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Zero Energy Districts: from building to city scale

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Abstract

This article presents a short literature review (2017-2022) on Zero Energy District (ZED) concept and its related terms - Nearly ZED, NetZED, PED, and Zero Energy Community. The scope of these terms was also evaluated and compared among different authors. Conceptual elements shaping up ZED projects were systematized. A brief review of the Zero Energy District Concept in tropical countries was provided. One of the purposes of the paper is the recommendation to transfer the Zero Energy District concept to realities of the Global South that have a higher level of economic and social vulnerability but at the same time a higher potential for energy production from renewable sources.

Keywords

Urban Planning; Zero-Energy District; Zero-Energy Building

1. Introduction

The United Nations (UN) has estimated that 70% of the world's population will live in urban areas by 2050 (UN, 2014). As of 2015, cities occupy 2% of the planet and consume 60% of energy and emit 70% of greenhouse gases (UN, 2015). According to these growth prospects, all around the world, it is predicted a massive creation of urban infrastructure with high energy consumption.

In the last decade, it has become clear that one, two, or even 10 energy-efficient buildings are not enough to achieve global decarbonization targets. The contribution of cities with their negative effects of urbanization is still high. In addition to buildings, transport systems, industries, infrastructure, equipment, urban furniture, green spaces, bodies of water and other subsystems can be mentioned. Saarlos and Quinn (2021) state that there are greater opportunities for energy efficiency at the district level than in individual buildings as there is an opportunity for energy exchange between buildings. According to Fonseca & Schlueter (2015), apud Amaral et al. (2018), the neighborhood is a suitable scale to go beyond the limits of a single building without losing its control and, at the same time, capable of approaching tangible solutions. In addition, the neighborhood scale serves precisely for the realization of concrete steps towards energy sustainability within built-up or expanding areas.

The emerging concept of Zero Energy District is an “evolutionary step” of the built environment aimed toward carbon-free urban planning.

The publication of directives and programs by the International Energy Agency (IEA 2015; IEA 2017) and the European Union (EU COMISSION 2010, EU COMISSION 2018) stimulated the intensive production of academic studies in the area of energy efficiency and decarbonization not only in Europe but throughout the world with its various climatic, social, political and economic conditions.

The article presents a short literature review on Zero Energy Districts with the aim to extend further a debate about Zero Energy District implementation in hot climates where the potential for solar and wind gains is high but should be increased towards resilient cooling strategies. Worth to mention that similar discussions were already raised in the works of Brozovky et al. (2021), Feng et al. (2019), and others.

After the introduction, section 2 describes the systematic research on the Zero Energy District topic in the following bibliometric databases: Web of Science and SCOPUS. The search covers papers published from 2017 to July 2022.

Section 3 presents the results of the literature review with an analysis of the scope of the terms and conceptual elements related to the Zero Energy District concept.

Section 4 raises questions about actual challenges in the ZED concept in developed countries and which positive and negative lessons cities with the hot climate in the Global South could learn in order to apply their own public policy on energy efficiency on the district level.

2. Methodology

The query started with a combination of “Zero Energy District” in titles, abstracts, and/or in keywords the on Web of Science and SCOPUS platform. The period of the search was limited to 5 years (2017-2022). 420 papers were found on the Web of Science and 340 on SCOPUS. The thematic categories of articles were filtered to such areas as “energy”, “engineering”, “architecture”, “urban planning”, “interdisciplinary studies”, “environment”, “social sciences”, “building materials” and “economy”. As a result, 167 articles were selected on the Web of Science and 219 the on SCOPUS Platform.

A further search had with following set of criteria:

Systematic reviews associated with Zero Energy Districts;

- Papers whose titles included the following terms: Zero Energy District, Net Zero Energy District - NetZED, Nearly Zero Energy District - NZED, Positive Energy District – PED, and Zero Energy Community;
- Papers that presented subtopics of ZED such as energy planning and active strategies; methodologies; passive strategies; socioeconomic impact, community involvement, and others.

As a third step, the citation rating of each article from both lists was analyzed. For each year of the period from 2017 to 2022, one to three most cited articles were selected. In total, 19 papers were obtained.

3. Results and discussion

After the systematic search, it was concluded that there were several specific topics and research focuses that circulated most of all in articles dedicated to Zero Energy District. According to those focuses, the literature was classified into the following groups: systematic reviews (11%), methodologies (16%), active strategies (32%), passive strategies (11%), socio-economic impact (26%), and community involvement (5%) (see Figure 1).

Table 1. Thematic topics of the Zero Energy District Concept

Subtopics	Number	Authors	Keywords	Brief description
Systematic review	1	Komninos (2022)	Zero emission; Zero energy; Positive energy; Neighborhoods Districts; Blocks; Systematic review; Zero Energy Building	Conception, terminology
	2	Brozovsky et al. (2021)		
Methodologies of ZED	3	Chacón et al. (2021)	Energy efficiency; multiobjective optimization;	Approaches, numeric studies,

	4	Koutra et al. (2021)	NZEB; NZED; retrofit; tropics; Nearly zero carbon Cost-efficient, 2030, Island	multidisciplinary studies
	5	Nematchoua (2021)		
Active strategies: - Energy planning - Operation - Storage	6	Kılkış (2017)	Agent-based modelling; agent-based simulation; urban energy system; district energy system; systematic literature review Multi-Energy systems; Expansion; Operation; Modeling; Zero-Energy districts; Renewable energy	Performance aspects, assessment tools; Energy systems: multi energy master planning, technical aspects of modeling, simulation
	7	Mohammad (2018)		
	8	Heendeniya et al. (2020)		
	9	Uspenskaia et al. (2021)		
	10	Akhatova et al. (2022)		
	11	Amaral (2018)		
Passive strategies - Urban morphology - Microclimate	12	de Leon (2018)	nZEB, nZED Urban texture; Building typology; Near-Zero energy Building; Energy simulation; compensating measures; different	Bioclimatism, passive strategies Geometric form, orientation, density Humidity, thermal comfort, cooling, outdoor comfort
	13	Beyaztaş (2020)		
Techno-economic analysis	14	Becchio et al. (2018)	Net-zero energy district; positive energy district; Net Zero-Energy District; Co-benefit; Energy refurbishment; Cost-benefit analysis; Socio-economic impact	Cost-benefit analysis, socioeconomic impact, feasibility of implementation
	15	Kim et al. (2019)		
	16	Hirvonen e Kosonen (2020)		
	17	Laitinen et al. (2021)		
	18	Saarloos and Quinn. (2021)		
Community involvement	19	Baer (2021)	Net-zero energy district; positive energy district; Net Zero-Energy District; Co-benefit; Energy refurbishment	Comunidade de Zero energy Community, phases of Project

The majority of articles were dedicated to active strategies (32%). The second most popular topic was techno-economic analysis (26%). The least developed topics included passive strategies (11%) and community involvement (5%).

It is important to note that the geography of studies was diverse. There were met two countries with cold climates (Norway and Finland), temperate climates (USA, Belgium, and France), Mediterranean climates (Greece, Italy, Turkey, Portugal), and two countries with hot tropical climates (Panama and Madagascar).

All articles except the systematic review of Brozovsky et al. (2021) contained a theoretical part and case of study. The highest productivity of articles fell in 2021 (42%), and the second most popular year for publication was 2018 (21%), after this comes 2020 (16%) and 2022 (11%), the least popular year for current selection was 2017 with 5% of contribution to a general list.

As a result, the discussion section there were included materials from a selected list of articles together with articles that served as references.

The definition of Zero Energy District takes one of the central places in contemporary research starting from 2008 when the legislative framework "European Union Building Directive/2010" was developed to stimulate practice and research of Zero Energy Building (ZEB), Nearly Zero Energy Building, and Zero Energy District. Authors who contributed to the definition development of ZEB and Nearly ZEB were: Torcellini (2009), Caislie (2009), D'Agostino (2018), and others.

According to Marique et al. (2013), Zero Energy District is defined as a district/neighborhood in which annual energy consumption for buildings and transportation of inhabitants are balanced by the local production of renewable energy. However, the same author notes that in order to achieve greater accuracy in energy planning and energy efficiency it is still necessary to carry out monthly or even hourly evaluations. The main objective of these measurements is to create alternatives in order to prevent conflicts between the demand and supply of renewable energy (MARIQUE ET AL., 2013).

Another possibility is to work with the idea of a Net Zero Energy District. In this case, energy consumption is compensated by the offsite solar energy farms or wind farms together with local plants, situated in the immediate vicinity (proximity) of buildings.

Positive Energy District, an "evolutive step" of Zero Energy District, established by the European SET-Plan Action 3.2 Smart Cities and Communities Implementation Plan, the assumption is that energy production exceeds the expected amount to be consumed (EUROPEAN COMMISSION, 2018). Excess energy emerges with the installation of renewable and intelligent energy storage [systems] in various infrastructures in the city such as lighting, urban mobility, waste collection, and others (KOMNINOS, 2022). Positive Energy District also incorporates aspects related to environmental issues such as clean energy and decarbonization, sustainable use of water, solid waste management, and other solutions that in a broad sense make part of the sustainability agenda (WHITE PAPER, 2021). Noteworthy, as Brozovsky et al. (2021) appoint, affordability for the inhabitants is highlighted in PED European SET Plan.

Brozovsky et al. in their systematic review (2021) collected the whole panorama of definitions and modifications of the term Zero Energy District: Climate Friendly Neighborhoods, Positive energy blocks, Zero emission neighborhoods, Sustainable plus energy neighborhoods, and others.

The variety of these definitions is derived from published projects that have been developing in the framework of the EU program for ZEB and Nearly ZEB, for example, SPARCS, Active Cities, etc. In many cases, such projects defined ZED according to specifics and particularities of an individual project like geography, energy production, clean energy, and techno-economic conditions. Consequently, the definitions for Zero or Nearly Zero Energy Districts received a different scope of elements, and many times are hardly comparable to each other. For example, some authors include electric transport as a source of overall energy consumption of the district (MARIQUE ET Al., 2013) while others include only buildings as the main consumers of energy (KOLODIY, 2020). The basic definitions that are most commonly used in the academic literature are given in Figure 2.

Table 2. Evolution of Zero Energy definitions: from building to city scale

Term	Description
Nearly Zero Energy Building	(EUROPEAN COMISSION, 2010) “Nearly zero-emission building (NZEB) means a building that has a very high energy performance, while the nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby”
Zero Energy Building	(US DEPARTMENT OF ENERGY, 2022) “Zero energy buildings are designed and built to consume as little energy as possible. When a renewable source of energy is added to these buildings, they are capable of producing enough energy to meet or exceed their requirements to run”.
Positive Energy Building	(EU HORIZON 2020 RESEARCH AND INNOVATION PROGRAMME) “An energy-efficient building that produces more energy than it uses via renewable sources, with high self-consumption rate and high energy flexibility, over a time span of one year”.
Net Zero Energy Building	(US DEPARTMENT OF ENERGY, 2022) “an energy-efficient building where, on a source energy basis, the actual annual delivered energy is less than or equal to the on-site renewable exported energy”
Zero Energy District - ZED	(MARIQUE ET AL. 2013, p.2) “The Zero Energy Neighborhood” concept is described, by analogy with the Zero Energy Building, as a neighbourhood in which annual energy consumption for buildings and transportation of inhabitants are balanced by the local production of renewable energy”.
Net Zero Energy District	(KOMNINOS, 2022, p.1): “Net-Zero Energy Districts (NZEDs) are city districts in which the annual amount of CO2 emissions released is balanced by emissions removed from the atmosphere”.
Nearly ZED	(AMARAL ET AL., 2018, p.10) “Nearly 205 Zero-Energy District (NZED) is a delimited part of a city that “has a very high energy performance (…)”, with the “nearly zero or very low amount of energy (…) covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby” (EPBD (recast), 2010, p. L 153/18). “It is proposed that the energy consumptions to be taken into account in a district performance assessment are the energy needs for buildings and for the district public spaces, such as the public lighting, traffic lights or landscape maintenance”.
Positive-Energy District - PED	(THE JOINT PROGRAMMING INITIATIVE (JPI) URBAN EUROPE): “A Positive Energy District is seen as an urban neighbourhood with annual net-zero energy import and net-zero CO2 emissions working towards a surplus production of renewable energy, integrated into an urban and regional energy system” […]”are energy-efficient and energy-flexible urban areas or groups of connected buildings which produce net zero greenhouse gas emissions

	and actively manage an annual local or regional surplus production of renewable energy”
Zero Energy Community	“Community that reduces energy needs through efficiency gains, such as the balance of energy for vehicles, thermal and electrical consumption” (CARSLIE ET AL., 2009, P.1).

The emergence of the terms Nearly Zero, Net Zero, and Positive Energy is also explained by the techno-economic conditions; established national electrical matrices; typology and age of buildings; infrastructure, access to investments, and other reasons.

According to Feng et al. (2019), definitions of terms serve as a conceptual basis for regulatory documents of public policy in energy efficiency. The more precise the definitions are, the clearer the public policy of Zero Energy Built Environment (Buildings and Districts) is.

So far, there are three elements studied profoundly in the academic literature that shape the Zero Energy District: buildings, renewable energy systems, and transport. However, other authors (AMARAL, 2018; BROZOVSKY, 2021; KOMNINOS, 2022) note that the district is more complex [a unit] than a building and it consumes energy not only for residential and commercial purposes but also for public spaces, mobility and great variation of urban infrastructure. The scope of possible elements of Zero Energy District is presented in Figure 3.

Table 3. The Structural Elements of a Zero-Energy District Urban planning elements

Elements	**Aspects of performance and energy consumption**
Land use and occupation (industries, commerce, residential)	End uses; production and distribution
Commercial, residential and social infrastructure: buildings	End uses; internal thermal comfort regime; heating, ventilation and cooling; wrapping materials
Equipment (space for public equipment)	Energy storage
Geographic elements: - Water	Maintenance, uses of irrigation apparatus; decarbonization and increased use of electricity
- Vegetation	Shading, mitigation of high temperatures, maintenance (grass cutting), appliance uses (irrigation), lighting; decarbonization and increased use of electricity
- Surfaces	Heat islands that impact the internal thermal comfort regime in buildings, increasing the use of electricity
Public spaces	Maintenance (cleaning transport), decarbonization and increased use of electricity
Urban furniture	Maintenance (cleaning), external thermal comfort (shading, cooling and heating, wind protection); decarbonization and increased use of electricity
Consumers	Habits and behavior of energy consumption

As it was described the selected list for literature review was classified into the following groups: active strategies, methodologies, techno-economic analysis, passive strategies, and community involvement. This section will describe each subtopic and the basic connection of one with the other.

As Brozovsky et al. (2021) and Koutra et al. (2021), Uspenskaia et al. (2021) note methodologies of ZED projects have been developed via case studies and many times have tailor-made approaches according to specifically defined objectives of the project. However, the most significant effort to give a generic framework for the ZED project was given by Koutra et al. (2021) in RESIZED project where a multidisciplinary approach was applied and 4 strategic phases were implemented: the strategic decision of the NZEDs' installation diagnosis and analysis, assessment of scenarios (action planning) and implementation. Three pillars of the project were the optimization of energy requirements, energetic hybridization, and organization of energy storage.

Zero Energy District, same as Zero Energy Building, implies two important components: passive and active strategies. As for passive strategies of Zero Energy Districts, researchers mainly study pre-technological aspects, those that have an early impact on energy production and consumption of buildings such as climate and urban morphology. As Feng et al. (2019) note, the climate is playing a significant role in energy-efficiency systems and energy consumption patterns in the building. At the district level, the climate is studied from temperature variables, wind design, and solar gains. Brozovsky et al. (2018) note that there is still a little percentage of publications dedicated to the topics of microclimate and urban climate and their impact on infrastructure and building energy consumption.

Urban morphology with its geometry, orientation, height of buildings, urban density, and age of buildings is another important factor in the performance of Zero-Energy Districts. According to Dietrich (2021), 35% of energy consumption can be optimized due to passive strategies. Among those strategies land use and occupation issues related to the installation of equipment and energy should be included (FENG ET AL., 2019). It is also possible to mention intercrossing urban aspects of urban climate related to passive or bioclimatic strategies (DE LEON, 2018) such as heat island effects, urban canyon, inter-building effect or mutual shading, envelope materials and facade and layout optimized for energy consumption. Finally, many studies are dedicated to energy retrofit (BYAZTYS, 2018) i.e., optimization of the thermal characteristics of a building's envelope.

Active strategies imply the implementation of energy systems, energy optimization, operation, production, distribution storage of energy, and others. These issues are studied in the works of Akhatova et al. (2022), Uspenskaia et al. (2021), Heendeniya et al. (2020), Laitinen and Kosonen (2021), and others. The most common approaches to studying active strategies derive from ZEB methodologies like numeric modeling, numeric studies, parametric analysis, and others. All of them are basically aimed at evaluating the overall energy consumption of the district. Another branch of studies is dedicated to information technologies of real-time monitoring and smart technologies. The inclusion of the option of energy exchange between buildings due to intelligent systems is the central issue related to the planning of Zero Energy Districts (MARIQUE ET AL. 2013; KOMNINOS, 2022).

Among the most common techno-economic impact assessment instruments, can be mentioned: Life Cycle Assessment; Life Cycle Cost; Multi-Criteria Decision Aid, and Cost-Benefit Analysis (BECCHIIO, 2018). Strategic problems stand out in choosing the appropriate technologies for each type of energy end-use (SAARLOS E QUINN, 2021).

Socio-economic impacts are studied by user behavior design studies. Another important component of the Zero Energy concept is the contribution of residential areas to the reduction of energy consumption. Zero Energy Community which means community basically residential that reduces energy needs through efficiency gains, such as the balance of energy for vehicles, and thermal and electrical consumption (BAER ET AL. 2021; CARSLIE ET AL., 2009).

The need to take advantage of more diverse load profiles, production and storage capacities, and the possibility of sharing costs and resources is another aspect that took the idea of zero building energy to the district level (BROZOVSKY ET AL., 2021).

Documentation and programs of the International Energy Agency and European Union significantly affected the evolution of Zero Energy Balance. Particularly, EU directives published between 2002 and 2018 have evolved from recommendations to the obligatory status of energy optimization in buildings toward new constructions in Europe.

In 2018 European Union launched the "Positive Energy Districts and Neighborhoods for Urban Development" program under Action 3.2 of the Energy Technology Strategic Plan (SET) "Smart Cities and Communities" (EUROPEAN COMISSION, 2018). This action gave stimulus to Zero Energy and Positive Energy District concept development.

In the Zero Energy District buildings and their energy production systems play a crucial role in meeting European Union requirements (WHITE PAPER, 2021). However, as many authors note (BROZOVKY ET AL. 2021, AKHATOVA ET AL. 2018).) the adaptation of the term Zero Energy District to urban particularities is necessary as it strongly depends on the specifics of the local climate, land-use regulations, land resources, limits of urban morphology, technology development, economic situation, and other constraints.

Even with the development of advanced documentation of public policy in the last decade, there are still challenges to the implementation of Zero Energy Districts. They include:

- Accurate calculations and consideration of all elements that consume energy within neighborhoods/districts (KOMNINOS 2022; MARIQUE ET AL. 2013);
- Lack of clear definitions of Zero Energy Districts and their related terms (BROZOVSKY 2021; KOUTRA ET AL. 2021; FENG ET AL. 2019). Definitions continue multiplying together with the variations of the scopes of terms which make projects hardly comparable with each other;
- Absence of transferable methodologies of projects (USPENSKAIA, 2021). Projects are tailor-made and respond to specific realities of one particular project;
- Lack of clear criteria for the definition of ZED physical boundaries: physical, virtual, and operational (BROZOVSKY, 2021; AMARAL ET AL. 2018);
- Security and stability of energy systems in ZED, the efficiency of hybrid renewable energy production systems and others (HEENDENIYA ET AL., 2020);
- Diversity of renewable energy production resources (AKHATOVA, 2022; USPENSKAIA 2021; HEENDENIYA, 2020);
- Economic viability of project investments, cooperation between agents involved, user participation, long-term investments Economic and social challenges in the initial phase (FENG ET AL. 2019, BROZOVSKY ET AL. 2021);
- Energy production limitations due to urban morphology (KOMNINOS, 2022; DIETRICH, 2021).

Broovsky (2021) raises the question of zero energy concepts outside the developed world. Since 2010 in the European Union, there are documents that regulate Zero Energy Buildings. This became feasible due to ample research realized previously in the framework of these initiatives. Starting from 2018 these documents include Zero Energy Balance Districts, but in the Global South’s National Energy Plans, the main concern is still the energy efficiency of single buildings. The following challenges are addressed for countries with hot climates:

- Clear definition corresponding to socioeconomic realities of the Global South incorporated into public policy. Particularly the issue of affordability could be adopted from the PED definition from European Program;
- Energy efficiency strategies that address issues of energy poverty and social vulnerability;
- Development of practice-oriented case studies of Zero Energy Districts;
- Development of strategies that limit investments in the initial stage of implementation of ZED, focusing on passive cooling strategies. For example, independence from mechanical cooling (air conditioning) would mean a decrease in energy consumption by up to 40% (DE LEON, 2018).

4. Conclusions

Two main aspects that determine the Zero Energy District idea are the reduction or optimization of energy consumption and energy production from renewable sources. It should be noted that Zero Energy Balance can be implemented at the building, neighborhood, district, city, and, as a final goal, country scale.

The energy transition from building to district scale is still a major challenge even for specialists from various fields of knowledge. The topic of Zero Energy Balance Districts is still very new and is going through a period of awareness and consolidation.

In practice, it is very difficult to cover all possible aspects which impact the performance of Zero Energy Districts, but it is important to continue analyzing complex relationships between various elements related to urban units which are larger than buildings. Energy-sustainable cities contribute to building resilience for climate change along with strategies for social inclusion, fighting poverty, housing crisis, water supply, and other goals identified in the UN Global Agenda 21.

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