

Global climate and urban challenges have spurred a shift in urban design towards resilience and sustainability. Rapid urbanization in the digital age of a changing climate, necessitates data-driven policies and tools to balance diverse environmental factors, including energy, carbon emissions, and indoor and outdoor environmental quality, in a multi-stakeholder context. This shift has elevated the discourse on positive energy districts (PEDs) as an emblem of decarbonized urban design. Key drivers of this trend include a transition from isolated building-focused approaches to a comprehensive focus on urban-scale energy and environmental performance, along with the nearly zero-energy design policy [1], highlighting on-site renewable energy generation and energy balance. Recent European Union policies have amplified the importance of PEDs, with the goal of establishing 100 operational PEDs across Europe by 2050 [2], in alignment with prior EU initiatives like the 100 climate-neutral cities by 2030 [3]. These policies have sparked the formation of various working groups and initiatives, including the European strategic energy technology (SET) Plan Action 3.2, the

* Corresponding author.
E-mail address: jonathann@technion.ac.il (J. Natanian).

https://doi.org/10.1016/j.buildenv.2024.111429
Received 18 December 2023; Received in revised form 11 March 2024; Accepted 15 March 2024
Available online 21 March 2024

Nomenclature

PED	positive energy district
SDG	sustainable development goal
ZEB	zero energy building
AI	artificial intelligence
ML	Machine learning
LCA	life cycle assessment
BIM	building information modeling
ICT	information and communication technology
BEM	building energy modeling
UBEM	urban building energy modeling
REN	renewable
NO-REN	non – renewable
H&C	heating and cooling
DHW	domestic hot water
EL	electricity
CO_{2eq}*-UP*	CO_{2eq} emissions (use-phase)
CO_{2eq}*-LC*	CO_{2eq} emissions (life cycle)
EE-LC	embodied energy (life cycle)
CO_2*-UP*	CO_2 emissions (use-phase)
PE-UP	primary energy (use phase)
CO_{2eq} *CUPM*	CO_{2eq} emissions (construction, use phase, mobility)
PED-CUPM	primary energy demand (construction, use phase, mobility)
DL	daylight
IAQ	indoor air quality
TC	thermal comfort
UHI	urban heat island
IC	investment cost
PBT	payback time
NPV	net present value
O&M	operation and maintenance costs
IPCC	intergovernmental panel on climate change
GCM	global climate models
RCM	regional climate models
UCM	urban climate modeling
POE	post occupancy evaluation
EV	electric vehicle
IoT	internet of things
UI	user interface
UX	user experience
DR	demand response
TSO	transmission system operator
DSO	distribution system operator

PED-EU-NET EU COST action program, and the international energy agency (IEA) Annex 83. Numerous research studies support these initiatives, exploring different aspects of PEDs, from their overarching framework [4] and precise definitions [5] to diverse implementation approaches [6] and their role in renovation projects [7], among other considerations.

The joint programming initiative (JPI) Urban Europe defines PEDs [8] as "energy-efficient and energy-flexible urban areas or groups of connected buildings that produce net zero greenhouse gas emissions and actively manage an annual local or regional surplus production of renewable energy. They require integration of different systems and infrastructures and interaction between buildings, the users, and the regional energy, mobility, and information and communication technology (ICT) systems, while securing the energy supply and a good life for all in line with social, economic, and environmental sustainability." This comprehensive definition underscores the multi-dimensional aspects of PED design, demanding novel tools and workflows to assess the impact of various design variables on a range of environmental considerations and facilitate communication with various stakeholders throughout the design process.

Recent advances in computational tools enable more efficient and precise assessments of various environmental criteria, including carbon footprint, energy performance, and indoor and outdoor environmental quality [9]. Parametric workflows and artificial intelligence (AI) are increasingly integrated into evaluation processes (e.g., Ref. [10]), extending the scope and scale of environmental performance assessments from single buildings to larger urban districts [11]. These improvements strike a balance between analytical speed and accuracy, facilitating seamless and, in some cases, interactive analyses. However, the current landscape remains fragmented, lacking the necessary interconnectivity between tools and a holistic framework essential for addressing the multi-dimensional challenges inherent in the design process of PEDs.

While there is a global ambition to promote PEDs, as well as an ongoing advancement in eco-computational urban design tools, a critical gap persists as these two domains lack integration. This integration is crucial for effective, evidence-based PED design, especially when considering the multifaceted nature of this process, which encompasses various aspects, stakeholders, and performance criteria. The limited number of available PED examples [8] illustrate a fragmented design environment in which disparate tools and performance criteria support different design objectives without continuity or a clear understanding of the mutual impacts of variables and environmental performance criteria. To bridge this gap, this paper leverages the authors' collective expertise in urban-scale environmental performance analysis to present a comprehensive framework for relevant tools, methods, and workflows, accommodating various design phases, stakeholder requirements, and environmental objectives within PED designs.

The subsequent questions and answers concerning tools and methods for PEDs encapsulate the multifaceted approach necessary to confront contemporary challenges in optimizing high environmental performance at the urban scale. These inquiries cover a spectrum of critical aspects (Fig. 1): the role of tools in PED development (Q1), the impact of scale (Q2), and the clarification of analytical boundaries, encompassing metrics, benchmarks, and standards (Q3). Additionally, the underlying analytical methodologies are explained in Q4, which forms the basis for several available PED tools, categorized in Q5. The subsequent questions (Q 6–9) clarify how these tools and metrics facilitate the design process, addressing the holistic interplay among different aspects of PEDs (Q6), their role in enhancing climate and urban resilience (Q7), their capacity to support collaborative efforts from diverse stakeholders (Q8), and the gaps that persist between theoretical principles and practical application in PED design (Q9). This paper concludes with an exploration of prospects, challenges, and opportunities for PED tools (Q10).

2. Ten questions and answers

2.1. What is the role of tools and methods in positive energy districts design?

The term "positive energy districts" (PEDs) initially appears to focus solely on the energy balance between supply and demand. However, when viewed in the context of broader discussions encompassing the 17 sustainable design goals (SDGs), regenerative design, environmental quality, and climate change, a more complex picture emerges. In this discussion, it becomes essential to examine the role of tools and methods in PED design within the larger performative framework required in our contemporary era. This framework is directly influenced by four key

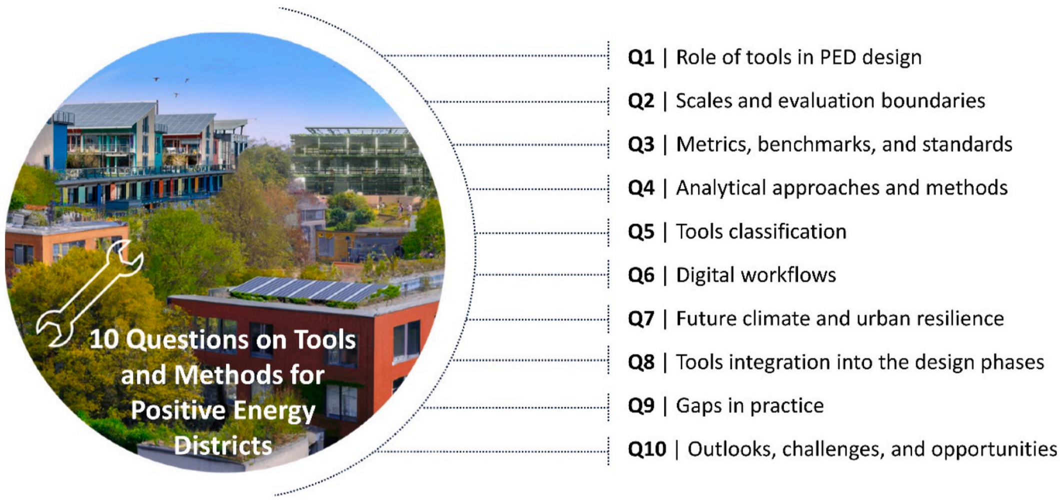

Fig. 1. Overview of the 10 Questions concerning tools and methods for PEDs discussed in this paper.

factors: (1) the shift in scale from single buildings to urban ecosystems; (2) the transition from singular environmental objectives to multifaceted analyses; (3) the growing involvement of multiple stakeholders in the design process; and (4) the increasing adoption of data-driven design processes.

Transition from nZEBs to PEDs: The shift from nearly (net) zero energy buildings (nZEBs or NZEBs) to positive energy districts (PEDs) signifies a transition from individual building energy efficiency to district-wide surplus energy generation and management in urban areas. Despite their differences, both terms prioritize the energy balance between supply and demand, promoting on-site renewable energy generation. Research efforts in pursuit of nZEB [1] and ZEB goals have led to studies focusing on energy performance prediction tools [12], renewable energy integration [13], life cycle assessment (LCA) [14], grid integration [15], energy monitoring and verification [16], and occupant behavior and user experience [17]. These efforts have also highlighted the need to expand the concept of nZEBs to an urban scale and consider both environmental quality and energy performance aspects within the design process [18]. The PED concept, which evolved a decade later, operates on similar principles: promoting surplus energy generation at the district scale while aiming towards carbon neutrality, incorporating further aspects like urban energy systems, energy mutualization, and building energy interactions. This shift in scale necessitates the adaptation of existing tools and methods developed for individual nZEB strategies to account for trade-offs between individual buildings and the district concerning systems, conditions, and occupancy patterns.

Transition to Multi-Environmental Performance Objectives: Since 2010, in parallel with the energy-centric discussions about ZEBs, the introduction of the 17 SDGs in 2015, standards like WELL community [19] and the Living Community Challenge [20] have introduced various carbon and climate-related KPI frameworks related to outdoor thermal comfort, wind comfort, urban heat islands, urban energy systems, and other ecologically related domains. This broader category of ecology may include various ecological indicators related to biodiversity, habitat preservation, green infrastructure, and water management. It focuses on maintaining or enhancing the natural environment within urban districts. The broader environmental performance perspective underscores the challenge of simultaneously accounting for multiple interrelated indicators during the design process. This challenge involves exploring trade-offs between conflicting KPIs, such as solar shading versus exposure analyses, visual versus thermal comfort factors, tree canopy vs. building density, community versus building scale energy storage and supply systems, and more. Additionally, reconciling different tools that measure indices using various simulation engines with distinct input parameters and computational loads poses difficulties. Finally, there is the unresolved issue of presenting and weighing results to optimize multiple performative objectives at the district scale.

Multi-Stakeholder Engagement Tools: Designing at the district scale necessitates collaboration among a diverse set of stakeholders [21], including design experts, homeowners, local communities, policymakers, urban ecologists, and energy service providers. Effective collaboration among these stakeholders is indispensable for devising a strategy that harmonizes the multifaceted objectives of such an ambitious project, encompassing social, economic, and environmental considerations. In the context of PED design, tools that support this collaborative effort are of paramount importance. These tools should enable iterative, multi-criteria decision-making through a cohesive platform that brings together the insights and inputs of all stakeholders. They should not only facilitate the integration of diverse expertise but also promote a widely participatory design process. To address a significant gap in PED design practices, these tools should offer a continuous conceptual framework that guides stakeholders throughout the various stages of the design process. This framework ensures that design decisions are not made in isolation but are part of a holistic and inclusive approach to creating sustainable and resilient urban districts.

Embracing Data-Driven Design: The role of tools in PED design should be viewed in the broader context of the architectural shift toward data-driven processes [22]. This transformative shift is propelled by a range of innovative methods and technologies, including smart controls, AI, digital twinning, and Building Information Modeling (BIM). These technologies serve as bridges between the physical and digital dimensions of design, potentially revolutionizing the entire design process and offering multifaceted benefits, spanning prediction and evaluation, collaboration, optimization, and operational phases. These technologies bridge the physical and digital realms, potentially revolutionizing the design process and offering benefits across the entire spectrum of design activities, from prediction and evaluation to collaboration, optimization, and operation. BIM, for instance, has already demonstrated its value in supporting higher performance decision-making on the building scale. A prominent trend within data-driven design involves the transition toward parametric and generative workflows. Within platforms like Grasshopper, designers can engage in rapid and interactive exploration of an extensive design space, drawing insights from diverse data sources and simulation engines. These workflows offer exceptional adaptability to different Key Performance Indicators (KPIs) and scales. Furthermore, their efficacy is increasingly bolstered through integration with AI, enhancing designers' ability to make informed decisions.

In summary, designing PEDs in the digital regenerative era requires an adaptive set of tools capable of engaging multiple stakeholders or addressing diverse KPIs to inform and potentially optimize the design process at various phases. The following sections will delve into the various dimensions associated with this multifaceted objective.

2.2. How different scales and evaluation boundaries are changing the analytical perspective of PEDs?

Researchers involved in different projects and initiatives are engaged in defining the scales and boundaries of PEDs to help municipalities, planners, and other stakeholders exploit their potential [5,23]. Although this discussion is ongoing, there is broad consensus that upscaling from the building to the district scale is not a mere sum of single building methods and requirements [24]. On the one hand, aggregations of buildings allow for more efficient management of energy supply and demand; on the other hand, additional complexities related to boundary definition and an increased number of interdependent design factors must be taken into account [25]. Thus, new analysis tools and methods, and domains such as infrastructural and environmental, come into play. We discuss here four categories of methods and tools for the design of PEDs related to as many operational scales: the spatial scale, the system scale, the microclimate scale, and the hybrid scale.

The spatial scale of hundreds or thousands of buildings in a district requires different energy analysis methods and tools from the single building scale, for two reasons. The first is the uncertainties related to the limited cadastral information and unavailable energy use data of the existing stock and the few pieces of information available on new buildings during the early stages of design. In this regard, PEDs planning can leverage urban building energy modeling (UBEM) tools that use building archetypes based on function that accelerate the energy modeling of entire districts [26] and on tools that allow the automatic subdivision of floors in schematic core and perimeter zones [27]. The second is the very long energy simulation times required by the urban scale. To shorten times while guaranteeing results reliability, methods were developed that use a few thermal zones assigned to building façades clustered by insolation levels [28] integrated into district energy analysis tools [29]. Further, researchers proved the reliability of simplified metrics based on solar radiation and shading, building form, and urban density to predict energy use without the need for simulations [30].

The planning of PEDs can benefit from the synergetic integration of the building domain with other urban analysis domains, such as the district systems one, to improve the efficiency of demand and supply management. The optimization of the heating system network topology in consideration of different thermal plant options, heating distribution scenarios, and simulated building energy use allowed to reduce full-site energy, greenhouse gas emissions, and the cost of purchased utilities [31]. The selection of different building clusters in consideration of decentralized or centralized systems and onsite PV energy generation allowed to explore district scenarios with reduced CO_2 emissions and heating costs and to identify KPI relationships [32].

A holistic approach to PEDs planning includes consideration of the accessibility of open areas that is significantly influenced by different urban climate phenomena characteristic of urban environments with different densities and fabrics, urban surface materials, and by the energy use of buildings. Thus, PEDs evaluation boundaries need to consider the microclimate scale of the outdoor domain and environmental design goals. The block scale was considered to investigate the influence of trees and grass patches of varying building cluster forms on wind comfort in public areas [33]. The neighborhood scale was considered to analyze the effect of dense historic urban fabric with high thermal mass surfaces on the mean radiant temperature of the outdoor environment and consequent perceived temperatures by dwellers [34]. The district and city scales were used to analyze the effects of composition, spatial pattern, and green type of urban green spaces on land surface temperature to measure the potential urban heat island effect [35].

The consideration of the building and spatial scales and of the outdoor domain in the planning of PEDs, can take advantage of recently developed digital methods and tools operating at the hybrid scale, integrating different simulation workflows to analyze the combined fulfillment of several KPIs of the design solution. Some studies analyzed energy use and generation load match, indoor daylight availability, and all-year outdoor thermal comfort of building clusters different for typology [36], density, and envelope characteristics [37], while others focused on layout variations of the same office building cluster in different existing urban environments for cooling energy use reduction and outdoor thermal comfort improvement during the hot season [38], and of patterns variations of residential building clusters in an existing urban environment to guarantee facade sunlight exposure as recommended by local regulations and outdoor wind comfort according to established metrics [39].

In conclusion, the analytical perspective of Positive Energy Districts (PEDs) is influenced by different scales, such as the spatial scale determined by the number of buildings under consideration, and the domain scale, which integrates different systems like buildings and heating networks. Additionally, different evaluation boundaries come into play to integrate energy goals with others, such as livability in spaces, necessitating microclimate considerations. Upscaling to district levels requires new tools and methods, while considering outdoor microclimates and environmental goals enhances holistic planning. Integration of various simulation workflows enables comprehensive performance evaluation.

2.3. Which metrics, benchmarks and standards are used to assess PEDs?

Several definitions within the field of PEDs and high-performance neighborhoods refer to very similar entities. Among the most commonly mentioned are Net Zero Emission Neighborhood, Net Zero Energy District, Positive Energy Community, Sustainable Plus Energy Neighborhood, Nearly Zero Energy Neighborhood, Net Zero Energy Community, Low Energy District, Nearly Zero Energy District, Net-Zero Energy District, and Positive Energy Block [7,40]. These definitions share several aspects [7], including the definition of a specific geographical boundary and a particular quantitative benchmark for meeting the definition. Positive energy districts are usually more quantitative in their balance definition and refer to some qualitative issues that need consideration. In addition to the previously mentioned JPI Urban Europe definition [8], more technology-oriented definitions [41] delve into energy flexibility in more detail. They encompass not only a mere mathematical energy balance but also aspects such as load-matching, self-use, short- and long-term energy storage, smart controls, and connection to the energy grid. All available PED definitions identify a quantifiable metric that should be computed and adhere to a precise mathematical clause. Typically, the chosen metric involves energy for heating, cooling, and electricity within the focus buildings during the operational stage of the neighborhood. Other solutions consider carbon emissions during the use stage of the district, calculated primarily from the energy consumption of operating the buildings. This has implications for comparing results between PEDs in different geographical areas, as the outcomes are directly influenced by carbon equivalent emission factors and the characteristics of national energy production systems.

To quantify these metrics, clear boundary conditions are necessary, which can either be geographical or virtual [42]. In the latter scenario, the boundaries encompass not just the urban agglomeration but also the energy infrastructure beyond the geographical limits. Depending on these boundary conditions, the PED can be categorized as [43]:

- Autonomous PED: does not exchange energy beyond its geographical boundaries.

- Dynamic PED: exchanges energy beyond its geographical boundaries, importing energy during shortages and exporting during internal surplus.
- Virtual PED: considers virtual boundaries, exchanging energy with the hinterland.

In all these cases, there's the requirement to achieve a net positive energy balance over a year, expressed in final or primary energy, as per the specific formulation of interest [44,45]. A similar balance can be utilized for accounting for the net zero carbon equivalent balance. Apart from the quantitative metrics highlighted in Ref. [8], which are associated with both energy generation—overall higher than consumption—and attaining zero carbon emissions, various qualitative metrics are discussed, particularly concerning sustainability. These qualitative metrics, especially in the social context, pose inherent challenges when attempting benchmarking comparisons. Nevertheless, there's consensus that achieving the PED level necessitates primarily improving energy efficiency and reducing demand, followed by optimizing local energy flows using any surpluses and employing low-carbon energy production to cover the remaining energy use.

Smart control and energy flexibility are pivotal for locally matching demand with production wherever possible, aiming to reduce burdens and optimize the efficacy of PEDs across the broader energy grid [41]. Recurring terms from the previously mentioned definitions encompass net zero CO2 equivalent emissions, local or regional deployment of renewable energy, energy efficiency, and energy flexibility within PEDs. While these definitions offer insights into the PED concept, they remain somewhat qualitative, thereby complicating the quantitative assessment of PED achievement. Evaluating this aspect can be relatively straightforward when formally applied through an energy balance extended to a set of buildings that includes only these specified energy uses. However, it's essential to note that a district's energy and carbon footprint also encompass numerous other uses, such as mobility, street lighting, and the embodied energy within cars, buildings, and systems. Therefore, these additional aspects should be formally incorporated into the calculations through an expanded methodology for computing PED balances in terms of primary energy and carbon equivalent emissions. This methodology should also encompass embodied energy and emissions, considering the transport sector [43], adopting a life-cycle approach [46].

This gives rise to a significant challenge stemming from the interplay of geometry, landscape/urban planning, and energy management at the local level. While meeting a stringent mathematical energy-positive balance is expected to be feasible in areas with low building density, the same cannot be easily asserted for high-density, multi-story buildings where energy consumption (along with carbon emissions) per square meter could be up to an order of magnitude higher [47]. Another issue surrounding PEDs is the lack of dedicated legislation specific to them. Currently, they operate within a legal framework shared with energy communities, particularly concerning aspects of energy sharing and peer-to-peer energy connections [48,49]. These European directives are subsequently implemented at the national level by Member States through laws, regulations, and administrative provisions [50,51]. Therefore, establishing distinct standards between these two entities and refining PED definitions, consistently supported by quantifiable metrics and a well-defined assessment methodology, becomes an urgent necessity.

In conclusion, evaluating positive energy districts involves quantitative metrics, considerations of geographical or virtual boundaries, and sustainability concerns. Nonetheless, challenges persist, especially in high-density areas and the absence of specific legislation. Standardized metrics and methodologies are crucial for the effective dissemination of PEDs and to truly impact the transformation of urban environments.

2.4. What are the available analytical approaches and methods to evaluate PED performance?

The IEA EBC Annex 83 on Positive Energy Districts [52] defines PEDs as clusters of interconnected buildings that generate energy exceeding their operational requirements. While acknowledging the significance of embodied energy, the primary goal of most PEDs is to achieve carbon neutrality through a positive operational energy balance across hundreds to thousands of buildings [53]. The energy equilibrium within interconnected buildings is shaped by their efficiency and flexibility. Within the PED context, energy efficiency refers to a building's capacity to operate with minimal energy consumption, while energy flexibility denotes its ability to adjust energy consumption and production in response to demand. Diverse multi-scale morphological, material measures, and systems like ICTs and electric mobility contribute to enhancing building efficiency and flexibility [54]. Hence, the evaluation of PED performance involves assessing energy efficiency and flexibility in buildings driven by multi-scale measures and systems.

Currently, numerous UBEM tools are tailored for analytically assessing energy efficiency and flexibility in buildings driven by multi-scale measures and systems. These tools compute metrics related to energy use, demand, and renewable energy generation for buildings interconnected with urban infrastructures, such as district heating and cooling systems within PED boundaries. Serving as vital energy related KPIs, these metrics evaluate the energy balance, efficiency, and flexibility objectives of PEDs. Similarly, UBEM tools calculate carbon, climate, and comfort-related metrics, acting as KPIs for assessing PEDs' multi-environmental performance objectives. These tools display variability in considering spatial-scale models and computational approaches, allowing simulations with diverse outputs and varying temporal resolutions.

In a recent study [55], UBEM tools were categorized into three groups: physics-based models, reduced-order models, and data-driven models, based on their modeling approaches. Expanding on this classification, this study introduces a fourth category—metadata-driven models. The subsequent discussion elaborates on the methodologies employed by these four modeling approaches, along with a comprehensive exploration of their challenges and opportunities in evaluating PEDs.

2.4.1. Physics-based models

The physics-based modeling approach involves conducting transient simulations of heat transfer and energy trade-offs within buildings. Tools following this approach consider building geometry, thermal, and optical properties, as well as appliances and equipment. This level of detail allows PED designers to pinpoint measures enhancing energy efficiency and encouraging renewable energy generation in buildings [56]. The building component-level energy-related metrics computed by Physics-based models enable modelers to assess multiscale strategies, promoting efficiency and flexibility of PEDs. While energy-related metrics are sources for calculating the carbon emission of operational phase, the Physics-based models further contribute to the computation of zone-level thermal comfort metrics, like PMV and surface-specific climate metrics, like mean radiant temperatures, which are critical for evaluating the environmental performance of PEDs.

Alongside buildings, these tools can also size and evaluate district thermal and energy systems, offering a means for buildings to offset their energy demand [11]. Furthermore, this tool category aids utilities and energy service providers in making informed decisions regarding demand-response initiatives, energy efficiency programs, and related technologies [56]. Despite comprehensively addressing most energy efficiency and flexibility evaluations required for PED design, physics-based modeling tools have notable shortcomings.

The detailed simulation methodology utilized by physics-based modeling tools results in computational expense, especially for simulating city-scale PED designs. Computational limitations further present challenges when attempting multi-objective optimization using these UBEM tools. While archetypes and floor multiplication techniques exist to address computational issues [57], they often reduce outcome accuracy, which is unsuitable for certain energy efficiency and flexibility evaluations.

2.4.2. Reduced order models

Unlike physics-based models, reduced-order modeling approaches do not exhibit computational limitations. UBEM tools in this category assess PEDs' performance using normative calculation methods established by organizations like the European committee for standardization (CEN) and the international organization for standardization (ISO) [55]. Reduced-order models lack the capacity for extensive simulations, resulting in coarse output resolutions that provide an overview of PEDs' performance. Primarily, they calculate energy-related metrics from the building to the district scale to assess PEDs' efficiency and flexibility objectives. The reduced order models only incorporate a limited number of PED design details for normative calculations, limiting their utility in multi-objective optimization and the identification of strategies to improve energy performance. Aside from carbon metrics, these models struggle to compute thermal comfort and climate-related metrics, a significant drawback for modelers aiming to evaluate PEDs' environmental performance alongside energy performance. Additionally, the suitability of applying normative calculation methods across diverse climates and contexts raises questions.

2.4.3. Data-driven models

Data-driven modeling approaches employ simple regression or advanced machine learning (ML) models developed from measured data to assess PEDs. Simulating PED designs with data-driven models is computationally less expensive, and the results are reliable. Similar to physics-based models, data-driven models can simulate energy and carbon metrics with high spatial and temporal resolution swiftly. However, due to the measured data representing existing boundaries, evaluating multi-scale retrofit measures becomes impractical. The ability to compute comfort and climate-related metrics hinges on the output variables selected for the model's development. Furthermore, the adaptability of mathematical or ML models to different climates and contexts may be limited [55].

2.4.4. Metadata-driven models

Similar to data-driven modeling approaches, the metadata-driven modeling approach also utilizes simple regression or ML models, but these are developed from simulated data, known as metadata. Initially, the physics-based modeling approach is used to simulate a few parametric PED design iterations and generate metadata. Subsequently, simple or advanced statistical methods are employed to test and train models using this metadata. Ultimately, the model facilitates the determination of multi-objective optimized PED designs with less computational power. Since simple regression or ML models are produced from metadata developed through physics-based modeling, the results tend to be reliable. Additionally, metadata-driven models can compute energy, carbon, climate, and comfort metrics with spatial and temporal resolutions akin to those provided by physics-based models. However, modelers must ensure the comprehensive inclusion of all pertinent metrics data in the development of metadata-driven models. It's worth noting that metadata-driven modeling approaches for simulating PEDs' performance are still evolving, with very few studies [18,58] available in the current literature.

In summary, evaluating PED performance involves assessing the energy efficiency and flexibility as well as other environmental quality KPIs of an interconnected cluster of buildings. In addition to the various research advancements that delve into different KPIs and the analytical approaches to effectively evaluate them, recent PED-associated projects, initiatives, and environmental performance rating systems have developed additional sets of self-standing KPI frameworks. While UBEM tools exist for evaluating hundreds to thousands of buildings and their associated district systems, there are notable limitations. Among the four UBEM approaches discussed, the metadata-driven modeling methodology stands out significantly in addressing concerns related to computation, accuracy, and optimization.

2.5. What are the available PED tools and how can we classify them?

Tools designed for energy modeling of PEDs vary in scope, resolution, objectives, and modeling techniques. A few tools encompass aspects of the social domain (e.g., intelligent community design (iCD) [59]) and mobility issues (e.g., City Energy Analyst [60]), while the majority focus on building energy demand and supply. Some tools employ simplified dynamic modeling approaches (e.g., City Energy Analyst [61], TEASER [62]) for calculating thermal loads, while most utilize physics-based dynamic simulations to assess thermal loads (e.g., EnergyPlus [63]). A comprehensive and exhaustive classification of these tools is a highly complex task, almost equivalent to a dissertation or book. However, for the purpose of this inquiry, certain specific aspects will be considered. Particularly, attention will be given to aspects of interest for modelers approaching the task of modeling positive energy districts. These aspects can be succinctly summarized by the following questions:

- What domains does the tool investigate? (e.g., can it model energy use in buildings? does it calculate CO2 emissions for transportation?)
- What is the tool based on? Which mathematical models does it implement?
- What outputs can the tool provide?

A total of 43 tools were analyzed, with 70% deemed suitable for research purposes, 58% for practitioners, and 28% useable by both researchers and practitioners.

2.5.1. Domains covered by the tools

Many tools primarily focus on energy-related aspects, analyzing energy generation (67%) and consumption (77%) at the building or district level. Only 9% of the tools consider mobility issues (e.g., LakeSIM [64]). Additionally, 40% of the tools incorporate environmental aspects, but merely 7% perform a full life cycle assessment for CO2 equivalent emissions. Among the analyzed tools, 33% account for indoor environmental aspects such as daylight, indoor air quality (IAQ), and thermal comfort. Outdoor environmental aspects, addressing outdoor thermal comfort and urban heat islands, are addressed by 16% of the tools. While economic aspects are covered by 51% of the PED tools, only 12% of them assess the payback time (PBT) or the net present value (NPV).

Decision support tools are included among the reviewed PED tools, although not all of them compute building thermal loads. Specifically, tools like Calliope [65], energyPRO [66], oemof [67], and MANGO [68] are single- or multi-objective optimization tools focusing mainly on energy supply technologies within geographical boundaries. Energy demand can be an exogenous parameter (Calliope, energyPRO, MANGO) or an endogenous one (oemof). Other decision support tools concentrate more on network topology and urban planning (DecodingSpaces Toolbox [69], Urbano [70], DigiWo [71]). Colibri [72] and Thread/DesignExplorer [73,74] serve as interfaces for visualizing key modeling results. Lastly, Opossum [75] and Octopus [76] support optimization tools for Rhino and Grasshopper. The specific fields covered by each tool are detailed in Table 1. The table groups various applications, including those related to the 'environmental boundary' category encompassing climate change, carbon emissions, acidification, eutrophication, land use, ecological footprints, particulate matter emissions, and human toxicological effects (not an exhaustive list). Table 1 covers only broad areas of categorization for the sake of brevity and readability. This means that all tools can provide further elaboration

Table 1
PED modeling tools and domains of interest.

Tool	DOMAIN OF APPLICATION: Energy – Energy demand	Energy – Energy supply	Energy – Mobility	Environmental boundary	Indoor environment	Outdoor environment	Economic	Social
Intelligent Community Design (iCD) [59]	H&C, DHW, EL	REN, NO-REN		CO_{2eq}-UP			O&M	other[1]
Insight [88]	H&C, EL	REN, NO-REN			DL		IC, PBT, O&M	
Urban Modeling Interface (UMI) [82]	H&C, DHW, EL	REN, NO-REN		CO_{2eq}-LC, EE-LC	DL			other[2]
Sefaira [81]	H&C, DHW, EL	REN, NO-REN		CO_2-UP	DL, TC		O&M	
ClimateStudio [83]	H&C, DHW, EL	REN		CO_2-UP	DL, TC		O&M	
Ladybug [86]						TC		
Honeybee [84]	H&C, DHW, EL	NO-REN		CO_2-UP	DL, TC			
Dragonfly [87]	H&C, DHW, EL	REN, NO-REN	X	CO_2-UP		UHI	IC	
Butterfly [88]					TC	TC		
Pollination [89]	H&C, DHW, EL	NO-REN			DL, TC			
Eddy3D [90]						TC		
Morpho [91]						TC		
Envimet [92]						TC		
CityBES [93]	H&C, DHW, EL	REN, NO-REN		CO_{2eq}-LC		TC, UHI	IC, PBT, O&M	
URBANopt [94]	H&C, DHW, EL	REN, NO-REN		CO_{2eq}-UP				
COFFEE [95]	H&C, DHW, EL	NO-REN						
CitySim [96]	H&C, DHW, EL	REN, NO-REN						
SEMANCO [97]	H&C, EL	REN, NO-REN		CO_2-UP			O&M	
SimStadt [77]	H&C, DHW, EL	REN, NO-REN		PE-UP, CO_2-UP			IC, O&M	
LakeSIM [64]	H&C, DHW, EL		X					
City Energy Analyst [60]	H&C, DHW, EL	REN, NO-REN	X	CO_{2eq}-CUPM, PED-CUPM			IC, O&M	
Tool For Energy Analysis and Simulation For Efficient Retrofit (TEASER) [62]	H&C	REN, NO-REN						
Calliope [65]	H&C, DHW, EL	REN, NO-REN					O&M	
energyPRO [66]	H&C, EL	REN, NO-REN					IC, PBT, NPV, O&M	
oemof (Open Energy Modeling	H&C, EL	REN, NO-					IC	

Framework) [78]		REN						
MANGO [68]	H&C, DHW, EL	REN, NO-REN		CO_2-UP			IC, O&M	
ICL (Intelligent Communities Life Cycle) [85]	H&C, DHW, EL	REN, NO-REN	X	CO_2-UP			IC, PBT, O&M	
DER-CAM [98]	H&C, DHW, EL	REN, NO-REN		CO_2-UP			IC, PBT, O&M	
Making City (ENERKAD®) [99]	H&C, DHW, EL	REN		CO_2-UP			O&M	
DeCodingSpaces Toolbox [69]	Not applicable[1]							
Urbano [70]								other[3]
DigiWo [70]	Not applicable[2]							
Design Explorer/ Thread[3] [74,73]	H&C, EL				DL			
Colibri[3] [72]	H&C, EL							
Opossum [75]	Not applicable[4]							
Octopus [76]	Not applicable[4]							
EnergyPlus [63]	H&C, DHW, EL	REN, NO-REN		CO_{2eq}-UP	DL, IAQ, TC		IC, O&M	
trnsys [100]	H&C, DHW, EL	REN, NO-REN			TC		IC, O&M	
DOE-2 [101]	H&C, DHW, EL	REN, NO-REN			DL		O&M	
eQUEST [102]	H&C, DHW, EL	REN, NO-REN			DL		O&M	
ESP-r [103]	H&C, DHW, EL				DL, TC			
OpenIDEAS [104]	H&C, DHW, EL	NO-REN					O&M	
DesignBuilder [105]	H&C, DHW, EL	REN, NO-REN		CO_{2eq}-LC	DL, IAQ, TC		IC, O&M	

Table 1 legend:

covered by the tools (green) — not covered by the tool (orange)

H&C	heating and cooling	**NO-REN**	non-renewable energy	**CO_{2eq}-CUPM**	CO_{2eq} emissions (construction, use phase, mobility)	**DL**	daylight	**IC**	investment cost
EL	electricity	**CO_{2eq}-UP**	CO_{2eq} emissions (use-phase)	**PE-UP**	primary energy (use phase)	**IAQ**	indoor air quality	**PBT**	payback time
DHW	domestic hot water	**CO_{2eq}-LC**	CO_{2eq} emissions (life cycle)	**CO_2-UP**	CO_2 emissions (use-phase)	**TC**	thermal comfort	**NPV**	net present value
REN	renewable energy	**EE-LC**	embodied energy (life cycle)	**PED-CUPM**	primary energy demand (construction, use phase, mobility)	**UHI**	urban heat island	**O&M**	operation and maintenance costs

[1] Collection of components for algorithmic architectural and urban planning, including street network generation and analysis, visibility, and statistical data analysis, building blocks generation

[2] The tool has the target to generate buildings starting from pre-defined blocks, to maximize some targets, such as the building density.

[3] The tool does not perform energy simulations; it is an interface that collects previous simulation results.

[4] The tool does not perform energy simulations; it can be exploited as a support optimization tool in Grasshopper.

Other[1]: Jobs created, disposable income, fuel poverty, property value, derelict development, Walkability, Accessibility, energy consumption reduction

Other[2]: Jobs created, walkability

Other[3]: Amenity demand profile, streetscore, amenityscore, walkscore

on the simple outputs. For example, they can elaborate on the composition of temperature outputs within adaptive comfort outputs or establish connections between indoor environment variables and generation/consumption for flexibility or load match indicators, either explicitly or through user input. Additionally, it denotes the tool's capacity to calculate aspects of both renewable energy-based systems (e.g., PV or wind turbines) and non-renewable energy-based systems (e.g., gas boilers). The landscape for PED modeling predominantly emphasizes energy demand (77%) and supply (67%), with limited consideration given to mobility (9%) and social issues (7%).

2.5.2. *Modeling approaches*

Over half of the analyzed PED tools rely on building energy dynamic simulation (55.8%), with only a few conducting static analyses (7%). Tools utilizing static-based simulation, like SimStadt [77], provide outputs with monthly timeframe resolution. Among dynamic simulation tools, further distinctions exist between simplified and physics-based dynamic simulation models. Simplified dynamics models, such as oemof [78], adhere to calculation standards based on technical norms, regulations, or national guidelines, constituting 8.3% of the dynamic-based tools. Other simplified dynamic tools (e.g., City Energy Analyst, TEASER) utilize reduced-order models from Modelica libraries [79], representing 12.5% of the dynamic-based tools. Such simplified approaches are typically focused on the early stages of PED design.

Physics-based simulation models offer detailed results and are utilized for more advanced stages of PED design (including energy flexibility considerations). These tools usually rely on the EnergyPlus [63] engine (e.g., Sefaira [80], UMI [81], ClimateStudio [82], Honeybee [83]). Additionally, iCD [59] and ICL [84] deploy the 'Digital Twin' modeling approach, incorporating real-time operational data alongside physics-based simulation. The modeling approaches employed by the analyzed tools are detailed in Table 2.

About 39.5% of the analyzed tools employ physics-based simulation models to simulate building behavior, while 18.6% utilize simplified dynamic models or static ones. The utilization of data-driven approaches, combining physics-based simulation models with real-time operational data, introduces a further refinement to modeling building behavior. However, similar to simplified dynamic and static models, these approaches remain relatively scarce (4.7%).

2.5.3. *Main outputs or results obtained by the tools*

While most PED tools consider the energy supply and demand of the PED itself, there's comparatively less focus on environmental aspects. Climate change is addressed as an impact category in all PED tools dealing with environmental issues (40%). Around 33% of PED tools evaluate carbon dioxide emissions during the operational phase, while only a few account for the entire life cycle (UMI [81], CityBES [86], DesignBuilder [104]). Only 7% of the tools assess primary energy demand throughout the operational phase (UMI [81], SimStadt [77], and City Energy Analyst [60]), while embodied energy is considered by 5% of the tools (UMI [81], City Energy Analyst [60]). Concerning economic aspects, investment costs are assessed at 30% and operational costs at 49% of the tools. However, only 12% estimate the payback time or net present value (Insight [85], CityBES [63], energyPRO [66], ICL [84], DER-CAM [97]). Social aspects are largely neglected by most PED tools (93%), with exceptions like iCD [88], UMI [81], and Urbano [70], which address social indicators like job creation and walkability. Table 1 details the main results obtainable from each tool.

There's a notable lack of emphasis on environmental and social issues, with only 40% and 7% of the tools, respectively, accounting for them. Moreover, additional environmental impact stages beyond operational phases should be considered. Furthermore, there's a deficiency in implementing metrics for assessing the financial viability of investments, such as payback time and net present value, in 88% of the analyzed tools.

In conclusion, the analysis highlights varied approaches to PED modeling potential, with diverse classifications based on investigated items and mathematical modeling. The current focus largely centers on energy balances and computing energy requirements for heating, cooling, and electricity consumption in buildings. However, true integration of modeling domains should be pursued for under-represented elements such as mobility modeling, social aspects, economic factors, life cycle environmental sustainability, and outdoor thermal comfort.

2.6. *How can digital workflows be leveraged to achieve advanced PED designs?*

This section explores digital workflows, namely Grasshopper for Rhino [105], and their transformative potential in PED designs. The focus lies in creating advanced PEDs that achieve a net positive energy balance while prioritizing ecology and health [106]. This dynamic and multifaceted perspective is particularly critical in rapidly changing urban climates [107,108].

Advanced PEDs should consider this complexity of

Table 2
Main modeling features of the PED tools (not applicable means that tools do not perform building thermal energy simulation).

MAIN CHARACTERISTICS				
Tool	Design phase	Scale (city, district, building)	Time-resolution (dynamic/static)	Modeling approach
Intelligent Community Design (iCD) [59]	Detailed design	District	Dynamic	Data-driven
Insight [85]	From early concept to detailed design	Building	Dynamic	Physics-based
Urban Modeling Interface (UMI) [81]	Early phase	District, city	Dynamic	Physics-based
Sefaira [80]	Early phase	Building	Dynamic	Physics-based
ClimateStudio [82]	From early concept to detailed design	Building, district	Dynamic	Physics-based
Ladybug [86]	Early phase	Building, district	Not applicable	Not applicable
Honeybee [83]	From mid concept to detailed design	Building	Dynamic	Physics-based
Dragonfly [87]	From early concept to detailed design	District	Dynamic	Physics-based
Butterfly [85]	Not applicable	Building, district	Not applicable	Not applicable
Pollination [88]	From early concept to detailed design	Building	Dynamic	Physics-based
Eddy3D [89]	Not applicable	district	Not applicable	Not applicable
Morpho [90]	Not applicable	District	Not applicable	Not applicable
Envimet [91]	Not applicable	District	Not applicable	Not applicable
CityBES [92]	Early phase	District, city	Dynamic	Physics-based
URBANopt [93]	From early to mid-concept	District	Dynamic	Physics-based
COFFEE [94]	Early phase	Building, district	Dynamic	Physics-based
CitySim [95]	Early phase	District, city	Dynamic	Reduced order calculation method
SEMANCO [96]	Early phase	District	Static	Standards-based
SimStadt [77]	Early phase	Building, district, city	Static	Standards-based
LakeSIM [64]	Early phase	District, city	Static	Reduced order calculation method
City Energy Analyst [60]	Early phase	District	Dynamic	Reduced order calculation method
Tool For Energy Analysis and Simulation For Efficient Retrofit (TEASER) [62]	Early phase	Building, District	Dynamic	Reduced order calculation method
Calliope [65]	Not applicable	From district to	Not applicable	Not applicable

(continued on next page)

Table 2 (*continued*)

MAIN CHARACTERISTICS				
Tool	Design phase	Scale (city, district, building)	Time-resolution (dynamic/static)	Modeling approach
		national scale		
EnergyPRO [66]	Not applicable	From district to regional scale	Not applicable	Not applicable
oemof (Open Energy Modeling Framework) [78]	Early phase	District	Dynamic	Standards-based
MANGO [68]	Not applicable	District, city	Not applicable	Not applicable
ICL (Intelligent Communities Life Cycle) [84]	Detailed design	District	Dynamic	Data-driven
DER-CAM [97]	Not applicable	Building, district	Not applicable	Not applicable
Making City (ENERKAD®) [98]	Early phase	Building, district, city	Dynamic	Standards-based
DeCodingSpaces Toolbox [69]	Not applicable	District, city	Not applicable	Not applicable
Urbano [70]	Not applicable	District, city	Not applicable	Not applicable
DigiWo [70]	Not applicable	Building, district	Not applicable	Not applicable
Design Explorer/ Thread [73,74]	Not applicable	Building, district	Not applicable	Not applicable
Colibri [72]	Not applicable	Building, district	Not applicable	Not applicable
Opossum [75]	Not applicable	Not applicable	Not applicable	Not applicable
Octopus [76]	Not applicable	Not applicable	Not applicable	Not applicable
EnergyPlus [63]	From early concept to detailed design	Building, district	Dynamic	Physics-based
TRNSYS [99]	From early concept to detailed design	Building, district	Dynamic	Physics-based
DOE-2 [100]	From early concept to detailed design	Building, district	Dynamic	Physics-based
eQUEST [101]	Early concept	Building, district	Dynamic	Physics-based
ESP-r [102]	Early phase	District	Dynamic	Physics-based
OpenIDEAS [103]	Early phase	Building, district	Dynamic	Physics-based
DesignBuilder [104]	From early concept to detailed design	Building, district	Dynamic	Physics-based

performances. They should integrate comprehensive digital workflows for dynamic energy management, employing predictive analytics to optimize consumption and responsive systems that adapt to climate variations. PED designs should harmonize with urban aspects like ecological systems, all bolstered by sophisticated digital frameworks that enhance health and sustainability. In contrast, less advanced PEDs often consider energy in isolation from broader sustainability aspects. The distinction between isolated tool use and integrated digital workflows is pivotal in PED design and crucial for grasping technological integration nuances and process optimization. Digital tools, like Modelica, City Energy Analyst (CEA), TRNSYS, and others, play a key role in tasks such as energy modeling, simulation, and data analysis. While no single tool perfectly combines all PED elements [11], current PEDs might struggle to effectively respond to climate change, environmental shifts, and community needs. However, employing digital workflows enables the amalgamation of these tools into a cohesive, integrated approach [109]. Shifting from singular tools to integrated digital workflows in advanced PEDs opens new possibilities, allowing them to better adapt to environmental changes and embrace a more sustainable, resilient urban living approach.

It is critical to operate in a digital environment where multiple tools can be combined. This mitigates the complexity of disparate systems by offering a unified platform for data exchange and tool interoperability. For example, Grasshopper enables the integration of various plugins and external data sources, simplifying complex analyses and design tasks. Combining tools from Table 3 in a unified workflow allows for cross-referencing of data and insights. In this advanced design context, parametric platforms facilitate seamless data transfer between different tools and computational methods via plugins (Table 4). Modules handling numerical and geometric data can connect for diverse assessment objectives. Integrated workflows streamline the capture and relay of simulation input parameters across various platforms, refining results without direct linkage [110]. For instance, digital tools for energy evaluation coupled with ecological tools like Meerkat for GIS data integration and Ladybug for climate data visualization [86] or Morpho (an ENVI-met interface) for climate modeling data integration enable PED adaptation to local microclimates [111,112].

District-level adaptation can notably reduce energy demand [113, 114]. The Elk plugin processes biodiversity-focused GIS data, enriching designs with ecological metrics such as habitat patches. The Mosquito plugin integrates public health data, assessing design impacts on health to support urban designs. Additionally, the DeCodingSpaces Toolbox promotes healthier PEDs by facilitating walkability and enhancing contact with nature, empowering PED planners to craft health-enhancing spaces. At the core of this workflow lies the tool's inherent capacity for seamless data transfer. For instance, Grasshopper, with its robust data management and interoperability via plugins like TT Toolbox (for data streaming), ensures consistent data flow (Table 4). This fosters an integrative, data-driven design approach addressing energy, ecology, and health metrics cohesively. Optimization tools like Galapagos, Octopus, and Opossum refine design workflows. Integrating emerging technologies—AI, the internet of things (IoT), and blockchain—is crucial to augmenting PED capabilities, especially for climate change adaptation and managing energy and ecological systems. These technologies offer new avenues for dynamic adaptation, efficient resource use, and predictive modeling within digital workflows, aligning environmental parameters with design needs. Machine learning's role in PED design, as demonstrated by plugins like Owl, Dodo, and Lunchbox, leverages learning paradigms that may supersede traditional simulations.

Synergy of digital capability and real-world applicability. This synergy is crucial for the effective integration of digital workflows, particularly in advancing PED design and implementation. Platforms like Grasshopper streamline tool integration and data management, yet they aren't universal solutions, requiring a balanced approach blending technical proficiency with an understanding of local context and community needs. Integrating multiple sophisticated tools presents challenges, especially for teams lacking technical expertise. Grasshopper, as an example of an integrated digital environment, mitigates complexities by providing a unified platform for simplifying analyses through plugin integration and external data sources. However, this.

Integration demands more than mere data aggregation; it requires nuanced understanding for optimizing PED designs. Implementing a holistic digital workflow necessitates robust IT infrastructure and technical expertise, which are crucial for reliable simulations. While platforms like Grasshopper streamline data processes, robust data collection and validation, along with stakeholder capacity building, remain vital. Balancing digital reliance with real-world contexts is paramount,

Table 3
PED digital workflow: Overview of key tools and plugins compatible with grasshopper for design optimization across energy, ecology, and health domains.

Category	Tool/Plugin Name	Functionality (Based on Existing Knowledge)	Data Received	Data Provided	PED Affected Design Variable
Energy	City Energy Analyst (CEA)	High-resolution urban energy demand simulations, integrating building physics & energy systems.	GIS data, Climate Data.	Building physics, energy systems, energy demand.	Building energy efficiency, HVAC systems optimization.
	TRNSYS	Specialized in district heating and cooling; traces energy sources, storage, and consumption.	District System designs, Solar installations.	Energy consumption, heating/cooling data.	District-level energy consumption, Storage & distribution optimization.
	CitySim	Simulates urban energy and environmental dynamics (assumed).	Building designs, Climate Data.	Energy consumption patterns, environmental interactions.	Urban energy balance, Interactions between buildings and environment.
	Honeybee	Dynamic building energy simulations.	Building designs, Weather data.	Energy consumption patterns, thermal properties.	Building-level energy consumption, Facade design optimization.
	Dragonfly	Urban-scale energy and environmental simulation.	Urban layouts, Climate data.	Energy and environmental performance data.	Urban form and fabric energy efficiency.
	UMI	Integrates various urban planning and design tools for comprehensive sustainability analysis.	Urban layouts, Climate data	Sustainability metrics, urban design impacts.	Urban sustainability strategies, holistic urban planning.
Ecology	Meerkat	GIS data integration tool within Grasshopper.	Site designs, Urban layouts.	GIS data, including topography, land use, etc.	Land use optimization, Site-specific design interventions.
	Ladybug	Integrates and visualizes climate-related data for design purposes.	Building designs, Urban layouts.	Climate data, weather patterns.	Climate adaptation strategies, Sunlight/shade optimization.
	Morpho	Interface to ENVI-met; focused on microclimate modeling.	Building designs, Urban layouts.	Climate data, microclimate interactions.	Microclimate management, green infrastructure design.
	Elk	Biodiversity-focused GIS data processing tool.	Site designs, Urban layouts.	GIS data, including habitat patches, biodiversity metrics.	Biodiversity enhancement, Habitat preservation & creation.
	Pando	Modeling of vegetation systems	Greenery Design	Vegetation types	Behavior of Vegetation, Microclimatic analysis
	Green Scenario	Environmental impact assessment of urban designs	Urban designs, ecological data	Environmental impact analysis, green infrastructure strategies	Ecological impact assessment, green infrastructure planning.
Health	Mosquito	Integrates public health data for design evaluation.	Urban designs, Building layouts.	Public health metrics, population data.	Public health promotion, Design for well-being & comfort.
	DeCoding Spaces Toolbox	Urban and architectural analysis tools enhancing spatial understanding.	Building designs, Urban layouts.	Topological, network, and spatial data.	Enhanced Walkability, and Vision of Natural Features

Table 4
PED digital workflow: Overview of grasshopper plugins categorized by functionality: Interoperability, optimization, machine learning, and visualization.

Category	Name of Plugin	Function & Data Interaction	Relevance to PED design
Interoperability & Integration	TT Toolbox	Ensures data streaming between Grasshopper and other platforms using multiple design data to provide streamlined data for other tools.	Data integration & seamless design workflows.
Optimization	Galapagos/ Octopus/ Opossum	Optimization tools refine design parameters using design data and environmental parameters to yield optimized design parameters.	Enhanced energy efficiency, Ecological balance, and Health promotion.
Machine Learning	Owl/Dodo/ Lunchbox	Learning paradigms supplant traditional simulations, using design data and previous simulations to offer predictive designs and simulations.	Proactive designs based on learning from data.
Visualization	Design Explorer	Tool that visualizes complex design spaces, employing design variations and simulated outcomes to present a visual representation of design spaces.	Design clarity, Decision-making support.

ensuring that over-reliance on digital tools doesn't overshadow on-ground realities. Adapting digital workflows to local contexts and incorporating qualitative insights ensures designs resonate with local environments and community needs.

In summary, the effective use of digital workflows in designing advanced PEDs hinges on integrating diverse tools within platforms like Grasshopper. While these platforms offer significant potential for optimizing PED designs across energy, ecology, and health parameters, they also present challenges in complexity, data management, and balancing digital capabilities with real-world contexts. Success in this endeavor requires technical proficiency and adaptability, considering local environmental and community dynamics.

2.7. Which new PED tools are needed considering future climate and urban resilience?

Considering future weather conditions in PED design is crucial due to escalating climate change impacts. The resilience and long-term sustainability of PEDs rely on adapting to shifting climate patterns and extreme weather events. Neglecting future climate scenarios may result in suboptimal energy performance, overestimation of heating or cooling demands, and potential mismatches in energy generation and consumption, jeopardizing PEDs' overall energy balance and environmental goals. To ensure PEDs' effectiveness amid climate change, using high-resolution future weather data and advanced modeling for evolving urban microclimates is vital. This chapter discussed the pivotal role of such considerations in PED design for developing resilient, energy-efficient districts capable of addressing uncertainties posed by an uncertain climate future.

Like buildings, the energy systems in PEDs can be categorized into base load and variable load systems based on their reliance on climatic conditions [115]. Base load systems, such as street lighting, exhibit energy consumption tied to usage, while variable load systems like district cooling depend on ambient climate conditions. UBEM tools evaluate these systems' energy performance using representative weather files [116], available in formats like "typical meteorological year," "test reference year," or "design summer year." Typically, statistical methods generate these files to eliminate infrequent extremities from historical weather datasets [117]. However, relying on present-day representative weather files for PED assessment offers insights into past climate conditions but overlooks future climate changes. Several studies [118,119] have highlighted potential overestimations of heating and underestimations of cooling demands in buildings when simulated with present-day representative weather files. These concerns raise questions about the energy efficiency and adaptability of PEDs in future climate change scenarios.

Presently, future weather file generators produce climate-specific files worldwide, aligning with climate change scenarios from the intergovernmental panel on climate change (IPCC). These files derive from global or regional climate models (GCMs or RCMs) validated by the IPCC's Working Groups. GCMs offer broader spatial resolutions, typically a few hundred kilometers, while RCMs provide finer resolutions, from a few tens of kilometers to meters. To enhance spatial accuracy, future weather file generators employ static and dynamic downscaling methods, especially where RCM outputs aren't available for every geolocation [120]. Although GCM and RCM outputs mostly offer daily or monthly data, weather files require hourly resolution. To address this, generators use static and dynamic temporal downscaling models, providing the necessary hourly climate data [121]. However, it's crucial to note that the high-resolution data used for downscaling captures a location's boundary layer climate.

Historical data used for present-day weather files or downscaling is collected from weather monitoring stations near airports or building rooftops, capturing the boundary layer climate [117]. However, in densely built areas like cities, this boundary layer climate might not accurately represent PEDs' energy systems. Buildings exhibit notable deviations in cooling and energy performance due to overlooking microclimatic influences from urban form and materiality [122]. Errors in building energy performance arise from neglecting microclimatic influences induced by nature-based solutions [123]. Hence, integrating urban climate modeling (UCM) with building energy modeling (BEM) tools becomes imperative for accurately simulating building energy performance [124]. Some researchers have devised chaining and coupling techniques to integrate microclimatic data into building energy simulations [125]. The chaining approach involves one-way data exchange between UCM tools and BEM tools for the same timestep, while the coupling approach engages in two-way data exchange either in parallel or in sequence. UCM tools, like urban weather file generators, modify present-day or future representative weather files, considering urban form and materiality, and are utilized for chaining with UBEM. The coupling approach effectively exchanges transient heat flux information between UBEM and UCM tools at each step. However, these coupling methods, although available, entail high computational expenses, especially for conducting annual simulations [126].

In conclusion, addressing future climate conditions is vital for the success of PEDs. Neglecting the impact of changing weather patterns can result in energy inefficiencies and pose risks to the overall sustainability of PEDs. Additionally, accounting for microclimatic conditions alongside future climatic scenarios is equally crucial in PEDs' energy evaluation. To effectively address these challenges, the development of user-friendly tools, high-resolution weather files, and advanced modeling techniques becomes imperative. This holistic approach is essential for designing resilient PEDs capable of effectively managing an ever-evolving climate and diverse microclimatic conditions, ensuring their sustainable energy performance and long-term viability.

2.8. How are PED tools integrated into the design phases and with which stakeholders do they interact?

The PED process, which links building and city levels, is complex and necessitates diverse tools and stakeholder inputs, thereby presenting challenges across scales and life-cycle stages. Understanding tool utilization throughout the PED process involves the simultaneous assessment of design phases, scales, and stakeholders. The PED design landscape showcases various methods to identify key phases, as reviewed by the PED-EU-NET team [127]: the MakingCity project's [128] six-phase approach, the Atelier project's [129] seven-step strategy, and Project RESPONSE's [130] four phases. The key phases identified by Cheng et al. [131]—master planning, energy planning, construction, implementation, monitoring, and POE—will aid in aligning goals, tools, and stakeholders for better categorization within this chapter.

Throughout the design phases of PEDs, effective multidisciplinary collaboration among stakeholders remains paramount. Li et al. [132] advocate for spatial-tiered stakeholder categorization, emphasizing the importance of multi-level decision-making. The Louisiana Planning Assembly Kit [133] and Positive Energy Districts Solution Booklet [134] delineate relevant planning scales, spanning from regional to building levels. However, harmonizing design phases, stakeholder interests, and scales can be challenging due to their frequent intersections. In practice, these elements are interconnected by critical decision-making junctures known as 'intervention points.' Stakeholders navigate challenges during these intervention points using various tools. Given the fluid roles of stakeholders in PED development, it becomes crucial to scrutinize the pertinent stakeholders and tools employed at each intervention point. For a comprehensive grasp of tools in PED development, Table 5 elucidates the connection between intervention points and design phases [131], and Table 6 delineates key stakeholders [128,129,131,132,134,135] associated with each point. Tables 5–6 use intervention points as a common thread, visually clarifying the complexity and hierarchy within the PED design process.

Upon reviewing the utilization of PED design tools addressing intervention points in real-world demonstrations [127], it becomes evident that during early phases like master planning and energy planning, tools focusing on sustainable energy vision are prominent, accompanied by methods for swift and iterative energy demand assessment (e.g., ENERKAD). As the process progresses into intermediate phases, encompassing energy planning and construction/refurbishment planning, the emphasis shifts towards tools enabling multi-scale energy assessment (e.g., ENERKAD, CEA, and Ladybug) and those analyzing specific intervention points, such as addressing flexibility issues like SpineOPT. In the later stages, particularly from the Construction/Refurbishment Planning phase at the building scale, the focus lies on tools for energy and comfort assessment, including EnergyPlus, IDA ICE, and TRNSYS. In the concluding phases of PED development, such as monitoring and post-occupancy evaluation (POE), the utilization of more experimental tools becomes evident, such as digital twins and model predictive control algorithms.

Table 2 illustrates a comprehensive array of PED tools, revealing that the majority (25 tools) are tailored for early phases, with 11 extending to detailed design. However, a noticeable shortage of tools is evident for later stages, particularly in post-implementation tasks such as POE and monitoring. This observation aligns with the insights gleaned from intervention points in Tables 5 and 6 Out of the 17 identified intervention points, 13 are associated with the design phases preceding implementation, while only 4 are linked to post-implementation stages. This trend also extends to stakeholder involvement, with all 30 identified stakeholders actively engaged in pre-implementation phases, underscoring their critical role throughout the entire design process until its final stages. Despite an apparent balance in tool distribution, the dearth of tools in later stages, especially for monitoring, energy and flexibility management, and energy accounting, remains conspicuous.

Table 5
PED design phases, and corresponding intervention points.

Design phases → Intervention points ↓	Master planning	Energy planning	Construction/renovation planning	Implementation	Monitoring	POE
Energy vision	X					
Renewable potential	X	X	X			
Building placement/insolation	X					
Outdoor comfort	X					
Energy and flexibility design	X	X				
User mix	X	X				
Integration with wider infrastructure		X	X			
Integrating EVs		X	X			
Passive design		X	X			
Indoor comfort		X	X			
Energy storage		X	X			
Micrigrids		X	X			
Active design system efficiency		X	X			
Energy and flexibility management			X	X	X	
Occupant behavior		X	X	X	X	X
Accounting of energy				X	X	X
Decision support	X	X	X	X	X	X

Table 6
Key stakeholders in each intervention point during the PED design process.

scales → Intervention points ↓	City scale	District scale	Building scale
Energy vision	Local authorities, Enterprises, Knowledge institutes, Citizens		
Renewable potential	Energy suppliers, TSOs, DSOs, Flexibility/Energy market operators, Local authorities, City energy engineers, Developers	Energy engineers, Architects, Local authorities	Architects, Electrical/Mechanical engineers, Manufacturers, Installation companies, Facility management, Local authorities
Building placement/insolation	City planners, Local authorities, Designers, Developers	District planners, Architects, Local authorities	
Outdoor comfort		District planner, Local authorities, Designers, Developers	
Energy and flexibility design	Energy suppliers, TSOs, DSOs, Flexibility/Energy market operators, Local authorities, City energy engineers, Developers	Energy suppliers, TSOs, DSOs, Flexibility/Energy market operators, Local authorities, City energy engineers, Developers	Energy engineers, Mechanical/Electrical engineers
User mix		Social planners, Energy engineers, Energy manager, DSO, Flexibility market operator, Energy communities	
Integration with wider infrastructure	Energy suppliers, TSOs, DSOs, Regional/local authorities, Developers		
Integrating EVs		Energy suppliers, TSOs, DSOs, Flexibility/Energy market operators, Local authorities, City energy engineers, Developers	Energy suppliers, TSOs, DSOs, Flexibility/Energy market operators, Local authorities, City energy engineers, Developers
Passive design			Architects, Manufacturers, Construction company
Indoor comfort			Architects, Mechanical/Electrical engineers, Occupants
Energy storage			Architects, Electrical/Mechanical engineers, Manufacturers, Installation companies, Facility management, Local authorities
Microgrids		Energy manager, Energy providers, DSO, Asset manager, Energy engineers, Local authorities	
Active design system efficiency			Architects, Electrical/Mechanical engineers, Manufacturers, Installation companies, Facility management
Energy and flexibility management		Energy suppliers, TSOs, DSOs, Flexibility/Energy market operators, Local authorities, City energy engineers, Developers	Flexibility market operator, Energy manager, Energy providers, DSO, Asset manager, Energy engineers, Local authorities, Energy communities
Occupant behavior			Occupants, Facility management
Accounting of energy		Energy manager, Energy providers, DSO, Energy manager, Asset manager, Energy engineers, Local authorities	
Decision support	All	All	All

Presently, only a handful of experimental tools, such as model predictive control algorithms and digital twins, address these pivotal aspects.

The narrative of PED design, encapsulated within the text and tables, underscores a multi-faceted approach that integrates diverse tools and stakeholder inputs across various phases. Initially, although optimization and energy analysis tools are available, their utilization isn't as widespread when compared to tools used in defining the project's vision. Tools tailored for intermediate-to-final design stages, spanning from district to building scales, are increasingly being incorporated into the planning process with greater efficacy. However, despite the critical importance of post-occupancy evaluation (POE) and monitoring in later stages, these areas still demand better tool integration and more advanced utilization. Consequently, a persistent gap remains in meeting the diverse tool needs of city, district, and building planners. Bridging this gap mandates the integration of missing tools and the adoption of a unified, comprehensive design approach aligned with the Integrated Energy Design [136] philosophy. This alignment is pivotal for unlocking the full potential inherent in PEDs.

2.9. What are the gaps between the existing tools and PED design in practice?

There is a significant gap in unified PED design frameworks, largely attributed to the field's novelty and the diversity of local contexts. Factors including varying regulations, types of renewables, energy storage, consumption patterns, and local economic opportunities require a tailored approach, necessitating distinct tools for different scenarios [137]. Examining case studies from PED-EU-NET [127] provided insights into the tools currently utilized in PED design. These tools predominantly include energy modeling software, either at the building level (TRNSYS [99], EnergyPlus [63], IDA-ICE [138]) or the neighborhood scale (CEA [60], ENERKAD [98]). Additionally, methods for flexibility assessment (grey-box modeling [139]) and technology selection (web-based decision tree module [3]) are utilized. In some case studies, virtual twins (GRIDS energyCity [140] platform, SPARCS Virtual Twin [141]) play a role during operational phases. However, the incompleteness of these tools reveals a spectrum of challenges, some of which are tool-addressable (energy and optimization) and others that are beyond tool capabilities (policy or political changes). This article specifically targets tool-addressable challenges, striving to identify necessary tools and connections by analyzing the barriers outlined in Table 7 from PED-EU-NET [127].

While the absence of certain tools is one reason for existing gaps, based on experience, there are other factors at play. Use cases from industry show that even tools with potential advantages might be underused because of various performance gaps, such as industry reluctance towards modern technologies, organizational and technical challenges, and lack of tool integration [142–144]. Under the umbrella of Annex 83 [145], aspects were identified based on five existing case studies, including a range of tools such as TRNSYS [99], CEA [60], EnergyPLAN [146], and EnergyPlus [63], where current energy modeling software must improve for better adoption, along with the associated challenges and potential paths for improvement [147].

From a design practice perspective, PED tools are categorized based on usage into three groups: First, those that are widely used and integrated into PED design. Second, those that are available but underutilized due to challenges with integration, usability, user interface and user experience (UI/UX), and accuracy, as detailed in Belda et al., [147]. Third are the absent tools, which include emergent behavior simulation and blockchain, along with necessary capabilities like fast, iterative scenario analysis and essential links between cost and renewable modeling. These gaps are discussed in Table 7.

The current fragmented toolkit for PED design complicates essential tasks like calibration, sensitivity analysis, and validation, rendering them resource intensive. Although AI and ML solutions are still in their infancy and have not yet been fully integrated, they hold the potential to streamline these processes, promising a future of enhanced design efficiency. By fostering interdisciplinary collaboration, we can harness these technologies to streamline design processes and navigate the complexities of urban development. Advancing this synergy of tools and expertise is imperative for the realization of PEDs, ensuring sustainable and adaptive urban environments for future generations.

Table 7
Mapping barriers in PED design practice and potential tool solutions.

Barriers	Challenge	Capability needed	Tool Gap
Regulatory	Missing cross-sectoral collaborations	Interoperability	Cross-sectoral tool connections
Economic	High initial investment for renewable transition	Econometric-renewable modeling connection	Econometric-renewable modeling link
	Energy-inefficient buildings or low-income tenants	Quick cost-benefit and impact assessment	Renovation scenario and impact analysis tool
	Optimizing energy flows cost-effectively	Low-data resolution cost-benefit optimization	Optimization for energy generation, storage, and consumption
	Identifying and monetizing multiple benefits	Easy-benefit monetization methods	Multiple benefits calculation
	Lack of models assessing local energy sharing	Multiple scenario calculation and energy sharing optimization	Tool modeling local energy sharing
Technical	Selecting energy-saving measures	Customizable multi-scale energy modeling	Adaptable energy modeling software
	Maximize renewable uses, local-regional network connections	Renewable potential analysis with broader system connection	Regional electricity and renewable modeling software
	Enabling sector coupling and exchange of energy	Multiple scenario calculations, connecting energy flows, energy sharing optimization	Software module capable of analyzing energy flow and sharing.
	Cost-effective energy storage exploration	Energy storage optimization linked to energy systems	Integrated energy storage modeling
	Integrating EVs in energy system design	Integrated or composable EV model	EV and energy modeling
	Exploring blockchain for local power management	Blockchain emulation, emergent behavior modeling	Integrated blockchain module analyzing costs and effects of blockchain implementation
	Demand response	Integrated or composable demand response (DR) model	DR optimization module
	Monodirectional infrastructure	Low-voltage microgrid scenario analysis	Integrated microgrid scenario analysis module
	Nature based solutions (NBS) integration	Coupling NBS with energy modeling	Integration of NBS analysis with energy modeling
Social	Passive users	Emergent behavior scenario analysis	Agent-based PED performance tool
	Limited energy flexibility	Emergent behavior scenario analysis	Agent-based PED performance tool

2.10. What are the outlooks, future challenges, and opportunities for PED tools?

The concept of PEDs is poised for global expansion as urban sustainability initiatives expand. To assess their potential, we can learn from the 15-year history of ZEB implementation, which has taught us that the gap between ZEB conceptualization and realization remains significant and that the majority of ZEBs have remained demonstration projects [148]. In contrast, PEDs have set clear policy-level implementation goals, with Europe aiming for 100 PEDs by 2050 [2]. Yet, bridging the high aspirations of PEDs with practical urban design realities poses significant challenges [149]. To facilitate PED implementation, a set of tools supporting PED design will be essential for city planners, designers, and developers to align with regulations and policies.

Considering the broader context, the future of PED design tools appears transformative [137]. This transformation will be driven by technological advancements, a heightened focus on high-energy-performance urban design, and environmental quality.

These tools will optimize energy efficiency, integrate nature-based solutions (NBS), renewable energy sources, and urban storage and supply systems, including advanced energy storage and water management. They will also prioritize environmental quality, addressing aspects like visual and thermal comfort, air and water quality, green and blue infrastructures, and biodiversity, fostering holistic, eco-friendly, and livable districts.

In the context of these aspects and the scopes, metrics, and toolsets discussed, this paper identifies key future challenges and opportunities for PED tools. These challenges and opportunities are categorized using the same framework introduced earlier (Q1), providing insights into the evolving landscape of PED implementation.

2.10.1. Transitioning from individual buildings to districts

Opportunities: Beyond BEM, UBEM tools gradually unlock the ability of tools to predict, optimize, and communicate energy-related aspects of district building interactions, such as district energy load balance, combined storage systems, mixed-use energy mutualization, district heating and cooling, and renewable energy interactions [9]. Beyond operational energy, the district-scale engagement expands the analytical life cycle analysis perspective and opens new horizons for exploring the mutual impacts of buildings, green systems, and the environmental quality of outdoor semiprivate and public spaces (e.g., outdoor thermal comfort).

Challenges: Upscaling the analysis and management boundary from the building to the district is computationally complex due to the datasets needed to perform a reliable analysis, the integration of several KPIs, and the computational loads needed to allow for such a comprehensive integration [150].

2.10.2. Multi-objective environmental analysis

Opportunities: The need in PED design to perform fast and large-scale calculations while accounting for several environmental performance KPIs at the district scale and generate optimized scenarios based on those KPIs necessitates the aid of artificial intelligence [151]. The evolution of AI- and ML-enhanced workflows for architectural design optimization is accelerating, and their incorporation into the PED design process is a natural next step. This is particularly important when considering the need for real-time analyses or when involving multiple stakeholders in a collaborative PED design process.

Challenges: (1) lack of established methods for appropriately weighing different KPIs during PED optimization in the design phase; (2) the integration of quantitative and qualitative indicators; (3) the harmonization of fragmented tools and metrics, each requiring distinct input data and evaluation protocols, resulting in potential inefficiencies in PED design as also highlighted by Ref. [42]; and (4) the constraint of computation time impedes effective and timely communication.

2.10.3. Multi-stakeholders' engagement

Opportunities: Collaborative design platforms facilitating the participation of multiple stakeholders in PED projects promise enhanced decision-making and consensus-building. Virtual reality (VR) and augmented reality (AR) technologies offer immersive visualization of PED designs, aiding stakeholders and the public in comprehending and engaging with proposed projects. Co-simulation and collaborative platforms are being developed to allow interactive exploration of PED design criteria or multiple design scenarios. Visual aids such as interactive screens help these tools communicate spatial and numerical results to diverse audiences [152].

Challenges found to be closely linked to the stakeholder engagement challenges found by Refs. [4,153]: (1) cost considerations, as smaller municipalities and design firms may encounter difficulties in affording advanced immersive PED design tools; (2) the need to develop tailored software-hardware interfaces for each type of project; and (3) the current limitations of available immersive technologies in terms of usability, response time, and user comfort (e.g., field of view in AR platforms).

2.10.4. Data-driven design

Opportunities: Rapid advances in IoT and GIS technologies link smart city and urban digital twinning initiatives. These advancements will create new middleware like urban geospatial workflows, dashboards, web-based applications, and GIS-driven tools for PED design [154]. These tools enable interactive, data-driven, multi-disciplinary PED design using data from various sources.

Challenges: (1) securing accurate and up-to-date energy consumption, microclimatic, and other data repositories necessary for coherent and precise performative prediction and analysis [155]; (2) addressing privacy concerns that limit data use for design; and (3) overcoming the lack of standardized protocols and data formats.

In conclusion, despite the challenges encountered, the field of PED tools offers many opportunities for innovation, collaboration, and integration into urban development initiatives. As PEDs become increasingly prevalent, these tools will emerge as indispensable instruments in advancing the objectives of establishing an effective collaborative and holistic data-driven environment for PED designs.

3. Conclusions

The emergence of Positive Energy Districts (PEDs) represents a significant shift toward sustainable urbanism and energy transition, underscoring the need for a comprehensive approach to address multi-faceted urban challenges. This publication delves into the intricate web of factors influencing PED development, emphasizing the necessity for integrated tools and methods. It unravels the complexities associated with PED designs, transcending mere energy balance by exploring the interplay of governance, technology, stakeholders, and urban dynamics. From the shift in scale to multifaceted analyses and the integration of diverse stakeholders, this paper illuminates how tools serve as essential conduits in navigating the contemporary landscape of PED design.

Each question tackled in this study provides key insights into the technical intricacies of PED tools. From the role of tools in a performative framework encompassing multiple sustainable design goals to the integration of simulations for holistic assessments, the paper navigates through the challenges posed by high-density areas, the absence of standardized metrics, and the necessity for improved databases and methodologies. Moreover, these sections emphasize the necessity of transcending traditional energy balance metrics. They stress the importance of embracing varied aspects such as outdoor microclimates, social dynamics, economic elements, future climatic scenarios, microclimatic conditions, and life cycle sustainability within the modeling domains for a comprehensive understanding. The discussions underscore that while energy balance remains pivotal, true integration of these diverse domains stands imperative for a more holistic assessment of PEDs. Recognizing this complexity, it becomes evident that the integration of tools like UBEM, simulations for microclimate assessment, and the convergence of various analytical perspectives—from energy evaluations to considerations of social, economic, and environmental elements—present an intricate yet essential facet of PED design.

As we conclude this exploration, it's evident that the realm of PED tools stands at the crossroads of innovation and challenge. The potential for collaboration, innovation, and integration into urban development initiatives is immense, as are the promises AI-driven solutions hold for PED tools in mitigating data complexities, scaling analyses to district-level precision, and streamlining multi-objective optimizations. However, this potential is counterbalanced by challenges ranging from computational complexities to the prioritization of key performance indicators, tool integration, affordability, data accuracy, privacy concerns, and standardization. Looking ahead, the trajectory for PED tools indicates a promising avenue for advancements, necessitating a collective effort to address challenges and capitalize on opportunities.

CRediT authorship contribution statement

Jonathan Natanian: Writing – review & editing, Writing – original draft, Visualization, Supervision, Project administration, Data curation, Conceptualization. **Francesco Guarino:** Writing – review & editing, Writing – original draft, Data curation, Conceptualization. **Naga Manapragada:** Writing – original draft, Conceptualization. **Abel Magyari:** Writing – original draft, Conceptualization. **Emanuele Naboni:** Writing – review & editing, Writing – original draft, Conceptualization. **Francesco De Luca:** Writing – review & editing, Writing – original draft, Conceptualization. **Salvatore Cellura:** Writing – original draft, Data curation, Conceptualization. **Alberto Brunetti:** Writing – original draft, Data curation, Conceptualization. **Andras Reith:** Writing – review & editing, Writing – original draft, Conceptualization.

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.

Data availability

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

Acknowledgements

This article is partially based upon work from COST Action 19126 Positive Energy Districts European Network PED-EU-NET (see https://pedeu.net), supported by COST (European Cooperation in Science and Technology, http://www.cost.eu). The work presented in this paper was partially funded within the KINETIC project (Knowledge Integration for Neighbourhoods in Energy Transition led by Inclusive Communities) under Positive Energy Districts and Neighbourhoods Joint Call for Proposals, PROJECT NUMBER: 43971918. The work is partially developed within the International Energy Agency's (IEA) Energy in Buildings and Communities (EBC) Annex 83 ″Positive Energy Districts" workgroup. The first and third authors acknowledge the support from the Israeli Ministry of Energy [grant number 221-11-037].

References

[1] EPBD, Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast), Off. J. Eur. Union 18 (6) (2010) 2010.
[2] S. Bossi, C. Gollner, S. Theierling, Towards 100 positive energy districts in Europe: preliminary data analysis of 61 European cases, Energies (2020).
[3] European Commission, 100 Climate-Neutral Cities by 2030—By and for the Citizens, Interim Report of the Mission Board for Climate-Neutral and Smart Cities, Publications Office of the European Union, Luxembourg, 2020.
[4] S. Sareen, V. Albert-Seifried, L. Aelenei, F. Reda, G. Etminan, M.-B. Andreucci, M. Kuzmic, N. Maas, O. Seco, P. Civiero, S. Gohari, M. Hukkalainen, H.-M. Neumann, Ten questions concerning positive energy districts, Build. Environ. 216 (2022) 109017.
[5] V. Albert-Seifried, L. Murauskaite, G. Massa, L. Aelenei, D. Baer, S.G. Krangsås, B. Alpagut, A. Mutule, N. Pokorny, H. Vandevyvere, Definitions of positive energy districts: a review of the status quo and challenges, Sustain. Energy Build. 2021 (2022) 493–506.
[6] S. Koutra, J. Terés-Zubiaga, P. Bouillard, V. Becue, 'Decarbonizing Europe' A critical review on positive energy districts approaches, Sustain. Cities Soc. 89 (2023) 104356.
[7] F. Guarino, R. Rincione, C. Mateu, M. Teixidó, L.F. Cabeza, M. Cellura, Renovation assessment of building districts: case studies and implications to the positive energy districts definition, Energy Build. 296 (2023) 113414, https://doi.org/10.1016/j.enbuild.2023.113414.
[8] JPI Urban Europe/SET Plan Action 3.2, White Paper–Reference Framework for Positive Energy Districts and Neighbourhoods, 2020. https://jpi-urbaneurope.eu/ped/.
[9] D. Mauree, E. Naboni, S. Coccolo, A.T.D. Perera, V.M. Nik, J.-L. Scartezzini, A review of assessment methods for the urban environment and its energy sustainability to guarantee climate adaptation of future cities, Renew. Sustain. Energy Rev. 112 (2019) 733–746.
[10] P. de Wilde, Building performance simulation in the brave new world of artificial intelligence and digital twins: a systematic review, Energy Build. 292 (2023) 113171.
[11] J. Allegrini, K. Orehounig, G. Mavromatidis, F. Ruesch, V. Dorer, R. Evins, A review of modelling approaches and tools for the simulation of district-scale energy systems, Renew. Sustain. Energy Rev. 52 (2015) 1391–1404.
[12] M.H. Abokersh, M. Spiekman, O. Vijlbrief, T.A.J. van Goch, M. Vallès, D. Boer, A real-time diagnostic tool for evaluating the thermal performance of nearly zero energy buildings, Appl. Energy 281 (2021) 116091.
[13] A. Ahmed, T. Ge, J. Peng, W.-C. Yan, B.T. Tee, S. You, Assessment of the renewable energy generation towards net-zero energy buildings: a review, Energy Build. 256 (2022) 111755.
[14] H. Omrany, V. Soebarto, Time to do more: realisation of life-cycle net-zero energy buildings, in: Reference Module in Earth Systems and Environmental Sciences, Elsevier, 2022.
[15] W. Zhang, C. Yan, Y. Xu, J. Fang, Y. Pan, A critical review of the performance evaluation and optimization of grid interactions between zero-energy buildings and power grids, Sustain. Cities Soc. 86 (2022) 104123.
[16] G. Dermentzis, F. Ochs, N. Franzoi, Four years monitoring of heat pump, solar thermal and PV system in two net-zero energy multi-family buildings, J. Build. Eng. 43 (2021) 103199.
[17] H. Kazmi, M. Keijsers, F. Mehmood, C. Miller, Energy balances, thermal performance, and heat stress: disentangling occupant behaviour and weather influences in a Dutch net-zero energy neighborhood, Energy Build. 263 (2022) 112020.
[18] J. Natanian, T. Auer, Beyond nearly zero energy urban design: a holistic microclimatic energy and environmental quality evaluation workflow, Sustain. Cities Soc. 56 (2020) 102094.
[19] WELL community standard. https://www.wellcertified.com/certification/community/.
[20] The living community challenge. https://living-future.org/lcc/.
[21] S. Koutra, J. Terés-Zubiaga, P. Bouillard, V. Becue, 'Decarbonizing Europe' A critical review on positive energy districts approaches, Sustain. Cities Soc. 89 (2023) 104356.
[22] S. Mousavi, M.G. Villarreal-Marroquín, M. Hajiaghaei-Keshteli, N.R. Smith, Data-driven prediction and optimization toward net-zero and positive-energy buildings: a systematic review, Build. Environ. 242 (2023) 110578.
[23] X. Zhang, S.R. Penaka, S. Giriraj, M.N. Sánchez, P. Civiero, H. Vandevyvere, Characterizing positive energy district (PED) through a preliminary review of 60 existing projects in Europe, Buildings 11 (2021), https://doi.org/10.3390/buildings11080318.
[24] S. Shnapp, D. Paci, P. Bertoldi, Enabling Positive Energy Districts across Europe: Energy Efficiency Couples Renewable Energy, 2020. https://publications.jrc.ec.europa.eu/repository/handle/JRC121405.
[25] A.R. Amaral, E. Rodrigues, A. Rodrigues Gaspar, Á. Gomes, Review on performance aspects of nearly zero-energy districts, Sustain. Cities Soc. 43 (2018) 406–420, https://doi.org/10.1016/J.SCS.2018.08.039.
[26] Y.Q. Ang, Z.M. Berzolla, C.F. Reinhart, From concept to application: a review of use cases in urban building energy modeling, Appl. Energy 279 (2020) 115738, https://doi.org/10.1016/J.APENERGY.2020.115738.
[27] T. Dogan, C. Reinhart, P. Michalatos, Autozoner: an algorithm for automatic thermal zoning of buildings with unknown interior space definitions, J. Build. Perform. Simulat. 9 (2016) 176–189, https://doi.org/10.1080/19401493.2015.1006527.
[28] T. Dogan, C. Reinhart, Shoeboxer: an algorithm for abstracted rapid multi-zone urban building energy model generation and simulation, Energy Build. 140 (2017) 140–153, https://doi.org/10.1016/J.ENBUILD.2017.01.030.
[29] Sustainable Design Lab, Urban Modeling Interface, 2023. http://web.mit.edu/sustainabledesignlab/projects/umi/index.html.
[30] E. Nault, G. Peronato, E. Rey, M. Andersen, Review and critical analysis of early-design phase evaluation metrics for the solar potential of neighborhood designs, Build. Environ. 92 (2015) 679–691, https://doi.org/10.1016/J.BUILDENV.2015.05.012.
[31] S. Letellier-Duchesne, S. Nagpal, M. Kummert, C. Reinhart, Balancing demand and supply: linking neighborhood-level building load calculations with detailed district energy network analysis models, Energy 150 (2018) 913–925, https://doi.org/10.1016/J.ENERGY.2018.02.138.
[32] T. Guo, A novel approach to address spatial uncertainties and simultaneously optimize concept, scope, and equipment design in district heating system, in: Build. Simul. Conf. Proceedings. 18th International Conference of the International Building Performance Simulation Association 2021, Shanghai, China, 2023.
[33] A. Norouziasas, P. Pilehchi Ha, M. Ahmadi, H.B. Rijal, Evaluation of urban form influence on pedestrians' wind comfort, Build. Environ. 224 (2022) 109522, https://doi.org/10.1016/J.BUILDENV.2022.109522.
[34] B. Gherri, D. Maiullari, C. Finizza, M. Maretto, E. Naboni, On the thermal resilience of Venetian open spaces, Heritage 4 (2021) 4286–4303, https://doi.org/10.3390/heritage4040236.
[35] C. Yang, X. He, R. Wang, F. Yan, L. Yu, K. Bu, J. Yang, L. Chang, S. Zhang, The effect of urban green spaces on the urban thermal environment and its seasonal variations, Forests 8 (2017), https://doi.org/10.3390/f8050153.
[36] J. Natanian, P. Kastner, T. Dogan, T. Auer, From energy performative to livable Mediterranean cities: an annual outdoor thermal comfort and energy balance cross-climatic typological study, Energy Build. 224 (2020) 110283.

[37] J. Natanian, O. Aleksandrowicz, T. Auer, A parametric approach to optimizing urban form, energy balance and environmental quality: the case of Mediterranean districts, Appl. Energy 254 (2019) 113637.
[38] F. De Luca, E. Naboni, G. Lobaccaro, Tall buildings cluster form rationalization in a Nordic climate by factoring in indoor-outdoor comfort and energy, Energy Build. 238 (2021) 110831, https://doi.org/10.1016/J.ENBUILD.2021.110831.
[39] F. De Luca, Sun and wind: integrated environmental performance analysis for building and pedestrian comfort, in: Simul. Ser. 51, Issue 8,10th the Symposium on Simulation for Architecture and Urban Design, 2019, pp. 3–10. SimAUD 2019, Atlanta (GE), USA, https://dl.acm.org/doi/10.5555/3390098.3390099.
[40] J. Brozovsky, A. Gustavsen, N. Gaitani, Zero emission neighbourhoods and positive energy districts – a state-of-the-art review, Sustain. Cities Soc. 72 (2021) 103013, https://doi.org/10.1016/j.scs.2021.103013.
[41] IEA EBC Annex 83, Positive Energy Districts, 2020.
[42] I. Marotta, F. Guarino, S. Longo, M. Cellura, Environmental sustainability approaches and positive energy districts: a literature review, Sustainability 13 (2021), https://doi.org/10.3390/su132313063.
[43] O. Lindholm, H. ur Rehman, F. Reda, Positioning positive energy districts in European cities, Buildings 11 (2021), https://doi.org/10.3390/buildings11010019.
[44] E. Derkenbaeva, S. Halleck Vega, G.J. Hofstede, E. van Leeuwen, Positive energy districts: mainstreaming energy transition in urban areas, Renew. Sustain. Energy Rev. 153 (2022) 111782, https://doi.org/10.1016/j.rser.2021.111782.
[45] A. Gabaldón Moreno, F. Vélez, B. Alpagut, P. Hernández, C. Sanz Montalvillo, How to achieve positive energy districts for sustainable cities: a proposed calculation methodology, Sustainability 13 (2021), https://doi.org/10.3390/su13020710.
[46] M. Ala-Juusela, T. Crosbie, M. Hukkalainen, Defining and operationalising the concept of an energy positive neighbourhood, Energy Convers. Manag. 125 (2016) 133–140, https://doi.org/10.1016/j.enconman.2016.05.052.
[47] F. Mostafavi, M. Tahsildoost, Z.S. Zomorodian, Energy efficiency and carbon emission in high-rise buildings: a review (2005-2020), Build. Environ. 206 (2021), https://doi.org/10.1016/j.buildenv.2021.108329.
[48] European Parliament and Council of the European Union, Directive (EU) 2019/944 of the European Parliament and of the Council of 5 June 2019 on Common Rules for the Internal Market for Electricity and Amending Directive 2012/27/EU, recast), 2022.
[49] European Parliament and Council of the European Union, Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the Promotion of the Use of Energy from Renewable Sources, recast), 2022.
[50] E. Cutore, R. Volpe, R. Sgroi, A. Fichera, Energy management and sustainability assessment of renewable energy communities: the Italian context, Energy Convers. Manag. 278 (2023) 116713, https://doi.org/10.1016/j.enconman.2023.116713.
[51] E. Cutore, A. Fichera, R. Volpe, A roadmap for the design, operation and monitoring of renewable energy communities in Italy, Sustainability 15 (10) (2023).
[52] Å. Hedman, H.U. Rehman, A. Gabaldón, A. Bisello, V. Albert-Seifried, X. Zhang, F. Guarino, S. Grynning, U. Eicker, H.-M. Neumann, P. Tuominen, F. Reda, IEA EBC Annex83 positive energy districts, Buildings 11 (2021) 130, https://doi.org/10.3390/buildings11030130.
[53] B. Alpagut, Ö. Akyürek, E.M. Mitre, Positive energy districts methodology and its replication potential, sustainable places 2019, in: https://doi.org/10.3390/proceedings2019020008, 2019.
[54] Y. Chen, P. Xu, J. Gu, F. Schmidt, W. Li, Measures to improve energy demand flexibility in buildings for demand response (DR): a review, Energy Build. 177 (2018) 125–139, https://doi.org/10.1016/j.enbuild.2018.08.003.
[55] T. Hong, Y. Chen, X. Luo, N. Luo, S.H. Lee, Ten questions on urban building energy modeling, Build. Environ. 168 (2020) 106508, https://doi.org/10.1016/j.buildenv.2019.106508.
[56] M. Ferrando, F. Causone, An Overview Of Urban Building Energy Modelling (UBEM) Tools, Building Simulation Conference Proceedings. (n.d.). https://doi.org/10.26868/25222708.2019.210632.
[57] M.H. Kristensen, R.E. Hedegaard, S. Petersen, Hierarchical calibration of archetypes for urban building energy modeling, Energy Build. 175 (2018) 219–234, https://doi.org/10.1016/j.enbuild.2018.07.030.
[58] J. Natanian, Optimizing mixed-use district designs in hot climates: a two-phase computational workflow for energy balance and environmental performance, Sustain. Cities Soc. 98 (2023) 104800, https://doi.org/10.1016/j.scs.2023.104800.
[59] IES, Intelligent community design (iCD), n.d. https://www.iesve.com/products/icd. (Accessed 14 September 2023).
[60] City Energy Analyst Documentation Release 3.33.0 Architecture and Building Systems, 2023.
[61] Dynamic demand forecast, n.d. https://docs.google.com/presentation/d/1o-xfDRPpt7zY2rxcsbTjmVwGqbWXSi_IrxKSaer59-M/edit#slide=id.g1d9e28bdfd_0_90. (Accessed 14 September 2023).
[62] P. Remmen, M. Lauster, M. Mans, M. Fuchs, T. Osterhage, D. Müller, TEASER: an open tool for urban energy modelling of building stocks, J. Build. Perform. Simul. 11 (2018) 84–98, https://doi.org/10.1080/19401493.2017.1283539.
[63] U.S. Department of Energy, EnergyPlus | EnergyPlus, U.S. Department of Energy's, 2020.
[64] J. Bergerson, R.T. Muehleisen, B.O. Rodda, J.A. Auld, L.B. Guzowski, J. Ozik, N. Collier, DESIGNING FUTURE CITIES LakeSIM integrated design tool for assessing short- and long-term imapcts of urban scale conceptual designs, Int. Soc. City Reg. Plan. (ISOCARP) Rev. 11 (2015).
[65] S. Pfenninger, B. Pickering, Calliope: a multi-scale energy systems modelling framework, J. Open Source Softw. 3 (2018), https://doi.org/10.21105/joss.00825.
[66] EMD International, energyPRO, EMD International - EnergyPRO, 2019. https://www.emd-international.com/energypro/. (Accessed 28 September 2023).
[67] Oemof, n.d. https://github.com/oemof/oemof. (Accessed 15 September 2023).
[68] G. Mavromatidis, I. Petkov, MANGO: a novel optimization model for the long-term, multi-stage planning of decentralized multi-energy systems, Appl. Energy 288 (2021), https://doi.org/10.1016/j.apenergy.2021.116585.
[69] DecodingSpaces Toolbox, n.d. https://toolbox.decodingspaces.net/. (Accessed 21 September 2023).
[70] Urbano, n.d. https://www.urbano.io/. (Accessed 21 September 2023).
[71] DigiWo, n.d. https://toolbox.decodingspaces.net/digiwo/. (Accessed 21 September 2023).
[72] COLIBRI (da COREstudio), n.d. https://www.food4rhino.com/en/app/colibri. (Accessed 15 September 2023).
[73] Thread, n.d. https://thread.thorntontomasetti.com/. (Accessed 15 November 2023).
[74] DesignExplorer, n.d. https://tt-acm.github.io/DesignExplorer/.
[75] Opossum — optimization solver with surrogate models, n.d. https://www.food4rhino.com/en/app/opossum-optimization-solver-surrogate-models. (Accessed 15 September 2023).
[76] OCTOPUS, n.d. https://www.food4rhino.com/en/app/octopus. (Accessed 15 September 2023).
[77] SimStadt, n.d. https://simstadt.hft-stuttgart.de/. (Accessed 15 September 2023).
[78] Oemof-Demandlib Release 0.1.9, 2023.
[79] Modelica libraries, n.d. https://modelica.org/libraries.html. (Accessed 15 September 2023).
[80] Sefaira, n.d. https://support.sefaira.com/hc/en-us/articles/4828128745629-EnergyPlus-simulation-troubleshooting-advice. (Accessed 23 September 2023).
[81] Umi, n.d. https://umidocs.readthedocs.io/en/latest/docs/energy-module-overview.html. (Accessed 23 September 2023).
[82] Climate studio, n.d. https://www.solemma.com/climatestudio. (Accessed 23 September 2023).
[83] Honeybee, n.d. https://www.ladybug.tools/honeybee.html. (Accessed 23 September 2023).
[84] IES intelligent communities lifecycle (ICL), n.d. https://digineb.eu/digital-toolkit/ies-intelligent-communities-lifecycle-icl. (Accessed 15 September 2023).
[85] Butterfly, n.d. https://www.ladybug.tools/butterfly.html. (Accessed 23 September 2023).
[86] Ladybug tools, n.d. https://www.ladybug.tools/index.html#header-slide-show. (Accessed 23 September 2023).
[87] Dragonfly, n.d. https://www.ladybug.tools/dragonfly.html. (Accessed 23 September 2023).
[88] Pollination, n.d. https://www.pollination.cloud/. (Accessed 23 September 2023).
[89] Eddy3D, Airflow and microclimate simulations for Rhino and grasshopper, n.d. https://www.eddy3d.com/. (Accessed 23 September 2023).
[90] Morpho, n.d. https://github.com/AntonelloDN/Morpho. (Accessed 23 September 2023).
[91] ENVI-met, n.d. https://www.envi-met.com/. (Accessed 23 September 2023).
[92] CityBES, n.d. https://citybes.lbl.gov/CityBES_Overview.mp4. (Accessed 23 September 2023).
[93] Urbanopt, n.d. https://docs.urbanopt.net/workflows/workflows. (Accessed 23 September 2023).
[94] N. Technical Contact, L.J. Brackney, Portfolio-scale optimization of customer energy efficiency incentive and marketing: cooperative research and development final report, CRADA Number CRD-13-535, www.nrel.gov/publications, 2016.
[95] Citysim, n.d. https://www.epfl.ch/labs/leso/transfer/software/citysim/. (Accessed 23 September 2023).
[96] L. Madrazo, Á. Sicilia, G. Gamboa, SEMANCO: semantic tools for carbon reduction in urban planning, in: EWork and EBusiness in Architecture, Engineering and Construction - Proceedings of the European Conference on Product and Process Modelling 2012, 2012. ECPPM 2012.
[97] The distributed energy resources customer adoption model (DER-CAM), n.d. https://gridintegration.lbl.gov/der-cam. (Accessed 23 September 2023).
[98] ENERKAD, Urban scenario energy assessment, n.d. https://www.enerkad.net/. (Accessed 23 September 2023).
[99] 18 TRNSYS, 0, Transient System Simulation Program, SEL, University of Wisconsin/TRANSSOLAR, Stuttgart, 2018.
[100] L.J. Berkeley National Laboratory James Hirsch, A. Volume, DOE-2.3 Building Energy Use and Cost Analysis Program Volume 2: Dictionary, 2018.
[101] eQUEST the QUick energy simulation tool, n.d. https://doe2.com/equest/index.html. (Accessed 23 September 2023).
[102] ESP-r, n.d. https://www.esru.strath.ac.uk/Courseware/ESP-r/tour/. (Accessed 23 September 2023).
[103] IDEAS v3.0.0, n.d. https://github.com/open-ideas/IDEAS. (Accessed 23 September 2023).
[104] DesignBuilder, n.d. https://designbuilder.co.uk/helpv7.0/Content/Simulation_Detailed_Results.htm. (Accessed 23 September 2023).
[105] Grasshopper for Rhino. https://www.grasshopper3d.com/. (Accessed 23 September 2023).
[106] M. Sadeghi, T. Chaston, I. Hanigan, R. de Dear, M. Santamouris, B. Jalaludin, G. G. Morgan, The health benefits of greening strategies to cool urban environments

– a heat health impact method, Build. Environ. 207 (2022) 108546, https://doi.org/10.1016/j.buildenv.2021.108546.
[107] M. Santamouris, Chapter 1 - urban climate change: reasons, magnitude, impact, and mitigation, in: R. Paolini, M. Santamouris (Eds.), Urban Climate Change and Heat Islands, Elsevier, 2023, pp. 1–27, https://doi.org/10.1016/B978-0-12-818977-1.00002-8.
[108] E. Naboni, L. Havinga, Regenerative design in digital practice, Handb. Built Environ. (2019).
[109] E. Naboni, J. Natanian, G. Brizzi, P. Florio, A. Chokhachian, T. Galanos, P. Rastogi, A digital workflow to quantify regenerative urban design in the context of a changing climate, Renew. Sustain. Energy Rev. 113 (2019) 109255.
[110] E. Naboni, F. De Luca, Digital tools to support district regenerative design and scale jumping, 179–196. [111] ESP-r, (n.d.), https://www.esru.strath.ac.uk/Courseware/ESP-r/tour/, 2021. (Accessed 23 September 2023).
[111] D. Maiullari, B. Gherri, C. Finizza, M. Maretto, E. Naboni, Climate change and indoor temperature variation in Venetian buildings: the role of density and urban form, J. Phys. Conf. 2042 (2021) 012060, https://doi.org/10.1088/1742-6596/2042/1/012060.
[112] E. Naboni, M. Meloni, S. Coccolo, J. Kaempf, J.-L. Scartezzini, An overview of simulation tools for predicting the mean radiant temperature in an outdoor space, Energy Proc. 122 (2017) 1111–1116, https://doi.org/10.1016/j.egypro.2017.07.471.
[113] I. Adilkhanova, M. Santamouris, G.Y. Yun, Coupling urban climate modeling and city-scale building energy simulations with the statistical analysis: climate and energy implications of high albedo materials in Seoul, Energy Build. 290 (2023) 113092.
[114] M. Mosteiro-Romero, D. Maiullari, M. Pijpers-van Esch, A. Schlueter, An integrated microclimate-energy demand simulation method for the assessment of urban districts, Front. Built Environ. 6 (2020) 553946.
[115] M. Chung, H.-C. Park, Comparison of building energy demand for hotels, hospitals, and offices in Korea, Energy 92 (2015) 383–393, https://doi.org/10.1016/j.energy.2015.04.016.
[116] F. Johari, G. Peronato, P. Sadeghian, X. Zhao, J. Widén, Urban building energy modeling: state of the art and future prospects, Renew. Sustain. Energy Rev. 128 (2020) 109902, https://doi.org/10.1016/j.rser.2020.109902.
[117] M. Herrera, S. Natarajan, D.A. Coley, T. Kershaw, A.P. Ramallo-González, M. Eames, D. Fosas, M. Wood, A review of current and future weather data for building simulation, Build. Serv. Eng. Res. Tecnol. 38 (2017) 602–627, https://doi.org/10.1177/0143624417705937.
[118] D.P. Jenkins, S. Patidar, P. Banfill, G. Gibson, Developing a probabilistic tool for assessing the risk of overheating in buildings for future climates, Renew. Energy 61 (2014) 7–11, https://doi.org/10.1016/j.renene.2012.04.035.
[119] M.A. Su, J. Ngarambe, M. Santamouris, G.Y. Yun, Empirical evidence on the impact of urban overheating on building cooling and heating energy consumption, iScience 24 (2021) 102495, https://doi.org/10.1016/j.isci.2021.102495.
[120] S. Trzaska, E. Schnarr, A Review of Downscaling Methods for Climate Change Projections, United States Agency for International Development (USAID), 2014. http://www.ciesin.org/documents/Downscaling_CLEARED_000.pdf. (Accessed 1 December 2023).
[121] S. Belcher, J. Hacker, D. Powell, Constructing design weather data for future climates, Build. Serv. Eng. Res. Tecnol. 26 (2005) 49–61, https://doi.org/10.1191/0143624405bt112oa.
[122] M. Santamouris, On the energy impact of urban heat island and global warming on buildings, Energy Build. 82 (2014) 100–113, https://doi.org/10.1016/j.enbuild.2014.07.022.
[123] Q. He, F. Tapia, A. Reith, Quantifying the influence of nature-based solutions on building cooling and heating energy demand: a climate specific review, Renew. Sustain. Energy Rev. 186 (2023) 113660, https://doi.org/10.1016/j.rser.2023.113660.
[124] C.F. Reinhart, C. Cerezo Davila, Urban building energy modeling – a review of a nascent field, Build. Environ. 97 (2016) 196–202, https://doi.org/10.1016/j.buildenv.2015.12.001.
[125] M. Palme, A. Salvati (Eds.), Urban Microclimate Modelling for Comfort and Energy Studies, 2021, https://doi.org/10.1007/978-3-030-65421-4.
[126] N. Lauzet, A. Rodler, M. Musy, M.-H. Azam, S. Guernouti, D. Mauree, T. Colinart, How building energy models take the local climate into account in an urban context – a review, Renew. Sustain. Energy Rev. 116 (2019) 109390, https://doi.org/10.1016/j.rser.2019.109390.
[127] G. Turci, B. Alpagut, P. Civiero, M. Kuzmic, S. Pagliula, G. Massa, V. Albert-Seifried, O. Seco, S. Soutullo, A comprehensive PED-database for mapping and comparing positive energy districts experiences at European level, Sustainability 14 (2021) 427, https://doi.org/10.3390/su14010427.
[128] B. Alpagut, C.S. Montalvillo, J.F.V. Jaramillo, P.H. Inarra, J. Brouwer, S. Hirvonen-Kantola, H. Kosunen, N.H. Martinez, P. Ahokangas, S. Rinne, N. de Koning, J. Kort, Y. Xu, A.G. Moreno, E.A. Gonzalez, M.P. Corral, B.G. Orden, R. Desmaris, S. Dourlens-Quaranta, E.M. Miter, P.R. Hesse, D. Huerta, G. Fenandez, D. Gomez, O. Tabanoglu, G. Akgul, Making city D4.20 - methodology and guidelines for PED design - initial version, MAKING-CITY consortium partners. https://makingcity.eu/wp-content/uploads/2023/10/MakingCity_D4_20_Methodology_and_Guidelines_for_PED_design_InitialVersion_V1.pdf, 2019. (Accessed 1 December 2023).
[129] E. Vallejo, C. Rodríguez, A. Gabaldón, P. Serrano, A. López, J. Brouwer, S. Schouten, J. Jansen, S. Rueda AUAS, J. González COB, R. Rooth COA, Amsterdam bilbao citizen driven smart cities deliverable 6.2: replication and upscaling strategy. https://smartcity-atelier.eu/app/uploads/D6.2.pdf, 2022. (Accessed 1 December 2023).
[130] F. Cugnach, C. Leroy, M. Valrey, A. Venturin, RESPONSE D8.1 FCs Replication activities planning and Sustainability roadmap creation. https://h2020response.eu/wp-content/uploads/2022/05/D8.1-FCs-Replication-activities-planning-and-Sustainability-roadmap-creation.pdf, 2022. (Accessed 2 December 2023).
[131] C. Cheng, V. Albert-Seifried, L. Aelenei, H. Vandevyvere, O. Seco, M. Nuria Sánchez, M. Hukkalainen, A systematic approach towards mapping stakeholders in different phases of PED development—extending the PED Toolbox, Sustain. Energy Build. (2021. (2021) 447–463, https://doi.org/10.1007/978-981-16-6269-0_38.
[132] Y. Li, J. O'Donnell, R. García-Castro, S. Vega-Sánchez, Identifying stakeholders and key performance indicators for district and building energy performance analysis, Energy Build. 155 (2017) 1–15, https://doi.org/10.1016/j.enbuild.2017.09.003.
[133] Urban Design Associates, Louisiana Speaks: Planning Toolkit, 2007. https://static1.squarespace.com/static/536d55f1e4b07afeea8cef61/t/58924e14893fc03ea431a0e7/1485983316897/LouisianaToolKit_printonly.pdf. (Accessed 2 December 2023).
[134] D. Ahlers, B. Alpagut, V. Cerna, V. Cimini, S. Haxhija, M. Hukkalainen, M. Kuzmic, K. Livik, M. Padilla, M. Poel, C.S. Montalvillo, S. Schouten, T. Myrstad, M. Van Wees, K. Williams, A. Wyckmans, A. Gabaldon, N. Fernandez Perez, S.H. Kantola, S. Dourlens, E. Struiving, G. Kaiser, A. Smok, PED solution booklet, making city. https://indd.adobe.com/view/54e12796-ed33-4547-abc8-460fb5626bf1, 2020. (Accessed 2 December 2023).
[135] L. Bourdic, S. Salat, Building energy models and assessment systems at the district and city scales: a review, Build. Res. Inf. 40 (2012) 518–526, https://doi.org/10.1080/09613218.2012.690951.
[136] P.F. Jørgensen, I. Andresen, K. Bramslev, Integrert EnergiDesign (IED). https://byggalliansen.no/wp-content/uploads/2018/11/Integrert_energidesign.pdf, 2009. (Accessed 2 December 2023).
[137] A. Monti, D. Pesch, K. Ellis, P. Mancarella, Energy Positive Neighborhoods and Smart Energy Districts, Academic Press, 2017. https://www.sciencedirect.com/book/9780128099513/energy-positive-neighborhoods-and-smart-energy-districts#book-description.
[138] I.D.A. Stefano, Ice - simulation software | EQUA, n.d. https://www.equa.se/en/ida-ice.
[139] S.S. Tohidi, D. Cali, M. Tamm, J. Ortiz, J. Salom, H. Madsen, From white-box to grey-box modelling of the heat dynamics of buildings, E3S Web Conf. 362 (2022) 12002, https://doi.org/10.1051/e3sconf/202236212002.
[140] K. Kourtzanidis, K. Angelakoglou, P. Giourka, P. Tsarchopoulos, N. Nikolopoulos, D. Ioannidis, J. Kantorovitch, J. Formiga, K. Verbeek, M. de Vries, T. Faassen, L. Gimenez, D. Zambrana, POCITYF D11.7: technical and innovation management plans. https://pocityf.eu/wp-content/uploads/2022/06/POCITYF-864400_D11.7_Technical-and-Innovation-Management-Plans.pdf, 2020. (Accessed 2 December 2023).
[141] M. Hukkalainen, F. Zarrin, K. Klobut, O. Lindholm, M. Ranta, P. Hajduk, T. Vainio-Kaila, E. Wanne, J. Tartia, H. Horn, K. Kontu, J. Juhmen, S.-S. Santala, R. Turtiainen, J. Töyräs, T. Koljonen, SPARCS D3.1 Detailed plan of the Espoo smart city lighthouse demonstrations. https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5d401e921&appId=PPGMS, 2020. (Accessed 2 December 2023).
[142] A.B. Saka, D.W.M. Chan, Profound barriers to building information modelling (BIM) adoption in construction small and medium-sized enterprises (SMEs), Construct. Innovat. 20 (2020) 261–284, https://doi.org/10.1108/ci-09-2019-0087.
[143] E. Kamel, A.M. Memari, Review of BIM's application in energy simulation: tools, issues, and solutions, Autom. ConStruct. 97 (2019) 164–180, https://doi.org/10.1016/j.autcon.2018.11.008.
[144] M. Chang, J.Z. Thellufsen, B. Zakeri, B. Pickering, S. Pfenninger, H. Lund, P. A. Østergaard, Trends in tools and approaches for modelling the energy transition, Appl. Energy 290 (2021) 116731, https://doi.org/10.1016/j.apenergy.2021.116731.
[145] International energy agency EBC Annex 83 PEDs, n.d. https://annex83.iea-ebc.org/. (Accessed 27 February 2021).
[146] EnergyPLAN | Advanced energy systems analysis computer model, n.d. https://www.energyplan.eu/. (Accessed 5 November 2021).
[147] A. Belda, E. Giancola, K. Williams, S. Dabirian, M. Jradi, R. Volpe, S. S. Abolhassani, A. Fichera, U. Eicker, Reviewing challenges and limitations of energy modelling software in the assessment of PEDs using case studies, Sustain. Energy Build. 2021 (2021) 465–477, https://doi.org/10.1007/978-981-16-6269-0_39.
[148] D. D'Agostino, L. Mazzarella, What is a Nearly zero energy building? Overview, implementation and comparison of definitions, J. Build. Eng. 21 (2019) 200–212, https://doi.org/10.1016/j.jobe.2018.10.019.
[149] H.T. Walnum, Å.L. Hauge, K.B. Lindberg, M. Mysen, B.F. Nielsen, K. Sørnes, Developing a scenario calculator for smart energy communities in Norway: identifying gaps between vision and practice, Sustain. Cities Soc. 46 (2019) 101418.
[150] T. Rakha, R. El Kontar, Community energy by design: a simulation-based design workflow using measured data clustering to calibrate Urban Building Energy Models (UBEMs), Environ. Plan. B Urban Anal. City Sci. 46 (8) (2019) 1517–1533.
[151] J. Reynolds, Y. Rezgui, J.-L. Hippolyte, Upscaling energy control from building to districts: current limitations and future perspectives, Sustain. Cities Soc. 35 (2017) 816–829.

[152] N. Perez, P. Riederer, C. Inard, Development of a multiobjective optimization procedure dedicated to the design of district energy concept, Energy Build. 178 (2018) 11–25.
[153] N. Förster, I. Bratoev, J. Fellner, G. Schubert, F. Petzold, Collaborating with the crowd, Int. J. Architect. Comput. 20 (1) (2022) 76–95.
[154] U. Ali, M.H. Shamsi, M. Bohacek, K. Purcell, C. Hoare, E. Mangina, J. O'Donnell, A data-driven approach for multi-scale GIS-based building energy modeling for analysis, planning and support decision making, Appl. Energy 279 (2020) 115834.
[155] N. Abbasabadi, M. Ashayeri, Urban energy use modeling methods and tools: a review and an outlook, Build. Environ. 161 (2019) 106270.