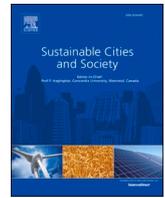




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Zero emission neighbourhoods and positive energy districts – A state-of-the-art review

Johannes Brozovsky*, Arild Gustavsen, Niki Gaitani

Department of Architecture and Technology, Faculty for Architecture and Design, NTNU – Norwegian University of Science and Technology, 7491, Trondheim, Norway

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ABSTRACT

Urban areas are critical in accomplishing the clean energy transition and meeting the climate goals in the Paris Agreement. The first part of this paper presents a systematic review of scientific publications on zero emission neighbourhoods, positive energy districts and similar concepts of climate friendly neighbourhoods (CFN). The second lists a selection of CFN definitions of public initiatives and research projects. The aim is to identify focus areas, research gaps and future research possibilities. In the systematic review, 144 papers were categorised and analysed according to their concept terminology, topic, location, used methodology, publication type, year, citations and keywords. The results document the growing but thematically and geographically unbalanced attention given to CFNs. Most research (31.9 %) was connected to the energy system, whereas social aspects (4.2 %) and the microclimate (3.5 %) were least researched. Within the analysed literature, 35 different terminologies for CFNs were used which highlights the lack of clear definitions and arbitrary use of terminologies. This issue is also reflected in the significant differences of CFN definitions from public initiatives and research projects. This article stresses the need for clear, comprehensible and structured definitions, including KPIs, system boundaries, as well as definitions of the spatial scales.

1. Introduction

Despite improvements in energy efficiency and various efforts to limit the building sector's impact on the environment, global emissions from buildings increased by about 2% for the second consecutive year from 2017 to 2018 (see Fig. 1). These increases were mainly driven by continuously rising building floor area and global population growth. Overall, the building and construction sector was responsible for 36 % of

final energy use and 39 % of energy process-related carbon dioxide (CO₂) emissions in 2018 (Global Alliance for Buildings and Construction et al., 2019). Thus, buildings hold a critical role for a clean energy transition (IEA, 2019). Responding to the Paris Agreement in 2015 (United Nations Framework Convention on Climate Change, 2015), the European Union (EU) has set an ambitious target to reduce greenhouse gas (GHG) emissions by at least 40 % below 1990-levels until 2030 (European Commission, 2014b). Moreover, the EU has adopted a wide

Abbreviations: BAU, Outdoor area; BRA, Heated floor area; CFN, Climate-friendly neighbourhood; CO₂, Carbon dioxide; DOE, Department of Energy; EBC, Energy in Buildings and Communities Programme; EIP-SSC, European Innovation Partnership on Smart Cities and Communities; EPBD, Energy Performane of Buildings Directive; EPN, Energy Positive Neighbourhood; ES, Energy system; EU, European Union; FME, ZEB Research Centre on Zero Emission Buildings; FME, ZEN Research Centre on Zero Emission Neighbourhoods in Smart Cities; GHG, Greenhouse gas; HPD, High Performance District; ICT, Information and communication technology; IT, Information technology; IEA, International Energy Agency; Int/Que/Exp, Interview/questionnaire/experiment; JPI, Joint Programming Initiative; LCA, Life cycle assessment; LCD, Low Carbon District; LCDH, Low Carbon District Heating; LCN, Low Carbon Neighbourhood; LED, Low Energy District; LEED, Leadership in Energy and Environmental Design; LEN, Low Energy Neighbourhood; M/FW/Tool, Methodology/framework/tool presentation; MC, Microclimate; MILP, Mixed-integer linear programming; UM, Urban morphology; MPC, Model predictive control; NMM, Numerical/mathematical modelling; NOK, Norwegian Kroner; NTNU, Norwegian University of Science and Technology; NZEHC, Net Zero Energy Housing Community; nZEB, Nearly Zero Energy Building; nZED, Nearly Zero Energy District; NZED, Net Zero Energy District; NZEN, Net Zero Energy Neighbourhood; nZEN, Nearly Zero Energy Neighbourhood; PEB, Positive Energy Block; PED, Positive Energy District; pED, Plus Energy District; POSE, Project organisation and stakeholder engagement; PV, Photovoltaics; Rev, Review; SA, Social Aspects; SHC, Solar Heating and Cooling Programme; SET, Strategic Energy Technology; SPEN, Sustainable Plus Energy Neighbourhoods; TEA/FS, Techno-economic analysis/feasibility study; Trans, Transition to a climate-friendly neighbourhood; UK, United Kingdom; ZED, Zero Energy District; ZEDA, Zero Energy Districts Accelerator; ZEN, Zero Energy Neighbourhood; ZEN*, Zero Emission Neighbourhood.

* Corresponding author.

E-mail addresses: johannes.brozovsky@ntnu.no (J. Brozovsky), arild.gustavsen@ntnu.no (A. Gustavsen), niki.gaitani@ntnu.no (N. Gaitani).<https://doi.org/10.1016/j.scs.2021.103013>

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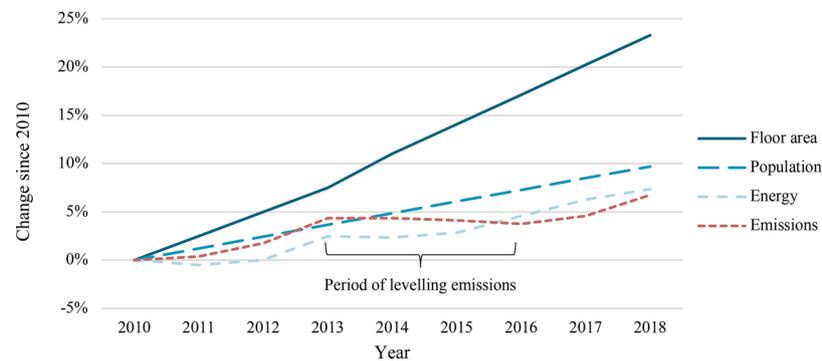


Fig. 1. Changes in floor area, population, buildings sector energy use and energy-related emissions globally since 2010, modified from Global Alliance for Buildings and Construction et al. (2019).

set of policies to become the first climate-neutral continent by 2050 with the introduction of the European Green Deal in December 2019, by moving to a clean, circular and sustainable economy (European Commission, 2019b). As a part of the Green Deal, the Renovation Wave (European Commission, 2020b) aims at not less than double the annual energy renovation rate of residential and non-residential buildings and to reach 35 million building units renovated by 2030. The legislative framework to reach the EU's climate goals is called "Clean Energy for All Europeans" which particularly highlights the importance of improving the energy and emission performance in the building sector (European Commission Directorate-General for Energy, 2019). Within the context of this framework, the recast Renewable Energy Directive (European Parliament & Council of the European Union, 2018a) entered into force in 2018, promoting the use of energy from renewable sources, especially in buildings.

A major stepping stone in this direction was the passage of the Energy Performance of Buildings Directive (EPBD) with its adaption to the EU Member States in 2010 and its recast in 2018 to transform Europe's building stock to be "highly energy efficient and decarbonised [...] by 2050, facilitating the cost-effective transformation of existing buildings into nearly zero-energy buildings" (European Parliament & Council of the European Union, 2010, 2018b). The aim of the EPBD is mainly to provide a common basis for calculating the energy performance of buildings and to establish minimum requirements for the energy performance of new and existing buildings. It is furthermore specified that after 2020 all new buildings must be nearly zero energy buildings (nZEB).

Continuing the success of Horizon 2020 (European Commission, 2014a), an €80 billion EU research and innovation programme which funded a large number of research projects on these topics from 2014 to 2020, its successor Horizon Europe (European Commission, 2019a) will invest €100 billion to pursue its targets between 2021 and 2027. For that, five mission areas have been identified. Two of them are highly relevant in the context of sustainable urban development: (i) A climate-resilient Europe – Prepare Europe for climate disruptions and accelerate the transformation in a climate-resilient and just Europe by 2030 (Directorate-General for Research & Innovation, 2020b) and (ii) 100 Climate-neutral Cities by 2030 – by and for the Citizens (Directorate-General for Research & Innovation, 2020a). These missions highlight not only the EU's ambitions to tackle climate change and reduce the environmental impact from the building sector, but also underline the absolute necessity for more research in these domains.

Over the years, a considerable number of different and coexisting definitions and standards for low-, nearly or zero energy/carbon buildings have been developed (Kibert & Fard, 2012; Marszal et al., 2011; Williams et al., 2016). Commonly, to reduce GHG emissions and energy use in the building stock and new constructions, such standards and national building codes provide minimum requirements for the energy performance and airtightness of the building envelope, or the use of

renewables-based technology and energy sources (Magrini et al., 2020; Williams et al., 2016). As electricity use in buildings has increased five times faster since 2000 than improvements in the carbon intensity of the power sector, renewable on-site electricity production is seen as a key element of achieving such building standards (IEA, 2019). However, the problem of variability in renewable energy production demands a high degree of demand-side flexibility, storage capabilities and optimised energy management strategies in the so-called "prosumer" buildings (PROducer and conSUMER of energy) to maximise self-consumption and minimise purchasing power from the public grid (Engeland et al., 2017; Velik & Nicolay, 2016).

To take advantage of more diverse load profiles, production and storage capabilities, and the possibility of sharing costs and resources, literature suggests taking the zero energy objective from the building to the district level (Amaral et al., 2018; Saheb et al., 2018). Moreover, positive energy neighbourhoods/districts/blocks are able to utilize in an efficient and flexible way the renewable energy generation and energy storage potential of the community. In respect of the environmental impact of urban areas, accommodating about 67 % of the world's population and accounting for approximately 70 % of global energy use and CO₂ emissions, their importance in the ongoing transition towards renewable energies and low-emission technologies is undisputed and actions are urgently required (Edenhofer, 2014; International Energy Agency, 2016; United Nations et al., 2018). Accordingly, the EU launched the "Positive Energy Districts and Neighbourhoods for Sustainable Urban Development" programme in the framework of the Strategic Energy Technology (SET) Plan Action 3.2 "Smart Cities and Communities" in 2018. The programme aims to support the planning, deployment and replication of 100 Positive Energy Districts (PED) by 2025 for sustainable urbanisation (European Commission Joint Research Centre, 2018). As of February 2020, there were 29 PED projects (most of them in the implementation stage) and 32 projects not declared as a PED but presenting "interesting features for the PED programme" registered by the Joint Programming Initiative (JPI) Urban Europe (Bossi et al., 2020; Gollner et al., 2020). Regulatory stimuli and public funding of research projects have led to a considerable amount of dissemination in this domain, as documented in the research paper from the International Energy Agency's Energy in Buildings and Communities Programme (IEA EBC) Annex 83 on Positive Energy Districts (Hedman et al., 2021). While several reviews have been published on (nearly/net) zero energy concepts at the building scale (Belussi et al., 2019; Deng et al., 2014; Feng et al., 2019; Li et al., 2013; Marszal et al., 2011; Panagiotidou & Fuller, 2013; Wells et al., 2018), and the district scale of performance aspects (Amaral et al., 2018), and sustainable approaches and assessment tools (Koutra et al., 2018), to the best of our knowledge, there hasn't been published a systematic review of low-, nearly zero, zero and positive energy/emission/carbon neighbourhoods/districts/blocks yet. This article fills this gap and provides important information about existing literature to assist researchers in this field to

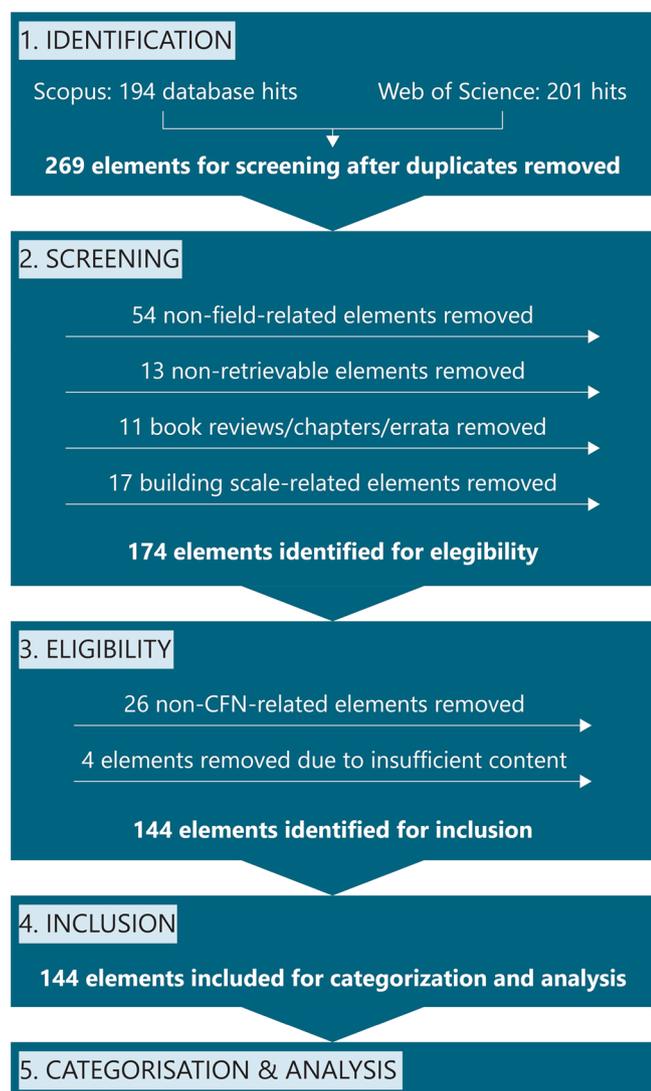


Fig. 2. Flow chart of the applied methodology in this research. Phases 1–4 represent the model for article inclusion according to Moher et al. (2010).

contextualize their work within global research activities, identify focus areas, research gaps and future research possibilities. Thus, this work will aid the global research community in speeding up the transition to a more sustainable built environment.

Assessing the environmental impact at neighbourhood/district/block scale is a vital step towards sustainable cities as neighbourhoods are their building blocks and usually represent the scale at which cities are expanded, redeveloped or transformed by urban planners and municipalities. Therefore, by addressing low-, nearly zero, zero and positive energy/emission/carbon concepts at the neighbourhood/district/block scale, this article aims to pave the way and provide important knowledge towards environmentally sustainable and resilient cities from a multi-disciplinary perspective.

The first part of this paper presents a systematic analysis of articles published in scientific journals and conferences in this context (chapter 3). In the second part, definitions of such concepts from selected research projects and public initiatives will be presented (chapter 4).

2. Method

For the first part of this article, the systematic review, relevant literature is identified by using a structured and reproducible search procedure. Although mainly used in medicine and health science, this

reviewing approach has been increasingly adopted in other disciplines as well. In the centre of a systematic review is a structured question formulation that assures the reproducibility of the work. In this article, the four-phase approach described by Moher, Liberati, Tetzlaff, and Altman (2010) was applied and extended with an additional phase, the *Categorisation and Analysis*. In each of the first four phases, articles that do not fit into the scope of the review or that have been identified twice are removed. As the flow chart in Fig. 2 shows, the reasons for excluding articles from the review are outlined as well. After that, included articles are categorised and analysed based on different attributes (see chapter 3). Note that the fifth phase is not explicitly outlined in Moher et al.'s systematic review methodology. However, it represents one of the core elements of the applied methodology in this research. Therefore, extending Moher et al.'s approach with this phase was considered necessary.

It should be noted that by using this method, a subset of all relevant literature will be identified. The extent of search hits is not only dependent on the databases themselves and their content but to a considerable degree on the search terms and question formulation. The ultimately deployed search phrase is often a trade-off between several other possible search phrases, either resulting in too many results to be screened and analysed within a reasonable amount of time or yielding too few elements to represent a meaningful subset of the literature of interest. However, by doing so, many relevant publications and reports may be missed, if they do not specifically mention the search terms in their title, abstract or keywords or have not been published in form of a peer-reviewed article. This is, for instance, the case with many research projects, institutions or public authorities who do not always publish their reports in academic journals or conference proceedings.

Therefore, the second part of this review article (chapter 4) presents an overview of relevant definitions from selected public initiatives and nationally or EU-funded research projects and critically discusses differences among these. The analysis in the results section (chapter 3) of this article, however, includes only the publications that were identified by the following methodology.

2.1. Article identification and inclusion in the systematic review

There is a vast number of different terminologies regarding concepts aiming for reduced or minimised carbon emissions or energy use in a cluster of buildings. In this article, *Climate Friendly Neighbourhood* (CFN) will be used as a collective term for all the different expressions to generally and neutrally address the whole spectrum of terms.

Following the practice in other studies (Brozovsky et al., 2021; Bustami et al., 2018; Mavriaggiannaki & Ampatzis, 2016), the electronic databases *Scopus* and *Web of Science* were used which require a slightly different syntax due to different search algorithms. To take account of the vast number of different CFN terms, the following search phrases were created:

Scopus: ((low OR “net zero” OR zero PRE/2 carbon) OR (plus OR positive OR “net zero” OR zero PRE/2 energy) OR (“net zero” OR zero PRE/2 emission)) PRE/2 (district OR neighbourhood OR block).

Web of Science: (((low OR “net zero” OR zero) NEAR/2 carbon) OR ((plus OR positive OR “net zero” OR zero) NEAR/2 energy) OR (“net zero” OR zero) NEAR/2 emission)) NEAR/2 (district OR neighbourhood OR block).

In *Scopus*, the search was conducted within the search fields *Article Title*, *Abstract* and *Keywords*. Analogously, in *Web of Science*, the search field was chosen to be *Topic*, which means *Title*, *Abstract*, *Author keywords* and *Keywords Plus*®. Both databases account for the different English spellings and apply word stemming. In other words, the databases will search for both British and American English spelling as well as different grammatical forms of the words in the search phrases given above. The search was performed on April 12, 2021.

Of the 395 identified elements, only 144 were included in the analysis in the end. A total of 126 elements were removed in the

Table 1
Abbreviations and descriptions of categories for topics and methods.

Topics		Method	
Abbreviation	Description	Abbreviation	Description
ES	Energy system	NMM	Numerical/mathematical modelling
Trans	Transition to CFN	TEA/FS	Techno-economic analysis and feasibility study
ICT	Information and communication technology	Int/Que/Exp	Interview/questionnaire/experiment
POSE	Project organization and stakeholder engagement	M/FW/Tool	Methodology/framework/tool presentation
UM	Urban morphology	Rev	Review
LCA	Life cycle assessment	Other	Methods not captured by previous categories
SA	Social aspects		
MC	Microclimate		
Other	Research not captured by previous categories		

identification stage where the element titles were used to sort out duplicates. In the screening stage, 95 articles were excluded. 54 of them had to be excluded as they did not cover the intended research domain and were mostly associated with chemistry or material science. 13 titles could not be downloaded due to missing licensing and other accessibility issues. Furthermore, 17 articles related only to the building scale and 11 book reviews, chapters, and article errata were excluded, as solely peer-reviewed scientific articles covering clusters of buildings were to be included in the analysis. Finally, in the eligibility stage, the remaining articles' contents and methods were examined. 26 of them did not specifically cover ecological concepts at the neighbourhood scale, and four elements were not regarded to be of sufficient quality to be included in the analysis of this systematic review.

2.2. Categorisation

After determining the elements to be included in this article's analysis, they were carefully examined and sorted into categories, according to their thematic focus and in the best judgement of this article's authors:

- 1 *Energy system*: Focusing mainly on the energy system of a building cluster, the management or integration of renewable energy sources etc.
- 2 *Transition to CFN*: Transforming existing clusters of buildings into a CFN.

- 3 *Information and communication technology*: Studies on information and communication technology and data management.
- 4 *Project organisation and stakeholder engagement*: Articles on the management, stakeholders and other organisational aspects of projects.
- 5 *Urban morphology*: Related to the arrangement of buildings in, and shape of, a CFN.
- 6 *Life cycle assessment*: Focusing on GHG emissions in CFN from a life cycle point of view.
- 7 *Social aspects*: Impact of CFN on humans and interactions between CFNs and people.
- 8 *Microclimate*: Mainly addressing microclimatic aspects in CFNs.
- 9 *Other*: Research not falling under the previous categories, for example with focus on economic evaluations, the assessment of indicator systems, monitoring results, position papers etc.

Furthermore, the included articles were grouped according to their methodological approaches: Numerical/mathematical modelling, Techno-economic analysis/feasibility study, Interview/questionnaire/experiment, Methodology/framework/tool presentation, Review, and Others not captured by the previous five methods. Table 1 gives an overview of the abbreviations and descriptions of the topic and methodology categories.

3. Results

Following the aforementioned methodology, of the initially identified 395 scientific articles, 144 were included in this study. In the following section, the included research was thoroughly analysed based on different attributes such as (i) the nomenclature used in the articles, (ii) usage and location of case studies, (iii) the main topic of the articles, (iv) the methodological approaches, (v) the publication channels, years, and citations, and (vi) the author keywords. This analysis aims to determine the structure, the focus areas and the gaps in the literature related to CFNs.

3.1. Terminology

As previously mentioned, there is a large number of different terms used for strategies aimed at reducing the energy use or GHG emissions in clusters of buildings. Fig. 3 shows the terminologies that were used by at the minimum three studies. In total, there were 35 different terminologies, of which 21 were used two times or less (note that "neighbourhood" also includes the corresponding American spelling). Sometimes authors addressed more than one CFN concept in their articles, others used different terms as synonyms for addressing the same CFN concept or case study. Especially regarding the spatial scale, there seems to be disagreement or at least ambiguity about when to call a cluster of buildings "neighbourhood", "district", "block", "community",

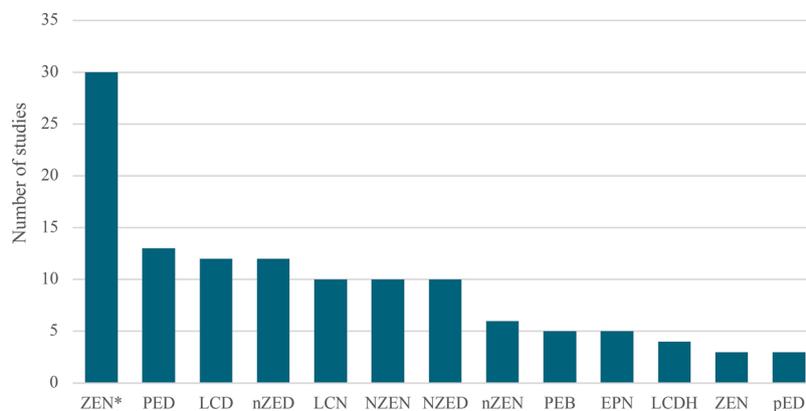


Fig. 3. Terminology of CFNs used in at least three studies.

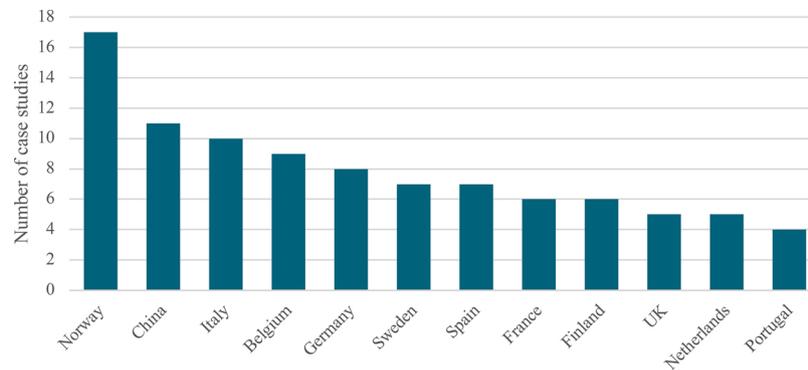


Fig. 4. Country of case study locations if used at least two times.

“settlement” or “precinct”.

In the included subset of literature, *Zero Emission Neighbourhood* (ZEN*) was by far the most frequently used CFN concept with a count of 30 studies (20.8 %). *Positive Energy District* (PED) was used in 13 (9.0 %), *Low Carbon District* (LCD) and *Nearly Zero Energy District* (nZED) each in 12 (8.3 %), and *Low Carbon Neighbourhood* (LCN), *Net Zero Energy Neighbourhood* (NZEN) and *Net Zero Energy District* (NZED) each in 10 research papers (6.9 %). Other terminologies used were:

- *Nearly Zero Energy Neighbourhood* (nZEN),
- *Positive Energy Block* (PEB),
- *Energy Positive Neighbourhood* (EPN),
- *Low Carbon District Heating* (LCDH),
- *Zero Energy Neighbourhood* (ZEN),
- *Plus Energy District* (pED),
- *Zero Energy District* (ZED),
- *Positive Energy Precinct*,
- *Zero Carbon District*,
- *Zero Carbon Neighbourhood*,
- *Smart City Eco District*,
- *Zero Energy Emission District*,
- *Zero Non-Renewable Energy Neighbourhood*,
- *Plus Energy Neighbourhood*,
- *Nearly Zero Energy Settlement*,
- *Net Zero Exergy District*,
- *Net Zero Carbon Emission District*,
- *Low or Zero Emission District Heating*,
- *Low Carbon Energy District*,
- *Low Carbon Local Energy Community*,
- *Net Positive Energy Neighbourhood*,
- *Energy Positive District*,
- *Smart Energy Community*,
- *Net Zero Energy Block*,
- *Nearly Zero Carbon Neighbourhood*,
- *Net Zero Energy Settlement*,
- *Net Zero Energy Campus*, and
- *Net Zero Energy Community*.

The outweighing part of articles (70) used “neighbourhood” as an expression for the spatial boundary, which corresponds to 48.6 %. 60 studies (41.6 %) used “district” and 8 (5.6 %) “block”. However, when just focusing on the spectrum of terminologies, “district” (15 out of 35) was used more often than “neighbourhood” (11 out of 35). The most used word in the CFN concept terminologies was “energy” (23 out of 35).

While most of the more frequently used terminologies are more or less defined, regarding their energy or emission balance (“zero”, “plus”, “positive” over a certain accounting period), *Low Carbon* is fairly vague. In the included subset of literature, this term was often used to describe any form of carbon reduction.

Table 2
Most-used case studies among included articles.

Name	Type	Status (04/2021)	Location	References
Ydalir	ZEN*	Under construction	Elverum, Norway	(Hamdan & Boer, 2019; Lausset et al., 2021; Lausset, Ellingsen et al., 2020; Lund et al., 2019; Nielsen et al., 2019; Ytterstian et al., 2019)
Campus Evenstad	ZEN*	Completed	Evenstad, Norway	(Askeland et al., 2019; Nielsen et al., 2019; Pinel et al., 2020, 2021; Woods & Berker, 2019)
Wüstenrot	pED	Completed	Wüstenrot, Germany	(Brennenstuhl et al., 2019; Ge et al., 2019; Pietruschka et al., 2015; Romero Rodríguez et al., 2019)
Milano4You	nZED	At planning stage	Milano, Italy	(Aste et al., 2017, 2020; Del Pero et al., 2021)
Zero Village Bergen	ZEN*	At planning stage	Bergen, Norway	(Lausset et al., 2019; Nielsen et al., 2018, 2019)

3.2. Case studies

More than half (87 or 60.4 %) of the 144 reviewed studies applied their research to case studies. Here, the term case study does not include generic and fictional, but only real neighbourhoods that either already

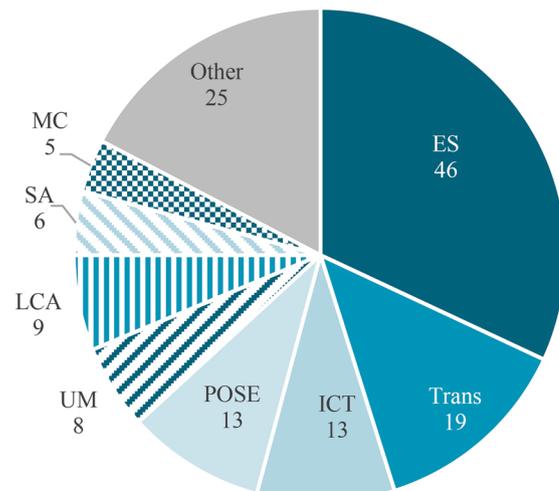


Fig. 5. Distribution of topics of included articles.

exist or are at the planning or construction stage. Fig. 4 shows the countries that had at least four case studies in the reviewed articles. However, the included subset of literature covers case studies from all continents, although the global distribution is quite unbalanced. As can be seen, 17 case studies were located in Norway and 11 in China, followed by Italy with 10, Belgium with 9, Germany with 8, and Sweden and Spain with 7. Note that when an article had more than one case study from the same country, the country was only counted once.

The most-used case studies are listed in Table 2. Note that Ydalir, Campus Evenstad and Zero Village Bergen are three of the nine pilot projects in the Research Centre on Zero Emission Neighbourhoods in Smart Cities (ZEN Research Centre, FME ZEN) (Bremvåg et al., 2018, 2020; Kvellheim et al., 2021; Woods et al., 2019).

3.3. Topics

This section analyses the primary topics of the included articles, as some of the articles covered more than one topic. During a careful examination of the included articles, their thematic focus was identified to the best of the authors' knowledge and judgement, which can be seen in Fig. 5.

3.3.1. Energy system

Most of the publications (46 articles or 31.9 %) focused on the energy system (ES) of a CFN. Traditionally accounting for the largest share of energy use (Fay et al., 2000; Koezjakov et al., 2018) and GHG emissions (Georges et al., 2015; Passer et al., 2012) in buildings, the energy supply during the use phase represents a key element for reaching a CFN, whatever the target unit or concept is. Although grouped within the same category, articles were dealing with a great range of aspects regarding the ES. The integration of multiple, and most importantly renewable energy sources in the energy supply system of a CFN is of central importance for reducing the share of fossil energy carriers and consequently GHG emissions. Therefore, a large part of the reviewed articles addressed multi-energy systems and the management of several energy sources (Bartolini et al., 2018; Capuder & Mancarella, 2016; Cheng et al., 2020; Comodi et al., 2019; Del Pero et al., 2021; Gabaldón Moreno et al., 2021; Garau et al., 2017; Ge et al., 2019; Hachem-Vermette & Singh, 2020; Heendeniya et al., 2020; Kim et al., 2019; Koutra et al., 2016; Morales Gonzalez et al., 2012; Pietruschka et al., 2015; Pinel et al., 2019; Pinel et al., 2020; Wang et al., 2015). It was common to evaluate different scenarios of energy production (Aste et al., 2015, 2017; Garau et al., 2017; Kılıç, 2014; Kim et al., 2019; Morales Gonzalez et al., 2012; Rezaei et al., 2021; Zwickl-Bernhard & Auer, 2021) or the inclusion of storage systems, with some articles focusing on thermal (Kim et al., 2019; Renaldi et al., 2017; Roccamena et al., 2019; Sameti & Haghghat, 2018), some on electrical (Sameti & Haghghat, 2018; Shafiullah et al., 2018; Shaw-Williams et al., 2020) storages. Frequently, mixed-integer linear programming (MILP) (Bartolini et al., 2018; Capuder & Mancarella, 2016; Iturriaga et al., 2021; Pinel, 2020; Pinel et al., 2020; Sameti & Haghghat, 2018; Shafiullah et al., 2018; Zwickl-Bernhard & Auer, 2021) was used, and in one case, model predictive control (MPC) (Pietruschka et al., 2015). Cortés, Auladell-León, Muñozuri, and Onieva (2020) and Hachem-Vermette and Singh (2020) used a non-linear model to simulate the distributed energy resources in a CFN and its connection to the public grid. Other studies elaborated on the role of a CFN in a bigger context, for example, the larger power system (Askeland et al., 2019; Backe et al., 2018; Klebow et al., 2013; Romero Rodríguez et al., 2019) or grid tariffs (Askeland et al., 2019; Pinel et al., 2019; Pinel et al., 2021). In three articles, the problem of overvoltage, or voltage rise/drop in the grid due to photovoltaics (PV) production was addressed (Baetens et al., 2011; Coninck et al., 2014; Shaw-Williams et al., 2020). Boccalatte, Fossa, and Ménézo (2020) discussed the optimal arrangement of building-integrated PV surfaces in existing districts in order to reach Nearly Zero Energy standard. Kılıç published two studies on a Net Zero Exergy District, where the goal is to

produce as much energy at the same grade or quality as it is consumed on an annual basis (Kılıç, 2014, 2015). Lowering the environmental impact through efficient district heating systems was the topic of research in four articles (Di Lucia & Ericsson, 2014; Finney et al., 2013; Hirvonen & Kosonen, 2020; Jadwiszczak, 2017). Yang, Chi, Wu, and Quan (2018) presented a multidisciplinary geodesign method to integrate systems of "renewable energy production, energy consumption, stormwater management, as well as a measurement of human experiences in cities". Koch, Girard, and McKoen (2012) examined load matching between a building's electrical and thermal needs and its distributed generation. Walker, Labeodan, Maassen, and Zeiler (2017) reviewed research on energy hubs for EPN.

3.3.2. Transition to CFN

19 of the included articles (13.2 %) addressed the transition (Trans) of an existing neighbourhood to a CFN. This category was dominated by articles proposing novel methodologies, frameworks or performance indicators to support implementing CFNs (Ala-Juusela et al., 2016; Blumberga et al., 2019; Clemente et al., 2019; García-Fuentes et al., 2018; Keough & Ghitler, 2020; Koutra et al., 2019; Koutra, Becue, Griffon et al., 2017; Koutra, Becue, & Ioakimidis, 2017; Marique & Reiter, 2014; Torre et al., 2021), mostly by using multi-criteria approaches (Blumberga et al., 2019; Koutra, Becue, Ioakimidis et al., 2017; García-Fuentes et al., 2018; Koutra et al., 2019). Commonly, the possibility of transformation to a CFN was evaluated through case studies (Ala-Juusela et al., 2016; Blumberga et al., 2020; Delmastro et al., 2017; García-Fuentes et al., 2018; Haneef et al., 2020; Janzadeh & Zandieh, 2021; Keough & Ghitler, 2020; Koutra et al., 2019; Koutra, Becue, Griffon et al., 2017; Leal et al., 2015; Leibold et al., 2020; Marique & Reiter, 2014; Nematchoua, 2020; Yamaguchi et al., 2013). In a paper by Ala-Juusela et al. (2016) KPIs for EPNs are given along with a decision support tool called AtLas. Such decision making support methodologies were also developed or applied in other papers of this category (Blumberga et al., 2019; García-Fuentes et al., 2018; Koutra et al., 2019).

3.3.3. Project organisation and stakeholder engagement (POSE)

This category contains 13 articles (9.0 %) that address a broad spectrum of different aspects, ranging for example from a critical discourse analysis in an LCN project in the UK (Genus & Theobald, 2016), over the role of utility companies in municipal planning of a Smart Energy Community (Nielsen et al., 2018), innovative public procurement (Hamdan & Boer, 2019), the roles of university researchers in CFN projects (Genus & Theobald, 2015), citizen engagement (Fatima et al., 2021), public-private collaboration (Ekambaram et al., 2020) to the visualisation of key performance indicators (KPI) for improved stakeholder participation by using virtual reality (Wiberg et al., 2019). Freeman and Yearworth (2017) discussed problem structuring methods in complex multiorganizational collaboration projects in the context of a project aiming to develop energy master plans for three city districts. Nielsen, Baer, and Lindkvist (2019) Klicker oder tippen Sie hier, um Text einzugeben. investigate exploitative and explorative innovation models and how they are applied by using Norwegian case study projects. Two articles analysed the practices of district energy planning in China in order to achieve a low carbon target (Xu et al., 2014; Xu et al., 2015). Two papers reported the experiences from EU Horizon 2020 projects and discussed an implementation framework for energy flexibility (Maas et al., 2020) and the challenges and barriers for the implementation of positive energy communities and districts (Uspenskaia et al., 2021).

3.3.4. Information and communication technology

A term that is frequently used in the CFN context is "smart". Smart City, Smart Grid, Smart Homes, Smart Appliances, etc. The basis for such smart systems is an information and communication technology (ICT) infrastructure for data management and sharing, a topic which was covered in 13 of the included articles (9.0 %). In the majority of cases,

management architectures for data (Sinaeepourfard, Krogstie, & Petersen, 2018; Sinaeepourfard, Krogstie, Petersen et al., 2018; Sinaeepourfard, Krogstie, Petersen, & Ahlers, 2019; Sinaeepourfard & Petersen, 2019; Soltvedt et al., 2020), smart technology (Sinaeepourfard, Krogstie, & Petersen, 2019; Sinaeepourfard, Petersen, & Ahlers, 2019) or software (Sinaeepourfard, Petersen, et al., 2019) in the ZEN* context were proposed. Other publications in this category addressed, for instance, the energy management (Bourdeau et al., 2013; Redmond et al., 2015), presented an in-house monitoring and control network (Carreiro et al., 2011) or an enterprise architecture framework for cities to create value-added services for its citizens (Petersen et al., 2019). One paper discusses IT-centred challenges that lie in designing a “flexible, open, transferable, and replicable smart city” architecture (Ahlers, Wienhofen et al., 2019). In another study by Petersen, Petersen, and Ahcin (2020), a mobile app to increase citizens’ awareness of their carbon footprint is discussed.

3.3.5. Urban morphology

The arrangement of buildings within a cluster has been addressed in 8 studies (5.6 %). Most commonly, the relationship between urban shape and mobility was investigated (Hou et al., 2019; Lima et al., 2016; Zhou et al., 2019). In a study by Lima et al. (2016), an algorithmic approach was presented to support city planning with effective sustainable methods towards better urban mobility. Amaral et al. (2018) conducted a review of the relevant aspects that influence energy performance, such as climatic and morphological, in nZED.

Guarino et al. (2016) optimised solar energy gains in the Mediterranean context with a parametric analysis of building shapes, building mutual distances, road shape, building orientation, and PV area available. Based on urban morphology, Wang, Zhao, He, Wang, and Peng (2016) proposed planning technologies and an indicator system for LCN design. Another Chinese study investigated the relationship between land use data and urban indicators, such as density, land use mix, accessibility to public transport etc., and household carbon emissions in Beijing (Qin & Han, 2013). Li, Quan, and Yang (2016) proposed a GIS-based simulation model to assess the influence of urban form and building typology on the energy performance and carbon emissions of two districts in Macau, China.

3.3.6. Life cycle assessment

In this category, 9 articles (6.3 %) were collected. 8 of them addressed ZEN*s, where the concept focuses on GHG of a neighbourhood over its life cycle. In three studies, a modular LCA model for ZEN*s was proposed (Lausselet et al., 2019; Lausselet et al., 2021; Lausselet et al., 2020), Lausselet, Urrego, Resch, and Brattebø (2020) developed a

dynamic material flow analysis LCA model. Lund, Lausselet, and Brattebø (2019) applied the model from Lausselet et al. (2019) to a Norwegian case study. Several studies (Lausselet et al., 2019; Lausselet, Ellingsen et al., 2020; Lund et al., 2019) highlight the significant contribution from mobility and transportation to the total emissions which is supported by Yttersian, Fuglseth, Lausselet, and Brattebø (2019), who developed an LCA tool, called OmrådeLCA (Norwegian for AreaLCA). Skaar, Solli, and Vevatne (2019) explored the system boundaries and ambition levels for a ZEN* campus based on key design choices. Skaar, Labonnote, and Gradeci (2018) conducted a mapping review to “analyse how parametric LCA and algorithms have been used to address neighbourhoods, buildings, and construction materials”. The only non-ZEN*-related study presented a comparison of the life cycle performance of two different urban energy systems in Calgary, Canada (Guarino et al., 2020).

3.3.7. Social aspects

A comparatively small number of articles (6 or 4.2 %) addressed social aspects. In two articles, the low-carbon behaviours of neighbourhood residents were investigated based on a survey (Peng, Wang, & Guo, 2018; Peng, Wang, Zhao, & Wang, 2018). Tironi (2020) reports on a public experiment in form of an urban laboratory in Santiago de Chile where a neighbourhood was temporarily transformed through design intervention. It included the introduction of bike lanes which replaced car lanes and sensor kits to measure air pollution and local climate conditions. Woods and Berker (2019) discussed the limitations and potentials associated with the concept of living labs in the ZEN* context and, in another study, present results from a survey conducted in a Norwegian case study (Woods & Berker, 2020). Soutullo, Aelenei, Nielsen, Ferrer, and Gonçalves (2020) present results from an empirical study using the testing facilities from the members of the Joint Program on Smart Cities of the European Energy Research Alliance.

3.3.8. Microclimate

Only 5 articles (3.5 %) are included in the category *Microclimate*. Two of which addressed urban heat island mitigation strategies (Castaldo et al., 2018; Lehmann, 2014). Gros, Bozonnet, Inard, and Musy (2016) presented the capabilities of two microclimatic and building energy simulation tools, EnviBatE and SOLENE-Microclimate, through a case study. Natanian and Auer (2020) proposed a holistic microclimatic energy and environmental quality evaluation workflow for Grasshopper to evaluate the impacts of building and urban design parameters on energy performance and environmental quality. Piselli, Di Grazia, and Pisello (2020) looked into the effect of outdoor microclimatic boundary conditions on air conditioning system efficiency and building energy demand.

3.3.9. Other

The 25 studies in this category, which represent 17.4 % of the included articles, addressed a variety of aspects of CFNs. Covered topics were for instance the design of buildings in a CFN (Acre & Wyckmans, 2015; Taveres-Cachat et al., 2019; Yang & Zhang, 2016), evaluating the economic benefits from CFNs (Becchio et al., 2018; Kalaycıoğlu & Yılmaz, 2017), or reporting the monitoring results from case studies (Guyot et al., 2020; Himpe, Janssens et al., 2015; Himpe, van de Putte et al., 2015). In some articles, indicator tools and systems were presented, e.g. Wiik, Fufa, Andresen, Brattebø, and Gustavsen (2019) for ZEN*s or Zhao, Yu, He, and Tu (2019) for the evaluation of rural LCN. Koutra et al. (2018) reviewed such assessment tools and sustainable approaches towards the development of nZED, while Zhang et al. (2019) reviewed green neighbourhood rating systems. Clerici Maestosi, Andreucci, and Civiero (2021) discussed frameworks and funding opportunities in Europe to drive the transition to PEDs and climate-neutral cities. Kominos, Kakderi, Mora, Panori, and Sefertzi (2021) addressed the knowledge gap about developing cross-sector, high-impact smart city systems and looked for a universal architecture, incorporating multiple

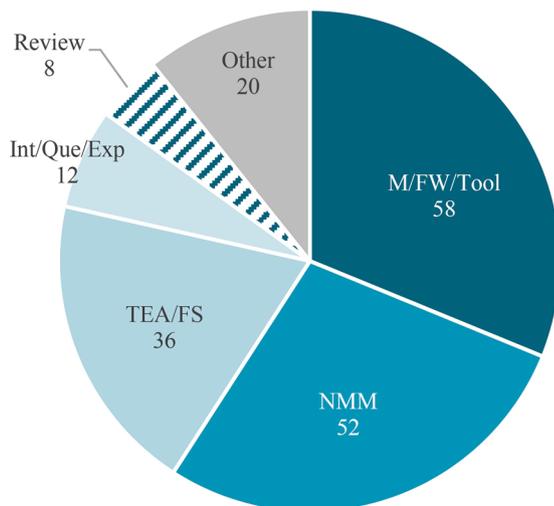


Fig. 6. Distribution of research methods used in the included studies.

Table 3
Journals and Conferences (disregarding the journal volume or conference edition) that published three or more of the included articles.

Journals	Conferences
<i>Applied Energy</i>	<i>Nordic Conference on Zero Emission and Plus Energy Buildings (Nordic ZEB+)</i>
<i>Energies</i>	<i>Conference on Smart Cities (IEEE Smart Cities)</i>
<i>Building and Environment</i>	
<i>Energy</i>	
<i>Sustainability</i>	
<i>Buildings</i>	
<i>Sustainable Cities and Society</i>	
<i>Energy and Buildings</i>	

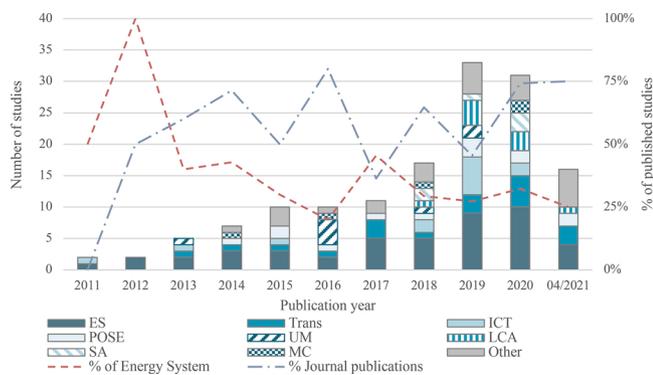


Fig. 7. Publication history of included articles according to the publication year.

dimensions of the smart city, including safety, transportation and energy. Other papers addressed solar shading in nZENS (Verbruggen et al., 2020), reviewed literature on net zero energy buildings to analyse the possibility to move to the neighbourhood scale (Nematchoua et al., 2021), or provided definitions of different PED types and a survey of the renewable energy market circumstances in the EU (Lindholm et al., 2021). Hedman et al. (2021) discussed challenges related to PEDs and provides an overview of the organization and tasks of IEA EBC Annex 83 Positive Energy Districts. The remaining articles in this category are given in the References (Ahlers, Driscoll et al., 2019; Good, Martínez Ceseña, Mancarella et al., 2017; Pinna et al., 2018; Scognamiglio et al., 2014).

Table 4
The 10 most cited articles of the included literature according to Web of Science.

Rank	Times cited	Title	Authors	Publ. channel	Category
1.	71	A simplified framework to assess the feasibility of zero-energy at the neighbourhood/community scale	(Marique & Reiter, 2014)	Energy Research & Social Science	Trans
2.	62	Low-carbon district heating in Sweden – Examining a successful energy transition	(Di Lucia & Ericsson, 2014)	Energy and Buildings	ES
3.	55	An optimisation framework for thermal energy storage integration in a residential heat pump heating system	(Renaldi et al., 2017)	Applied Energy	ES
4.	42	Energy system analysis of a pilot net-zero exergy district	(Kilkış, 2014)	Energy Conversion and Management	ES
4.	42	Low carbon districts: Mitigating the urban heat island with green roof infrastructure	(Lehmann, 2014)	City, Culture and Society	MC
6.	38	Integration of distributed energy storage into net-zero energy district systems: Optimum design and operation	(Sameti & Haghighat, 2018)	Energy	ES
7.	32	Rule-based demand-side management of domestic hot water production with heat pumps in zero energy neighbourhoods	(Coninck et al., 2014)	Habitat International	ES
7.	32	Planning parameters and household carbon emission: Evidence from high- and low-carbon neighborhoods in Beijing	(Qin & Han, 2013)	Journal of Building Performance Simulation	UM
9.	29	Simulation tools to assess microclimate and building energy – A case study on the design of a new district	(Gros et al., 2016)	Energy and Buildings	MC
10.	27	Ten questions concerning smart districts	(Good et al., 2017)	Building and Environment	Other

3.4. Methods

Fig. 6 shows how often a specific research method has been used in the included literature. Many articles used more than one method and most commonly (in 58 publications or 40.3 %), the articles presented a new method, framework or tool (M/FW/Tool) which illustrates that the field is still quite new and a lot of methodological groundwork is carried out. The second most frequently used method (in 52 articles or 36.1 %) was numerical and mathematical Modelling (NMM), often in connection with M/FW/Tool (14 times). In 36 publications (25.0 %), a techno-economic analysis or feasibility study (TEA/FS) was carried out. In 12 studies (8.3 %), a survey in form of interviews or a questionnaire, or an experiment (Int/Que/Exp) was conducted. An experiment in this context means for example studies using a living laboratory. 8 of the studies (5.6 %) conducted a review (Rev). Studies marked as *Other* comprise for instance position papers, project reports and other kinds of analyses that are not captured by the previously mentioned research methods.

3.5. Publication channels, timeline and citations

In this section, the type of publication will be examined closer. 90 of the 144 (62.5 %) included elements were published as journal papers, 54 (37.5 %) as conference papers. As shown in chapter 2.1, book chapters, editorials, errata and all other kinds of publications were excluded from this analysis. Table 3 shows the journals and conferences (disregarding the journal volume/issue or conference edition) that published at least 3 of the included articles. *Applied Energy* published a total of 8 articles, followed by *Energies* with 7, *Building and Environment* with 6 and *Energy, Sustainability, and Buildings* with each 5. *Sustainable Cities and Society* and *Energy and Buildings* have 4 publications each.

By far the most conference papers (9) were published at the *Nordic Conference on Zero Emission and Plus Energy Buildings* (Nordic ZEB+), albeit the conference’s name suggests a focus on the buildings rather than the neighbourhood scale. At the *Conference on Smart Cities* (IEEE Smart Cities), three of the included articles were published.

Fig. 7 shows the distribution of article topics and type according to the year of publication. 2011 marks the first year in which scientific articles related to CFNs were published. In that year, two conference articles with a focus on the ES and ICT were published. In the following, the number of published articles per year has been surpassing or has at least been equal to the number of published articles from the previous year until 2020, where three articles less than 2019 were published. As of April 2021, the time of literature identification, 16 articles were

Table 5
The 10 most used author keywords in the included studies.

Rank	Keyword	No. of times used
1.	Smart city/Smart cities	19
2.	Positive Energy District(s)/PED	10
3.	Optimisation/Optimization	9
4.	Multi-energy carriers/Multi energy carrier systems/Multi energy systems	8
4.	District/District scale	8
4.	Zero emission neighbo(u)rhoods/ZEN	8
4.	(Local) renewable energy (integration)	8
5.	Photovoltaics/Photovoltaic energy/Photovoltaic systems	7
5.	Life cycle assessment (LCA)/LCA	7
5.	Energy efficiency	7

published. From 2012 onwards, the share of journal articles of the total number of publications has been at least 40 %, except for 2017 where it was 36 %. Unlike all other categories, *ES* studies have been published every year, with the highest percentage reached in 2012 (100 %). Over the last decade, there has been a declining trend in the share of *ES* publications. In 2021, so far 25 % of the published articles have been categorised as *ES*, the second-lowest value after 2016 with 20 %. Studies in the categories *SA* and *LCA* emerged as recently as 2018, while the earliest year of publication in the category *Trans* and *UM* was 2013, and in *POSE* and *MC* 2014.

The popularity of studies about the *ES* is also reflected by the list of the most cited (according to *Web of Science*) articles of included literature (see also Table 4). Half of the 10 most cited articles, as well as one of the two articles with the highest citation score, are assigned to category *ES*. The articles in category *ES* received 394 citations in total which are far more than in the other categories. The second most cited category is *Other* with 157, followed by *Trans* with 130, and *Urban morphology* with 113 citations. The category with the lowest citation count is *SA* with 5 citations. All 10 most cited articles were published in journals, the most cited conference paper, a review study of the concept and current research on energy hubs in energy positive neighbourhoods, received 12 citations (Walker et al., 2017). The citation analysis is biased towards the fact that more recent articles generally received fewer citations, simply because they might not be known to an equally large audience yet than articles from earlier publication years.

3.6. Author keyword analysis

The analysis of author keywords showed that *Smart city/Smart cities* were utilised the most among the included articles with a count of 19 (see also Table 5). Following the recent developments on a European scale, *Positive Energy District(s)/PED* takes second place with being used 10 times. After that, *Optimization/Optimisation comes in with a count of 9 and Multi-energy carriers/Multi-energy carrier systems/Multi-energy systems, District/District scale, Zero emission neighbo(u)rhoods/ZEN, and (Local) renewable energy (integration)* take a shared third place having been used 8 times each. The fourth most used keywords, used 7 times, were *Photovoltaics/Photovoltaic energy/Photovoltaic systems, Life cycle assessment (LCA)/LCA, and Energy efficiency*.

4. Definitions of climate friendly neighbourhoods

As mentioned earlier, there are numerous concepts for CFNs which is illustrated by the great number of terms for CFNs from the systematic review (see Section 3.1). However, there aren't always clear definitions for every term and sometimes slightly differing definitions for the same term exist. Additionally, clear definitions of CFN concepts are rarely included in scientific articles. In the following, frequently used and well-defined CFN concepts mostly from EU-projects (see also Appendix A) and other literature are presented to complement the systematic review. The included projects are based on an ordinary web search and, in the

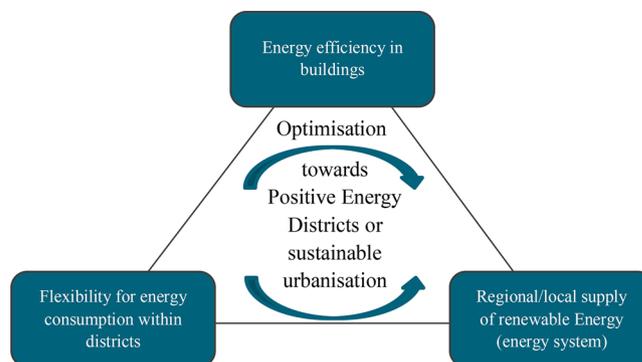


Fig. 8. Definition of Positive Energy Districts, modified from (European Commission Joint Research Centre, 2018).

case of the EU-funded projects, the cordis database (<https://cordis.europa.eu/>). Here, no structured approach was followed. This section provides an overview of some selected, existing definitions and projects that apply them. It is not intended to be exhaustive but to provide the reader with an overview of KPIs, targets, boundaries, assessment criteria and the most important references to the respective definitions.

4.1. Positive energy district

The PED concept is a common objective in many ongoing EU research projects, like for instance *SPARCS, POCITYF, ATELIER, +CityxChange, and Making City* (see also Appendix A). It is defined in the European SET Plan Action 3.2 Smart Cities and Communities Implementation Plan as “a district with annual net zero energy import, and net zero CO₂ emission working towards an annual local surplus production of renewable energy” (European Commission Joint Research Centre, 2018). PEDs are part of an urban and regional energy system to ensure security and flexibility of supply and storage. The key to a PED is to keep annual local energy use below the amount of locally produced renewable energy. PEDs also promote charging capabilities for electric vehicles and make use of advanced materials, local renewable energy sources, local storage, smart energy grids, demand response, energy management, user interaction and involvement, and ICT (see Fig. 8). At the same time, affordability for the inhabitants is highlighted in the implementation plan (European Commission Joint Research Centre, 2018).

In the *White Paper on the Reference Framework for Positive Energy Districts and Neighbourhoods* by Hinterberger, Gollner, Noll, Meyer, and Schwarz (2020) an essentially similar definition can be found. In their paper, however, PEDs and Positive Energy Neighbourhoods (PEN) are used sometimes interchangeably.

“Positive Energy Districts 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. They require integration of different systems and infrastructures and interaction between buildings, the users and the regional energy, mobility and ICT systems while securing the energy supply and a good life for all in line with social, economic and environmental sustainability”.

As to the size of a PED/PEN, no clear definition is given due to varying national conditions. Hinterberger et al. (2020) write that a definition at the national level might be appropriate and add that PEDs/PENs comprise a “group of connected buildings (respectively, more than one building)”. An overview of 61 PEDs and projects that did not declare a PED ambition but are interesting for the PED program at different project stages is given by Gollner et al. (2020).

Although largely concurrent with the previously mentioned definitions, in IEA EBC Annex 83, the description of a PED is given without the clear focus on net zero GHG emissions. It is merely stated that PEDs are

“intended to shape cities into carbon neutral communities in the near future” and use low-carbon energy production (IEA EBC Annex 83, 2020). The whole definition is:

“[A]n area within the city boundaries, capable of generating more energy than is used, and agile/flexible enough to respond to energy market variations. Rather than simply achieving an annual net energy surplus, it should also support minimizing impacts on the connected centralized energy networks by offering options for increasing onsite load-matching and self-use of energy, technologies for short- and long-term energy storage, and providing energy flexibility with smart control. PEDs can include all types of buildings present in the urban environment and they are not isolated from the energy grid. Within the research community, the PED is an emerging concept intended to shape cities into carbon neutral communities in the near future. Reaching the goal of a PED requires firstly improving energy efficiency, secondly cascading local energy flows by making use of any surpluses, and thirdly using low-carbon energy production to cover the remaining energy use. Smart control and energy flexibility are needed to match demand with production locally as far as practical, and also to minimize the burdens and maximize the usefulness of PEDs on the grid at large.”

4.2. Positive energy block

The European Commission Smart Cities Marketplace: Positive energy blocks, 2021 defines a Positive Energy Block (PEB) as a “group of at least three connected neighbouring buildings producing on a yearly basis more primary energy than what they use” (Cartuyvels et al., 2018; European Commission Smart Cities Marketplace: Positive energy blocks, 2021). To utilise advantages from complementary consumption curves and local renewable energy production, consumption and storage, this group of buildings must be mixed-use. An important aspect of PEBs is the focus on energy. Embodied emissions are not included in its definition. The first PEB in operation in Europe is HIKARI in Lyon Confluence, France (European Commission Smart Cities Marketplace: Positive energy blocks, 2021). This project was also a case study in a paper by Roccamena et al. (Roccamena et al., 2019) which has been included in this article’s review. However, in their paper, Roccamena et al. did not use the term block but district.

The European Commission uses PEB and PED interchangeably in their definition for the Horizon 2020 Work Programme 2018–2020 and do not mention the three-building-minimum but use the term “several buildings” which can be new, retro-fitted or both (European Commission, 2020a). Similar to the SET Plan Action 3.2 definition of a PED (European Commission Joint Research Centre, 2018), local renewable energy production and storage, as well as advanced materials, smart energy grids, demand-response, energy management and user

interaction/involvement are the basis for PEB/PED (European Commission, 2020a). EU research projects that included PEBs in their objectives are for example SPARCS and +CityxChange (see also Appendix A).

4.3. Nearly zero energy neighbourhood

The definition of the *Nearly Zero Energy Neighbourhood research project (ZenN)* for a Nearly Zero Energy Neighbourhood (NZEN) is focussing on residential building clusters (Sørnes et al., 2014). The energy demand in such a cluster is to be low and partly met by renewable energy self-produced within the neighbourhood. The balance boundary for NZENs includes heating, cooling, ventilation, and domestic hot water. Lighting is only included in two non-residential demo case buildings in the project. Appliances were a priori excluded. The physical boundary includes the sites of renewable energy production besides the buildings themselves.

4.4. Zero emission neighbourhood

ZEN* is a term primarily coined by the Research Centre on Zero Emission Neighbourhoods and Smart Cities (FME ZEN) (Brennvåg et al., 2018, 2020; Kvellheim et al., 2021; Woods et al., 2019). Continuing the work from the Research Centre on Zero Emission Buildings (FME ZEB) (Hestnes & Eik-Nes, 2017) that was active from 2009 to 2017, it lifts the zero emission concept from the building to the neighbourhood scale.

In FME ZEN, a neighbourhood is defined as a group of interconnected buildings (new, existing, retrofitted or a combination) in a confined geographical area with associated infrastructure like for instance pavements, roads, grids, technologies for supply, generation, storage, and export of electricity and heat, and may also include grids and technologies for water, sewage, waste, mobility and ICT. The area needs to have a defined physical boundary to external grids. This physical boundary does not necessarily need to be the same as the boundary for analysis of energy facilities serving the neighbourhood.

In a ZEN*, depending on the chosen ambition level, different life cycle modules and building and infrastructure elements are included in its aim to reduce its direct and indirect GHG emissions towards zero over the analysis period. For buildings, normally a period of 60 years, for infrastructure 100 years are assumed. The definition underlines that a ZEN* should focus on the following (Wiik, Fufa, Baer et al., 2018; Wiik, Fufa, Krogstie et al., 2018):

- Plan, design and operate buildings and associated infrastructure components towards zero life cycle GHG emissions.

Table 6
ZEN* assessment criteria and KPIs covered in the ZEN* definition guideline (Wiik, Fufa, Baer et al., 2018; Wiik, Fufa, Krogstie et al., 2018).

Category	Assessment criteria	KPI
GHG emission	Total GHG emissions	Total GHG emissions in tCO _{2eq} /m ² BRA/a; kgCO _{2eq} /m ² BAU/a; tCO _{2eq} /capita
	GHG emission reduction	% reduction compared to the base case
Energy	Energy efficiency in buildings	Net energy need in kWh/m ² BRA/a; Gross energy need in kWh/m ² BRA/a; Total energy need in kWh/m ² BRA/a
	Energy carriers	Energy use in kWh/a; Energy generation in kWh/a; Delivered energy in kWh/a; Exported energy in kWh/a; Self-consumption in %; Self-generation in %; Colour coded carpet plot in kWh/a
Power/Load	Power/load performance	Net load early profile in kW; Net load duration curve in kW; Peak load in kW; Peak export in kW; Utilisation factor in %
	Power/load flexibility	Daily net load profile in kW
Mobility	Mode of transport	% share
Economy	Access to public transportation	Meters; Frequency
	Life cycle cost (LCC)	NOK; NOK/m ² BRA/a; NOK/m ² BAU/a; NOK/capita
Spatial qualities	Demographic needs and consultation plan	Qualitative
	Delivery and proximity to amenities	Number of amenities; Meters (distance from buildings)
	Public space	Qualitative
Innovation ¹	-	-

Abbreviations: Heated floor area (BRA); Outdoor space (BAU); Norwegian Kroner (NOK)¹Assessment criteria and KPIs not yet decided upon.

Table 7
Categories, subcategories and KPIs defined in the syn.ikia evaluation framework (Salom & Tamm, 2020).

Category	Assessment criteria	KPI
Energy and Environmental Performance	Overall performance	Non-renewable primary energy balance, Renewable energy ratio
	Matching factors	Grid purchase factor, Load cover factor/Self-generation, Supply cover factor/Self-consumption
	Grid interaction factors	Net energy/Net power, Peak delivered/Peak exported power, Connection capacity credit
Economic Performance	Environmental balance	Total greenhouse gas emissions
	Capital costs	Investment costs, Share of investments covered by grants
	Operational costs	Maintenance-related costs, Requirement-related costs, Operation-related costs, Other costs
	Overall performance	Net Present Value, Internal Rate of Return, Economic Value Added, Payback Period, nZEB Cost Comparison
Indoor Environmental Quality	Indoor air quality	CO ₂
	Thermal comfort	Predicted Mean Vote (PMV), Predicted Percentage Dissatisfied (PPD), Temperature, Relative Humidity
	Lighting and visual comfort	Illuminance, Daylight factor
	Acoustics comfort	Sound Pressure Level
Social Performance	Equity	Access to amenities, Access to services, Affordability of energy, Affordability of housing, Democratic legitimacy, Living conditions, Sustainable mobility, Universal design
	Community	Demographic composition, Diverse community, Social cohesion
	People	Personal safety, Energy consciousness, Healthy community
Smartness and Flexibility	Flexibility	Flexibility index
	Smartness	Smartness Readiness Indicator (SRI)

- Become highly energy efficient and powered by a high share of new renewable energy in the neighbourhood energy supply system.
- Manage energy flows (within and between buildings) and exchanges with the surrounding energy system in a smart and flexible way.
- Promote sustainable transport patterns and smart mobility systems.
- Plan, design and operate with respect to economic sustainability, by minimising total life cycle costs.
- Plan and locate amenities in the neighbourhood to provide good spatial qualities and stimulate sustainable behaviour.
- Development of the area is characterised by innovative processes based on new forms of cooperation between the involved partners leading to innovative solutions.

Consequently, the ZEN* definition includes the following seven categories: GHG emissions, energy, power/load, mobility, economy, spatial qualities, and innovation. These categories each contain several assessment criteria and for each of those a set of KPIs. The ZEN* assessment criteria and KPIs that are covered in the ZEN* definition guideline are listed in Table 6.

4.5. Sustainable plus energy neighbourhood

The EU research project *syn.ikia* focuses on Sustainable Plus Energy Neighbourhoods (SPEN). The definition of a SPEN is closely aligned with the PED concept and describes a group of interconnected buildings with associated infrastructure, located within both a confined geographical area and a virtual boundary (Salom & Tamm, 2020). It aims to reduce its direct and indirect annual energy use towards zero and increased use and production of renewable energy. There is also a strong focus on cost efficiency, indoor environmental quality, occupant satisfaction, social factors (co-use, shared services and infrastructure) and power performance (peak shaving, flexibility, self-consumption). The following are the key aspects of a SPEN, according to (Salom & Tamm, 2020):

- Embedded in an urban and regional energy system and driven by renewable energy to provide optimized security and flexibility of supply
- Based on a high level of energy efficiency in order to keep annual local energy consumption lower than the amount of locally produced renewable energy
- Enables increased use of renewable energy within the local and regional energy system by offering optimized flexibility and by managing consumption and storage capacities according to demand

- Couples the built environment with sustainable energy production, consumption, and mobility (e.g. EV charging) to create added value and incentives for the consumers and the society
- Makes optimal use of advanced materials, local renewable energy supply, and other low carbon solutions (i.e. local storage, smart energy grids, demand-response, cutting-edge energy management systems, user interaction, and ICT).
- Offers affordable living, improved indoor environment, and well-being for the inhabitants

syn.ikia also addresses the common issue of where to draw the system boundaries for the evaluation of a SPEN. Three different boundary types are defined (Salom & Tamm, 2020):

- *Geographical boundary*: where the spatial-physical limits of the building portfolio, sites and infrastructures may be contiguous or in a configuration of detached patches
- *Functional boundary*: where the limits are with regard to the energy grids
- *Virtual boundary*: where the limits are in terms of contractual boundaries, e.g. including an energy production infrastructure owned by the occupants but situated outside the normal geographical boundaries.

“[T]he net positive yearly energy balance of a SPEN will be assessed within the virtual and/or geographical boundaries. Thus, a SPEN is able to achieve a net positive yearly energy balance and dynamic exchanges within the geographical/functional boundaries, but in addition, it will provide a connection between buildings within the virtual boundaries of the neighbourhood. In a SPEN, buildings are digitally connected via digital cloud hub [...], common ICT infrastructure and Energy Management Systems. Dynamic exchanges with the hinterland may be provided to compensate for momentary surpluses and shortages according to the assessment boundary methods.” Reference (Salom & Tamm, 2020) also provides a list of KPIs in the *syn.ikia* evaluation framework (see Table 7).

4.6. Near zero energy retrofit district

In transition track 1 of the EU research project *IRIS*, several terms for CFNs are used. While the name of this track is “Renewable and energy positive districts” the designation of the integrated solution relevant in the context of a CFN is “Near zero energy districts”. In the deliverables, however, the term “Near zero energy retrofit district” (nZERD) is used for this solution and KPIs have been developed for it (see Table 8)

Table 8
Categories and KPIs defined in the IRIS research project (Tryferidis et al., 2019).

Category	KPI
Technical	Energy demand and consumption, Energy savings, Degree of energetic self-supply by renewable energy sources, Maximum Hourly Deficit, Technical compatibility, Improved interoperability
Environmental	CO ₂ Emission Reduction, Increase in Local Renewable Energy Generation, Reduction in annual final energy consumption
Economic	Total investments, Grants, Total annual costs, Payback, Return on Investment, Fuel poverty, CO ₂ reduction cost efficiency, Financial benefit for the end user, Reduction of energy cost, Stimulating an innovative environment
Social	Professional stakeholder involvement, Advantages for end-users, Increased environmental awareness, Increased consciousness of citizenship, Increased participation of vulnerable groups, Ease of use for end users of the solution, People reached, Advantages for stakeholders, Social compatibility, Consumers engagement
ICT	Reliability, Increased system flexibility for energy players
Legal	Change in rules and regulations, Green Building self-consumption Legal Framework Compatibility

(Tryferidis et al., 2018, 2019). Energy consumption is to be reduced and renewable production to be increased which will lead to more stable and lower housing bills in combination with higher comfort/less draught and humidity in homes for the citizens. Within the IRIS framework, the following nZED solutions are expected to be demonstrated (Tryferidis et al., 2018):

- Near zero energy building retrofit in the social housing sector
- Smart street lighting
- Smart hybrid heat pumps
- Energy efficient deep retrofitting
- District heating optimization
- Citizen Utilities Savings through awareness
- House with integrated technologies in façade and roof
- Geothermal energy for preheating incoming ventilation

4.7. Low energy district

In the recently finished projects *REMO Urban* and *GrowSmarter*, Low Energy Districts (LED) were to be developed. Neither of the two projects gives a detailed definition of what constitutes an LED, but list actions connected to them. In *REMO Urban*, monitoring tools for energy, district scale retrofitting, renewable heating and cooling, electricity distributed generation, and advanced building energy management systems are specified. Furthermore, “[a] 50 % reduction of the building energy consumption will be achieved through retrofitting interventions, but also by improving lighting and equipment efficiency. Low carbon solutions for thermal energy supply and optimized electric facilities by means of decentralized electricity generation and smart grid management will be deployed in order to achieve near zero energy and zero emission districts”. Again, several CFN terms are used in the same context without clearly differentiating between the single concepts or defining a clear goal.

In *GrowSmarter*, the LED action area focuses on reducing the energy use, environmental impact, and carbon footprint by implementing affordable and sustainable retrofit solutions at a large scale. The solutions that were applied in the participating demo cities were energy efficient refurbishments, smart energy management systems, sometimes also including photovoltaics and energy storage at the building and district level (Sanmarti & Sola, 2019).

4.8. Zero energy community

Quite early on, Carlisle, van Geet, and Pless (2009) from the National Renewable Energy Laboratory presented a report in which the definition of a Zero Energy Community (ZEC) is included. The terminology used in

Table 9
ZEC classification system according to different energy supply options from Carlisle et al. (2009).

ZEC classification	Renewable energy supply option
A	1 Energy efficiency opportunities maximized 2 100 % energy load met by renewables in the built environment and unbuildable brownfield sites within the community
B	1 Energy-efficiency opportunities maximized 2 A fraction of the energy load met by renewables in the built environment and unbuildable brownfield sites within the community 3 A fraction of the energy load met by renewable generation on community greenfield sites or from off-site renewables used on site
C	1 Energy-efficiency opportunities maximized 2 A fraction of the energy load met by renewables in the built environment and unbuildable brownfield sites within the community 3 A fraction of the energy load met by renewable generation on community resources or from off-site renewables used on site 4 A fraction of the energy load met through RECs ¹ that add new grid generation capacity
D	1 Energy efficiency opportunities maximized 2 The remainder of the load is met through RECs that add new grid generation capacity

¹ RECs represent the attributes of electricity generated from renewable energy. These attributes can be unbundled from the electricity and bought and sold separately.

this document comprises Zero Energy Community, Net-Zero Energy Community and Zero Net Energy Community. It is not made clear why these different terms were used or if they are supposed to be used as synonyms. Generally, the definition is based on the work by Torcellini, Pless, Deru, and Crawley (2006) who focused on the building scale. Carlisle et al. (2009) write a ZEC is “one that has greatly reduced energy needs through efficiency gains such that the balance of energy for vehicles, thermal, and electrical energy within the community is met by renewable energy”. They further specify that if the community produces at least 75 % of its required energy through the use of on-site renewable energy, it is considered a near-zero community. In Table 9, the classification system where ZECs are rated according to different energy supply options from Carlisle et al. (2009) is presented.

4.9. Other concepts

In *Sharing Cities*, the significant benefits of smart city concepts and solutions are demonstrated by focusing on the needs of Low Energy Neighbourhoods. Specifically, retrofitting buildings, installing integrated energy management systems and smart lamp posts, as well as introducing electric mobility services are named. However, no set of KPIs or further explanation of the term is given.

In the *MATCHUP* project, high-performance districts (HPD) are aimed at through building energy efficiency improvements, integrating high shares of renewables in the energy supply, and implementing advanced energy management systems in combination with innovative storage systems. Specific focus is put on reducing the grid impact of the urban energy infrastructure. A list of targets, KPIs or assessment criteria of

Table 10
KPIs and targets as defined by the Zero-Plus research project (Zero-Plus, 2020b).

KPI	Target
Net regulated energy consumption (kWh/m ² /year)	< 20 kWh/m ² /year
Renewable Energy production (kWh/m ² /year)	> 50 kWh/m ² /year
Cost reduction	16 % reduction compared to the reference case

Table 11

Key energy-related elements to address in the Zero Energy District (ZED) master plan structure based on the DOE's experience with the ZEDA partners (Pless et al., 2018).

General energy strategy	<ul style="list-style-type: none"> Definitions of energy-related metrics being considered/used (e.g., zero energy) Energy modelling/analysis approach for different district design scenarios <ul style="list-style-type: none"> - Existing consumption/benchmarking/minimum code scenario - Alternative design scenarios Building and energy systems retrofit/construction phasing strategy Design guidelines and design advisory board Utility interconnection technical considerations
Building-scale energy requirements	<ul style="list-style-type: none"> Building types and areas, including structured parking Building efficiency levels for both new construction and existing building upgrades <ul style="list-style-type: none"> - Relevant efficiency codes and targeted percentage reductions relative to code - Energy use intensity targets - Labeling/certification/recognition options <ul style="list-style-type: none"> • Residential: Home Energy Rating System, DOE Zero Energy Ready Home, ENERGY STAR® Certified Homes, LEED, Passive House, Home Energy Score, Home Performance with ENERGY STAR, etc. • Commercial: LEED, ENERGY STAR, International Living Future Building Institute Living Building Challenge, New Buildings Institute, etc. Building systems to interface with district systems Solar access <ul style="list-style-type: none"> - Available roof area maximization - Solar-ready design guidelines Batteries/load control for demand management and microgrids
District-scale energy strategies	<ul style="list-style-type: none"> Energy-efficiency characteristics of nonbuilding infrastructure <ul style="list-style-type: none"> - Site and surface parking lighting District thermal systems <ul style="list-style-type: none"> - Load diversity and shared heat opportunities - Centralized waste heat recovery opportunities <ul style="list-style-type: none"> • Data centres, sewer lines, shared ground wells Large solar <ul style="list-style-type: none"> - Parking canopy, community solar Microgrids/batteries/load control at distribution/utility scale Electric vehicle charging infrastructure and anticipated loads Other sustainability strategies (e.g., water efficiency, waste reduction) and how they interact with energy strategy

HPDs, however, is missing.

Net Zero Energy Settlements (NZES) were the targeted CFN concept in *Zero-Plus*. The KPIs and targets for NZES within the *Zero-Plus* research project are listed in Table 10.

But also outside of Europe, governments have taken action and supported projects to address the zero energy objective at the district scale. In the United States, for instance, the Department of Energy (DOE) launched the *Zero Energy Districts Accelerator* (ZEDA) in late 2016. ZEDA was a three-year effort that provided a platform for districts, researchers, experts, and related national organizations to explore and address issues facing the implementation of ZEDs. The aim was to help partners further develop their projects and find solutions while identifying and refining promising practices with each other and the market (Better Buildings, 2021; Pless et al., 2018). Pless et al. (2018) report a ZED master plan structure with key energy strategies of a ZED to help guide each district through the energy planning process. These strategies are divided into a general energy strategy, building-scale efficiency requirements, and district-scale energy strategies (see Table 11). The ZED master plan structure also contains other key sections, including District Description and Vision/Goals, Stakeholders/Community Engagement, Utility Engagement, Financial Strategy, and Operations. Unfortunately, no KPIs or targets are reported.

In Canada, the *Net Zero Homes* project is funded by Natural Resources Canada under the ecoENERGY Innovation Initiative and in-kind contributions of the building industry with over \$4 million (Net Zero Homes, 2015). Founded in 2013, the objective of the project is to demonstrate the feasibility of building Net Zero Energy Housing Communities (NZEHC) in Ontario, Quebec, Nova Scotia, and Alberta, to address challenges to NZEHC specific to production housing, and to act as a platform for the broader application of NZEHC across the country. To the best of our knowledge, a definition of the NZEHC concept, however, is not available.

5. Discussion

5.1. Systematic review

As can be seen in the results of this work's systematic review, there is a large variety of topics addressed in scientific publications on CFNs. The interest in the scientific community has been growing continuously over the years with the earliest included studies dating back one decade (2011). Similar to the situation of the low, net/nearly zero energy/emission concept at the building scale (Kibert & Fard, 2012; Marszal et al., 2011; Williams et al., 2016), a great number of different and coexisting terminologies have been introduced over the years. In the 144 included articles of the systematic review, more than 35 different terminologies were used. This proliferation of terms causes not only confusion among the authors of scientific papers but makes it unnecessarily difficult for non-expert readers to follow. It furthermore complicates comparing methodologies or projects with each other as at the same time targets are often not defined. This issue has also been identified by Saheb et al. (2018). Interestingly, even the same case study projects have been addressed with different terminologies for its CFN concept. A more consistent and uniform description of targets, key performance indicators, system boundaries, and scales would not only facilitate but foster the adaption of CFN concepts in municipalities and local initiatives that are interested in becoming more sustainable.

The review has shown that there is a distinct imbalance in the number of articles in each category. While most of the studies were focussing on the energy system in building clusters, there is a clear lack of articles dealing for instance with embodied energy/emissions and LCA, the microclimate or the social aspects in CFNs. It is also visible from the results that transforming existing neighbourhoods into a CFN, one of the main research areas of the EU does not receive the same level of attention in published scientific articles. Although representing the second-largest category, only a quite small percentage of included articles (13.2 %) addressed this topic. The reviewed articles still focus

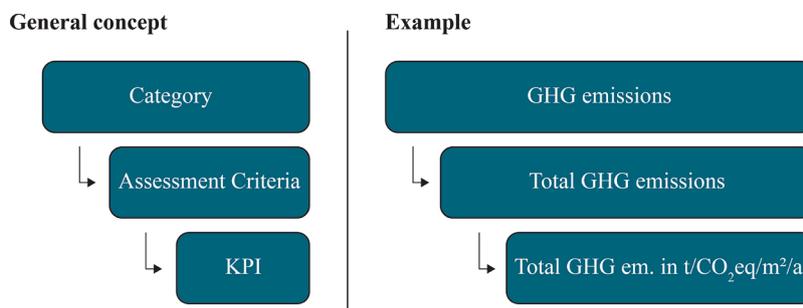


Fig. 9. System of category, assessment criteria and KPIs (general concept to the left and an example to the right).

predominantly on building-related issues, while little attention is paid to other important dimensions of a neighbourhood/district/block etc. It is important to realise that neighbourhoods/districts/blocks etc. do not only encompass buildings but also the air-filled space between them, as well as infrastructure and people with their associated activities (like mobility). Hallman (1984) definition of a neighbourhood particularly puts weight on the social aspect, describing it as “[...] a limited territory within a larger urban area, where people inhabit dwellings and interact socially”. More research on how a neighbourhood/district/block can promote peoples’ interaction with each other, their environment and technology to support sustainable awareness and behaviour is critical. Furthermore, microclimatic effects have only rarely been addressed in the reviewed studies. With the climate changing, especially the spatial quality and wellbeing (incl. thermal comfort) in outdoor spaces are aspects with increasing importance in urban planning which should not be neglected in the context of CFNs (Wu, 2014).

The novelty of this research domain explains the large fraction of articles proposing new methodologies, frameworks or tools, as its theoretical foundation has not yet fully been laid. This is also partly illustrated by the already mentioned variety of terminologies that are often used interchangeably. The novelty of this field might also explain, why the most-discussed topic among the literature subset has been the energy system, as it is responsible for the largest fraction of emissions or energy use, thus beyond doubt the most important element in reaching a CFN target. The overall attention has therefore been concentrated on this central aspect of a CFN, while the more secondary aspects like social, microclimatic, economic considerations etc. have received less attention. Because of that, research in these areas has the potential to fill wide research gaps.

As shown in this review, in more than half of the included articles, case studies have been used to apply research. Although case studies from all continents have been used in the included subset of literature, the global distribution is quite unbalanced. Certainly fueled by the ambitions and consequently public funding of research and demonstration projects in the EU, Europe is a hotspot for case studies (Joint Programming Initiative (JPI) Urban Europe (2021)). Also, China hosts a number of case studies. There, however, the vaguely defined low carbon concept is dominant. More research outside of Europe and China is needed to cover a broader spectrum of climates and facilitate the application of CFNs in a wider geographical context, especially where the main increase of global population is expected to take place.

5.2. Definitions of climate friendly neighbourhoods

When looking at existing definitions for CFN concepts, initiatives at the European level, as well as nationally and EU-funded research projects play an important role. In several of these projects, definitions for

CFNs have been developed and/or applied. Most commonly, the PED concept is targeted, as defined by the European SET Plan Action 3.2 Smart Cities and Communities Implementation Plan (European Commission Joint Research Centre, 2018). Another frequently applied concept is the PEB (Cartuyvels et al., 2018; European Commission Smart Cities Marketplace: Positive energy blocks, 2021). Other quite detailed definitions that also include a list of categories and KPIs were developed for example by FME ZEN for ZEN* (Wiik, Fufa, Baer et al., 2018; Wiik, Fufa, Krogstie et al., 2018), syn.ikia for SPEN (Salom & Tamm, 2020), and IRIS for nZED (Tryferidis et al., 2018, 2019). In some research projects, rather vaguely defined concepts are targeted, like the LED or LEN.

However, there is an ongoing discussion on whether to include mobility in the CFN definitions and consequently allocate this “burden” to the buildings or not, as urban form undoubtedly has a significant influence on energy use and emissions from mobility. While in some of the definitions, mobility is explicitly mentioned, in others it is left out. In some research projects, mobility is not part of the CFN concept but represents an own action area, like for example in the projects REMO Urban, MAtchUP and GrowSmarter. Generally, where to draw the boundaries is a common problem among such definitions and therefore needs to be stated clearly. In syn.ikia’s SPEN concept, different boundaries are defined which can be used as an example for other definitions as well.

KPIs are often listed as third level after categories and assessment criteria or subcategories (see Fig. 9). This way, the concept-specific priorities can be grasped quickly. A more standardized set of KPIs, however, would facilitate comparing case studies of different CFN types.

As shown, there are various international efforts and collaborations dedicated to paving the way to a cleaner, healthier and more resilient built environment in the future. Still, there are many barriers, namely political/regulatory, economic, social, and technological, as identified by Good, Martínez Ceseña, Mancarella, Monti et al. (2017) that need to be overcome before CFNs can find a broad application.

6. Conclusion

During the last years, there has been considerable research activities and thus dissemination in the field of Climate Friendly Neighbourhoods (CFN). This paper presented a systematic review of scientific literature from the databases *Scopus* and *Web of Science*. The results of this study help researchers to contextualize their research, as well as to identify focus areas, research gaps, future research possibilities, and similar studies within their research domain. The databases were searched by using a pre-defined syntax. In total, 144 articles have been found eligible, categorised and analysed according to the terminology used, their publication year, topic, method, location of case studies (if

applicable), keywords (where specified), citations, and publication channels. The main findings were:

- In the literature subset of 144 articles, a total of 35 different terminologies were used. There is a lack of common definitions, targets and key performance indicators which makes it unnecessarily difficult for academics and especially non-expert readers to follow or to compare different projects using the same terms.
- The first publication in the included literature dates back one decade (2011). Since then, the yearly number of publications has been rising continuously with exception of 2020. Whereas in 2011, two of the included articles were published, in 2019 it was 33. As of April 2021, when the literature identification has been carried out, so far 16 publications were registered for this year. In total, 90 publications (62.5 %) were published in academic journals, the remaining ones as conference papers. The most used keyword among the articles was *Smart city/Smart cities*, being used 19 times.
- A distinct imbalance has been identified regarding the number of articles in each topic category. While most of the studies were focussing on the energy system in building clusters, there is a clear lack of articles dealing for instance with embodied energy/emissions and LCA, the microclimate or the social interdependencies in CFNs. The reviewed articles still focus predominantly on building-related issues, while little attention is paid to other important dimensions of a neighbourhood/district/block like social and spatial aspects (microclimate, outdoor thermal comfort etc.). More research is needed to fill this gap.
- A considerable part of the included articles presented new methodologies, frameworks or tools (58 publications or 40.3 %) which illustrates that the field is still quite new and a lot of methodological groundwork is carried out. The second most frequently used method (52 articles or 36.1 %) was numerical and mathematical modelling, often in connection with presenting a new methodology, framework or tool (14 times).
- More than half (87 or 60.4 %) of the 144 reviewed studies applied their research to case studies. 17 case studies were located in Norway and 11 in China, followed by Italy with 10, Belgium with 9, Germany with 8, and Sweden and Spain with 7.

Finally, some selected CFN definitions from research projects, mainly in Europe, are shown. This paper stresses the need for clear definitions and a more structured approach in developing them. The levels of detail of CFN definitions vary widely and range from a few describing sentences to detailed descriptions of system boundaries, KPIs and targets. However, most existing definitions of CFNs are not yet methodologically sound, meaning that key performance indicators, system boundaries and targets are not always clearly defined. This makes it hard for policy-makers, researchers and planning professionals to carry out an independent assessment of reported CFN performances. Especially in large, publicly funded research projects, clear definitions are needed to facilitate the comparability of case studies (also of different CFN types) and increase transparency. A standard set of categories, KPIs, system boundary types, and clear definitions of the spatial scales could help to systematically develop CFN base definitions that still offer the possibility for customization, as every case study presents individual features and circumstances. Research in the future should, therefore, focus on clear common definition guidelines.

7. Limitations

As mentioned earlier, there are some limitations in this study that

need to be kept in mind. First of all, the identification of articles is strongly dependent on the content of the searched databases and the used search phrases. The ultimately deployed search phrase is often a trade-off between several other possible search phrases, either resulting in too many results to be screened and analysed within a reasonable amount of time or yielding too few elements to represent a meaningful subset of the literature of interest. However, by doing that, many relevant publications and reports may be missed, if they do not specifically mention the search terms in their title, abstract or keywords or have not been published in form of a peer-reviewed article. Moreover, there have been articles that were not accessible due to licensing restrictions but might be highly relevant.

During the screening and eligibility phase of the applied methodology, many articles have been sorted out due to their content or poor quality. While this has been done to the best of the authors' judgement, it is highly subjective and a different group of authors might have come to a different subset of literature. The same applies to the categorisation of the included articles.

In the second part of this article, selected definitions of frequently used or well-defined CFN concepts and projects were shown. This selection is not complete as it does not include research projects and initiatives for example from Asia, South America, Oceania or Africa. Moreover, it was not possible to list all the relevant information connected to the CFN definitions within the scope of this article. For more information, it is recommended to visit the respective project websites, or referenced publications in this section.

Declaration of Competing Interest

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

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Appendix A

In line with Europe's ambition to be a global role model in energy transition and reducing its carbon footprint, the EU funded a number of projects with a focus on sustainability, the reduction of energy use, and GHG emissions at the neighbourhood/district/block scale ([Joint Programming Initiative \(JPI\) Urban Europe \(2021\)](#)). They are funded by Horizon 2020, the biggest EU research and innovation programme so far with a budget of almost €80 billion over 7 years (2014–2020) in addition to private and national public investments ([European Commission, 2014a](#)). Within the 6th and 7th EU Framework Programmes of the EU, a number of projects have been funded under the CONCERTO initiative (<https://smartcities-infosystem.eu/sites-projects/projects>). [Table A1](#) lists a selection of ongoing and recently finished projects focusing on CFNs. More Horizon 2020 funded projects can be found at <https://cordis.europa.eu/en>. At this point, also the research activities of the International Energy Agency, namely IEA EBC Annex 83 (<https://annex83.iea-ebc.org/>) on *Positive Energy Districts* (2020–2024) and Task 63 in the IEA Solar Heating and Cooling Programme (SHC) (<https://task63.iea-shc.org/>) about Solar Neighbourhood Planning (2019–2023) are worth mentioning.

Table A1
List of selected EU-funded projects.

Project name and ID	CFN type	Website and project period	Participating cities	Additional References
<i>REMO Urban</i> ID: 646511	LED	http://www.remourban.eu/ 01/2015–12/2019	Valladolid (ESP) Nottingham (GBR) Tepebaşı (TUR) Seraing (BEL) Miskolc (HUN)	(REMO Urban, 2020)
<i>GrowSmarter</i> ID: 646456	LED	https://grow-smarter.eu/ 01/2015–12/2019	Stockholm (SWE) Cologne (DEU) Barcelona (ESP) Graz (AUT) Porto (PRT) Suceava (ROU) Cork (IRL) Valletta (MLT)	(Pejstrup et al., 2019; Sanmarti & Sola, 2019)
<i>Sharing Cities</i> ID: 691895	LEN	http://www.sharingcities.eu/ 01/2016–12/2020	London (GBR) Lisbon (PRT) Milan (ITA) Warsaw (POL) Bordeaux (FRA) Burgas (BGR)	(Eurocities, 2017)
<i>SPARCS</i> ID: 864242	PEB/PED	https://www.sparcs.info/ 10/2019–09/2024	Espoo (FIN) Leipzig (DEU) Reykjavik (ISL) Maia (PRT) Kladno (CZE) Lviv (UKR) Kifissia (GRC) Alkmaar (NLD) Évora (PRT) Bari (ITA) Celje (SVN) Granada (ESP) Hvidovre (DNK) Ioánnina (GRC) Újpest (HUN)	
<i>POCITYF</i> ID: 864400	PED	https://pocityf.eu 10/2019–09/2024	Amsterdam (NLD) Bilbao (ESP) Bratislava (SVK) Budapest (HUN) Copenhagen (DNK) Krakow (POL) Matosinhos (PRT) Riga (LVA)	
<i>ATELIER</i> ID: 864374	PED	https://smartcity-atelier.eu/ 11/2019–10/2024	Trondheim (NOR) Limerick (IRL) Sestao (ESP) Alba Iulia (ROU) Pisek (CZE) Vöru (EST) Smolyan (BGR) Groningen (NLD) Oulu (FIN) Bassano Del Grappa (ITA) León (ESP) Trenčín (SVK) Kadiköy (TUR) Lublin (POL) Vidin (BGR)	(Ahlens, Driscoll et al., 2019)
<i>+CityxChange</i> ID: 824260	PEB/PED	https://cityxchange.eu/ 11/2018–10/2023	Utrecht (NLD) Nice (FRA) Gothenburg (SWE) Vaasa (FIN) Alexandroupolis (GRC) Santa Cruz de Tenerife (ESP) Foscani (ROU)	(Tryferidis et al., 2018, 2019)
<i>Making-City</i> ID: 824418	PED	http://makingcity.eu/ 12/2018–11/2023	Case studies in: York (GBR) Granarolo dell'Emilia (ITA) Nicosia (CYP) Voreppe (FRA)	(Alpagut et al., 2019)
<i>IRIS</i> ID: 774199	nZERD	https://www.irissmartcities.eu/ 10/2017–09/2022	Demo neighbourhoods in: Oslo (NOR) Uden (NLD) Salzburg (AUT) Santa Coloma de Gramenet (ESP)	(Zero-Plus, 2017, 2018, 2020a, 2020b)
<i>Zero-Plus</i> ID: 678407	NZES	http://www.zeroplus.org/ 10/2015–09/2019		
<i>syn.ikia</i> ID: 869918	SpEN	https://synikia.eu 01/2020–06/2024		(Salom & Tamm, 2020)

(continued on next page)

Table A1 (continued)

Project name and ID	CFN type	Website and project period	Participating cities	Additional References
RESPONSE ID: 957751	PED	https://h2020response.eu/ 10/2020–09/2025	Turku (FIN) Dijon (FRA) Brussels (BEL) Zaragoza (ESP) Botosani (ROU) Ptolemaida (GRC) Gabrovo (BGR) Severodonetsk (UKR)	
MatchUP ID: 774477	HPD	https://www.matchup-project.eu/ 10/2017–09/2022	Valencia (ESP) Dresden (DEU) Antalya (TUR) Herzliya (Israel) Kerava (FIN) Ostend (BEL) Skopje (MKD)	

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