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Achieving net zero neighborhoods: A case study review of circular economy initiatives for South Wales

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ABSTRACT

Adopting net zero neighborhoods (NZN) combined with circular economy are increasingly recognized as an essential strategy for construction companies, allowing their transition towards sustainability and contributing to climate change mitigation. Transforming existing neighborhoods into NZN is necessary to achieve energy self-sufficiency and net zero by 2050. The success of NZN hinges on government initiatives. However, existing studies appear to lack a comprehensive exploration of the transformation initiatives within NZN, spanning aspects like raw materials, construction practices, transportation, and waste management, particularly in terms of technological advancements. To address the gap, this research introduces a conceptual framework that integrates the multiple case studies design method with an urban transformative capacity model. This innovative framework is the first application of a multi-level urban transformative capacity model in transforming existing neighborhoods into NZN within a specific region. This research specifically utilizes South Wales in the UK as a case study. It identified four key initiatives in technology, construction, transportation, and waste management. These initiatives offer significant benefits, including fostering a more sustainable and environmentally friendly construction industry through enhanced traceability and efficiency, and simultaneously promoting social sustainability by improving community engagement, providing social benefits through sharing economy initiatives, and creating new green job opportunities.

1. Introduction

The global significance of mitigating human impact on the planet has been emphasized through the establishment of sustainable development goals (SDGs) (Bertoncini et al., 2022). Special emphasis has been given to foster healthy and inclusive cities and communities (SDG 11), as well as ensuring access to sustainable and clean energy (SDG 7), all while implementing measures to mitigate climate change (SDG 13) (UNFCCC, 2017). 110 countries have recognized climate change as the most significant challenge facing humanity and have committed to achieving net-zero targets by 2050 (Satola et al., 2022). The construction and buildings industry, known for its detrimental impact on the environment, is regarded as one of the most polluting industries worldwide (Satola et al., 2022). This is partly due to the resource-intensive processes of the industry and the increasing demand for housing and infrastructure (Rahla et al., 2021). For instance, the construction sector account for 33% of total energy consumption and represent the largest contributors to greenhouse gas emissions in Europe (Tirelli and Besana, 2023). Furthermore, the U.S. Energy Information Administration projects a 56% rise in global energy consumption between 2010 and 2040, emphasizing the need for substantive changes in construction, housing, and infrastructure sectors (US Energy Information Administration, 2013). These statistics underscore the necessity for transformation, with net zero neighborhoods (NZN) emerging as a pivotal solution to address these challenges, notably in achieving energy self-sufficiency (Tirelli and Besana, 2023).

NZN are a vital component of the UK government's plans to reach net zero by 2050 to mitigate the challenge of climate change, particularly given the resource-intensive nature of the construction industry (Janzadeh and Zandieh, 2021). Research focused on net-zero emission neighborhoods provides a unique opportunity to assess buildings, mobility, and energy systems for mitigating global climate change

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(Lausselet et al., 2021). The study of net zero energy neighborhood implementation in Qazvin reveals the feasibility of such project, highlighting drivers, barriers, and key choices to make buildings more sustainable, with notable economic and environmental benefits (Janzadeh and Zandieh, 2021). Nevertheless, Satola et al. (2022) pointed out that the lack of government regulations poses a significant obstacle to the realization of NZN and buildings, calling for government support to make net-zero products and materials more affordable. Thus, government initiatives are crucial for the success of NZN. Additionally, existing research predominantly focuses on climate friendly neighborhoods (CFN) with limited exploration of NZN transformations. This gap is particularly notable in the comprehensive investigation of how circular economy (CE) principles can be applied to transform existing neighborhoods into net zero ones. Current literature also appears to lack a comprehensive exploration of the transformation initiatives within NZN, spanning aspects like raw materials, construction practices, transportation, and waste management in light of technological advancements.

To address the existing research gap, this research aims to establish a conceptual framework that explores the application of the CE principles in transforming existing neighborhoods into net zero ones. This exploration takes into account the unique national and cultural contexts of the region. More specifically, this research introduces a multi-level urban transformative capacity model, which first integrates a multiple-level case study design with urban transformative capacity model to form the conceptual backbone. Subsequently, a series of initiatives are proposed to facilitate the transition of the target region's neighborhoods into NZN. These initiatives are formulated considering current regional efforts and are guided by the insights gained from the proposed model. The conceptual framework offers valuable perspectives on the implementation of the CE at the net-zero neighborhood level, aligning with the ambitious goal of achieving net-zero by 2050.

This research specifically employs South Wales, the United Kingdom (UK) as a case study. The expected outcome of this research will be a set of initiatives spanning four key areas: technology, construction, transportation, and waste management systems. These initiatives could be implemented in South Wales to promote NZN and contribute to the region's goal of achieving net-zero status by 2050. The expected results will also encompass an evaluation of the status of the construction, energy, waste, and transportation sectors in South Wales serving to determine the necessity of each initiative. Additionally, it will offer a comprehensive overview of the advantages and challenges associated with each proposed initiative. This research enriches the understanding of NZN by examining the integration of sustainable practices within specific regional contexts. Practically, the identified key initiatives can promote decarbonization and improve construction industry transparency, essential for effective CE practices. Furthermore, the research underscores the social advantages of these initiatives, which contribute to social cohesion and economic stability, particularly benefiting marginalized communities.

The rest of the research is as follows. Section 2 presents a comprehensive literature review, focusing on NZN and their attainment through the CE. Section 3 illustrates the proposed conceptual framework. Section 4 details the case study, where multiple cases are thoroughly analyzed to extract initiatives for subsequent application in South Wales. Section 5 discusses the analysis results and the limitations. Lastly, Section 6 draws a conclusion and highlights future research.

2. Literature review

This section firstly defines NZN based on a brief overview of net zero emissions buildings and NZN. Then, relevant studies concerning the integration of CE in the pursuit of NZN are analyzed. In summary, the review highlights research gaps.

2.1. Net zero emission buildings and net zero neighborhoods

The net-zero approach typically involves balancing the extraction and consumption of natural environment (e.g., energy or water) at a local site over a specified time period, usually annually (Lützkendorf et al., 2015). Buildings play a crucial role in allowing neighborhoods and cities to become net zero due to their substantial carbon emissions. The building sector accounted for a 38% of all carbon emissions (Tirelli and Besana, 2023). A net-zero building is defined as one that produces at least as much energy on-site (e.g., from renewable sources like solar photovoltaic (PV) panels) as it and its occupants consume from external sources (e.g., the electricity grid) over a one-year period (Lützkendorf et al., 2015). In 2020, the building sector in Europe accounted for 33% of electricity consumption, projected to increase to 72% by 2050, while in OECD countries, 53% of electricity was produced from the combustion fossil fuels, emphasizing the need for carbon-neutral or net-zero buildings (Tirelli and Besana, 2023). A main strategy often overlooked for achieving net zero emissions buildings is their potential to generate additional energy they need (Andresen, 2017). To complement this, the importance of buildings generating extra energy from renewable or circular sources has been emphasized (Tirelli and Besana, 2023). This not only enhances energy and resource efficiency but also reduces dependence on the grid.

Nonetheless, economic barriers, such as high upfront expenses for sustainable products and new technologies, pose significant challenges to achieving net-zero buildings (Tirelli and Besana, 2023). Estimates suggest these cost may be approximately 10% higher than for standard office buildings (Andresen, 2017). The financial constraints may hinder net-zero buildings from aligning with all three sustainability pillars in Elkington's triple bottom line (Elkington, 2018), potentially making them environmentally sound but not economically sustainable.

To attain net-zero buildings, strategies must incorporate CE principles through the construction process. This involves using recycled and recyclable materials, local suppliers, and adaptable building designs for future sustainability (Tirelli and Besana, 2023). This aligns with the view that the CE can transform the construction industry (Macarthur and Heading, 2019).

Research on net-zero concepts at the city level tends to be supported by more substantial resources and extensive experience, which provides invaluable insights and learning opportunities, especially in policy development, technology application, and community engagement (Seto et al., 2021). Although net-zero cities offer a broad framework, implementing net-zero initiatives at the neighborhood level enables the creation of operational, customizable, and flexible approaches. These approaches are designed based on the unique characteristics of each community such as building types, geographical locations, resident behaviors. Therefore, this research focuses on investigating NZN with the consideration of both city-level and neighborhood-level experiences, laying a foundation for sustainable city-level development.

NZN encompass not just net zero emissions buildings but also address waste management, energy efficiency, vehicles, infrastructure, and transportation. For example, a life cycle assessment study conducted in Ydalir revealed that 61% of greenhouse gas emissions came from mobility, while 6% were attributed to infrastructure (Lausselet et al., 2021). NZN are defined as districts with a significant reduction in energy demands, achieved by balancing energy usage for vehicles, thermal and electrical energy within the community with renewable energy (Carlisle et al., 2009). Another definition characterizes NZN as districts with zero net energy consumption, meaning the total energy consumed annually matches the energy generated, allowing self-sufficiency in renewable energy and eliminating reliance on fossil fuels (Nematchoua, 2020).

Building on the literature, NZN in this research can be described as a collection of buildings, vehicles and infrastructure embodying CE principles, ensuring self-sufficiency in renewable energy supply and demand while also facilitating the sale of surplus energy back to the local grid.

2.2. Transition towards net zero neighborhoods through circular the economy

Several concepts are named climate friendly neighborhoods (CFN), including zero emission neighborhoods, low carbon neighborhoods, net zero energy neighborhoods, zero carbon neighborhoods, and net positive energy neighborhoods (Brozovsky et al., 2021). CFN involves various strategies to reduce the carbon footprint, but not all exclusively aim for net zero energy emissions. Current research on transitioning towards CFN primarily evaluates its transformation possibility through case studies (Blumberga et al., 2020). Additionally, innovative methodologies and performance indicators for CFN implementation has been introduced (Bakhtavar et al., 2020; Keough and Ghitter, 2020), often utilizing multi-criteria approaches (Koutra et al., 2019). Unlike CFN, the aim of NZN is to balance carbon emissions with emissions reductions across the community. However, studies on transitioning towards NZN are scarce, which can be attributed to several potential factors, namely the complexity of the concept, difficulties in data acquisition, and high implementation costs. More specifically, NZN includes not only self-sufficiency in energy but also the comprehensive management of waste, water, and other resources, along with a balanced approach to carbon emissions. Moreover, supporting data for NZN requires detailed field monitoring, including energy consumption, production data, and transportation patterns. The unique characteristics of each community further limit the generalizability and comparability of the data. Additionally, achieving net-zero emissions in a community often necessitates extensive infrastructure modifications and the adoption of new technologies, which usually require significant initial investments. Consequently, this makes CFN a reference point for such transitions.

In recent years, CE initiatives have gained considerable significance in the sustainability sector, addressing the negative impacts of unsustainable production and consumption on environmental integrity, social equity, and economic stability (Millar et al., 2019). The concept of CE extends beyond the traditional "3R" framework of Reduce, Reuse, and Recycling. While the 3R principles are integral to CE, they represent only a subset of a broader, systemic approach that seeks to redefine growth, focusing on positive society-wide benefits. This approach entails gradually decoupling economic activity from the consumption of finite resources, and designing waste out of the system. Unlike the 3R strategy, which focuses on minimizing waste after it has been created, CE is rooted in a redesign of business and economic systems, playing a crucial role in sustainable development through waste minimization and resources efficiency (Zeng et al., 2017). Technological advancements further enhance the efficacy and feasibility of CE practices, facilitating better resource management (Khan et al., 2022).

The forthcoming ISO 59000 family of standards, along with the British standard BS 8001 and the French standard XP X30-901, are pivotal in shaping CE management strategies (Arana-Landin et al., 2023). These standards refine practices that ensure environmental integrity, social equity, and economic stability. Incorporating these standards can potentially reduce greenhouse gas emissions by 22–44% by 2050 (Ellen Macarthur Foundation), particularly in the construction industry (Chen et al., 2022). Additionally, these standards play a crucial role in the energy sector by promoting the integration of sustainable energy practices. This includes the adoption of energy-efficient technologies and the shift towards renewable energy sources, which are essential for reducing the energy sector's carbon footprint.

The construction industry plays a crucial role in realizing NZN. The application of CE principles in construction, such as using recycled and recyclable materials, engaging local suppliers, and adopting adaptable building designs, is vital for future sustainability (Tirelli and Besana, 2023). These practices not only align with the broader goals of CE to transform industry norms but also promote sustainability (Macarthur and Heading, 2019). The objective of CE in construction is to close and narrow material loops, tackling the emissions-intensive nature of the industry and excessive material use (Chen et al., 2022). For instance, applying CE principles in building insulation can lead to a notable 40% reduction in carbon emissions (Nasir et al., 2017). Integrating CE practices in construction addresses critical issues like raw materials overconsumption, high energy demands, and excessive waste generation (Benachio et al., 2020). It is advised that the industry shift towards material conservation and principles (i.e. designing for disassembly, material reuse) to progress towards net zero (Eberhardt et al., 2019; Hossain et al., 2020). Consequently, the CE could be a vital link in integrating resources, energy, and community activities in NZN, enhancing overall sustainability. However, current CFN research mainly focuses on energy aspects (Ascione et al., 2021), occasionally including transportation (McPherson et al., 2023).

In conclusion, existing studies concentrate more on the transition towards CFN, with limited exploration of NZN transformation. Given that the CE significantly aids the construction industry in progressing towards net zero goals, its role in achieving NZN is indispensable. Moreover, with the support of technological advancements, the CE can further enhance efforts to attain NZN. To date, a comprehensive investigation of NZN transformation, considering aspects such as raw materials, construction practices, transportation, and waste management in the context of technological advancements, remains inadequately explored. To fill the research gap and align with the proposed NZN definition (see Section 2.1), this research introduces a conceptual framework. Leveraging the CE and technological advancements, the framework integrates a multiple-level case study design with urban transformative capacity model, facilitating the transformation of existing neighborhoods into NZN.

3. Methodology and conceptual framework

By integrating the multi-level case study design (see Section 3.1.1) with the urban transformative capacity model (see Section 3.1.2), we have developed a novel conceptual framework, termed the multi-level urban transformative capacity model (see Section 3.2). This framework, informed by insights from the multiple case studies and urban transformative capacity analysis, proposes a set of initiatives aimed at guiding the transformation of existing neighborhoods in the target region towards NZN.

3.1. Methodology

3.1.1. Multiple case studies design

Given the exploratory nature of this research, our approach begins with the application of a multiple case studies design method, wherein we compare initiatives at both Macro and Micro levels due to their size differences. As a highly used method in social science, qualitative multiple case studies design methodology is an established method to conduct exploratory research at different levels where the researcher aims to incorporate three cases for each level (Yin, 2011). Case studies are strong and reliable sources of information from a particular real-life scenario (Baxter and Jack, 2008). This method allows the researchers to explore the complex issues and problems within a specific context and gain a better understanding of the differences and similarities between cases, which can help create a more robust theoretical understanding coupled with the ability to gain a wider exploration of the research area (Gustafsson, 2017). For example, multiple case studies have been conducted to collect empirical evidence from Dutch social housing organizations, and the authors found that digital technologies support data collection and analysis to close the material loops (Çetin et al., 2022).

Then, a cross-case analysis is conducted, offering insights into effective CE and sustainable practices. A within-case approach is used to give a brief understanding of each case, and a cross-case analysis can highlight key information, similarities, and differences from each case.

3.1.2. Urban transformative capacity model

The applicability of the analyzed sustainable practices in the target

Table 1
The key factors of components (Wolfram, 2016).

Model components	Factors
C1: Inclusive and multiform urban governance	- Participation and inclusiveness - Diverse governance modes and network structures - Sustained intermediaries and hybridization
C2: Transformative leadership	- Systematic change for sustainability - Commitment to systematic change towards sustainability
C3: Empowered and autonomous communities of practice	- Addressing social needs - Community empowerment
C4: Systems awareness and memory	- Baseline analysis and systems awareness - Recognition of path dependencies
C5: Urban sustainability foresight	- Diversity and collaborative knowledge production - Collective vision for sustainability changes - Alternative scenarios and future pathways
C6: Community Experimentation	- Experimentation is undertaken by place - Seeking to rebalance economic, social, and ecological developments - Experiences are multi-dimensional, simultaneously addressing innovations in urban environments
C7: Effective Sustainability Innovations.	- Access to resources for capacity development - Planning and mainstreaming transformative action - Reflexive and supportive regulatory frameworks
C8: Social Learning	- Wider stakeholder and leadership relativity is enabled through formal and informal interactions - Practical know how for initiating and performing change towards sustainability
C9: Working across human agency levels.	- Address multiple level of agency in public, private and civil society sectors
C10: Working across political-administrative levels and geographical access.	- Interaction between political and administrative levels and geographical scales

region is assessed through the urban transformative capacity model. The urban transformative capacity model represents the capacity of urban stakeholders to drive transformative change towards sustainability (Wolfram, 2016).

The primary objective of the model is to foster sustainable development and facilitate systematic progress towards sustainability. Consequently, it aligns with the aims of this research. Comprising 10 essential components, the model serves as a framework for identifying conditions for transformation, with the factors of these components are summarized in Table 1 below.

3.2. Conceptual framework

In this research, we use multiple case studies for a variety of cross-sectional secondary qualitative data to extract and compare CE initiatives across the three cities and three neighborhoods through a within-case and a cross-case analysis. The case studies of CE presented in city-level (Macro-level) and neighborhood-level (Micro-level) are found using the Ellen MacArthur Foundation and the European Union website. Data and information associated with these case studies are extracted from numerous sources, including websites, newspaper articles, published journals, and public reports.

As for the selection of case studies, purposive sampling method has been used (Etikan and Bala, 2017), which can not only give the researchers more leverage to uncover the best information possible (Rai and Thapa, 2015), but also achieve increased confidence in findings (Miles and Huberman, 1994). As a form of non-probability sampling, case selection criteria are outlined in Table 2 below, ensuring cases give sufficient information for this research. More specifically, for city-level cases, the criteria focus on identifying small cities with a population of less than 150,000 to explore CE initiatives in less-densely populated urban environments. These cities are required to have sufficient evidence of ongoing or completed CE initiatives, particularly those that are part of European Commission-funded projects. This criterion is chosen to ensure that the case studies are supported by robust funding mechanisms and are aligned with broader European sustainability goals. In addition, at the neighborhood level, criteria selection is based on finding diverse examples within Europe that include both ongoing and completed projects. This mix allows us to analyze different stages of CE initiative implementation. The neighborhoods that incorporate transport and mobility solutions within their CE initiatives are selected, as these are critical components for reducing environmental impact and enhancing urban livability.

This urban transformative capacity model will be further customized and used as a filtering system to identify the initiatives derived from cross-case analysis that are most relevant to the target region, thereby assessing their suitability and applicability. Besides, the successful implementations from these cases can serve as a valuable reference for South Wales.

4. Case study

We first select three city-level and three neighborhood-level case studies that meet our criteria and have excelled in implementing CE and sustainable initiatives. These case studies experience a cross-case study analysis, providing valuable references for the transformation of South Wales in the UK into NZN. We utilize the urban transformative capacity model to assess the feasibility and applicability for the target region, considering the characteristics and potential. Based on the insights from the multiple case studies and the urban transformative capacity analysis, we present a tailored set of initiatives to promote sustainability and a CE in the target region. The overall framework of this case study comprises three steps, as shown in Fig. 1 below.

4.1. Description of city-level and neighborhood-level case studies

There are three city-level and neighborhood-level case studies, with data sources shown in Table 3 below.

Table 2
Criteria for city-level and neighborhood-level cases.

Cases	Criteria
City-level	Sufficient evidence of CE initiatives. City within Europe. European Commission-funded projects within the city. Sub 150,000 inhabitants, therefore relatively small cities.
Neighborhood-level	Sufficient evidence of CE initiatives. Neighborhoods within Europe. A mix of both ongoing projects and finished projects. Includes transport and mobility solutions.

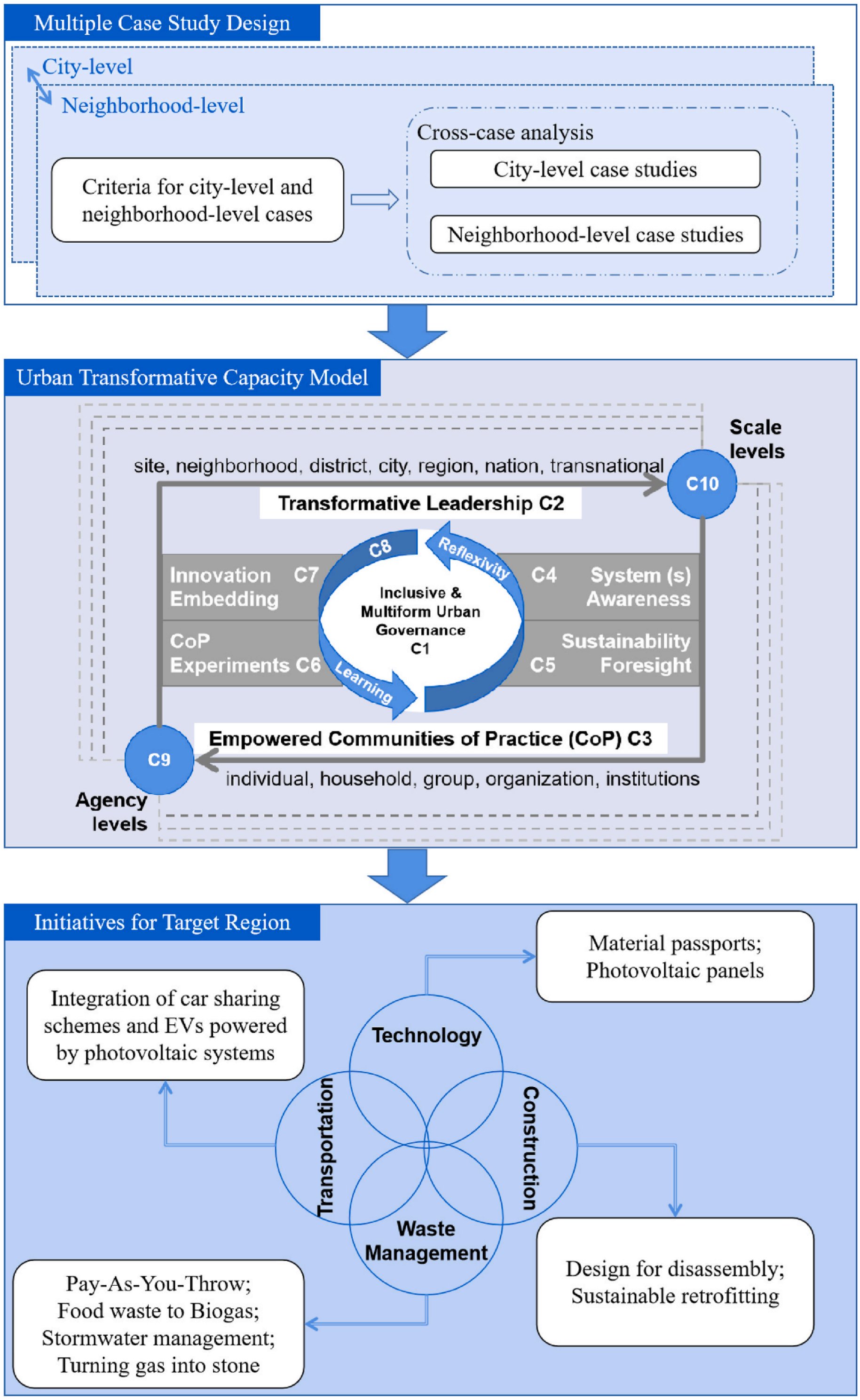

Fig. 1. Framework of the research.

4.1.1. City-level (macro-level) case studies

Cities are crucial in addressing climate change, as they account for 80% of global energy consumption, with an expected 80% of the population residing in urban areas by 2050 (POCITYF). Many European cities have prioritized sustainability and climate action in their development (European Commission, Smart Cities Marketplace). Notably, 339 cities have set emissions targets, and 710 cities have incorporated sustainability into their plans (CDP, 2021). The selected European cities, namely Evora, Alkmaar, and Reykjavik, serve as "Lighthouse Cities" for European Commission-funded projects, sharing similar goals.[1] Evora and Alkmaar have been selected from the POCITYF project, and Reykjavik from the SPARCS project, which are part of the ongoing smart cities and communities projects funded by European Commission's

[1] A full list of lighthouse cities can be found on this website: https://smart-cities-marketplace.ec.europa.eu/projects-and-sites/cities?f%5B0%5D=lighthouse_city%3A1.

Table 3
Data sources of city-level and neighborhood-level case studies.

Area	Sources
City-level case studies	
Evora, Portugal	(POCITYF)
Alkmaar, Netherlands	(POCITYF)
Reykjavik, Iceland	(City of Reykjavik, 2021); (Reykjavik); (SPARCS)
Neighborhood-level case studies	
L'Innesto, Milan, Italy	(ARUP); (Dezeen); (Housing Europe, 2022; Urban File, 2019)
Augustenborg, Sweden	(World Habitat); (Ellen Macarthur Foundation); (Urban Nature Atlas, 2022); (EcoDistricts)
The Circle House, Lisbjerg, Denmark	(State Of Green, 2021); (Vandkunsten Arhcitechs); (Building Society Ecology); (The Circle House Book); (BloxHub)

Scalable Cities initiative. Scalable Cities is dedicated to establishing a forward-thinking, sustainable, and city-driven community of smart and climate-neutral cities across Europe. It encompasses 124 unique cities participating in 20 Smart Cities and Communities (SCC) projects. These projects are supported by the HorizonEurope programs and involve collaborations with academia, industry, associations, and consultants.[2]

Evora, in Portugal, is one of the cities that are dedicated to deploying energy-positive districts by 2050 through circular initiatives. This city, nestled in a United Nations Educational Scientific and Cultural Organization (UNESCO) heritage site, faces unique challenges due to its rich heritage. Evora focuses on sustainability, citizen engagement, technology, energy, and transport to combat climate change (European Commission, POCITYF Evora). The objectives include solutions at the building and district levels, such as self-consumption, energy savings, renewable energy, grid flexibility, and active citizen participation.

Alkmaar, a city in the Netherlands, shares similar objectives with Evora. Like Evora, the historical and cultural significance of Alkmaar presents challenges. The city is committed to sustainable energy and has set a goal to be natural gas-free by 2050. Notably, Alkmaar boasts the most sustainable heating network in the Netherlands, linked to a bio-energy plant. To achieve their goals, houses will be retrofitted, equipped with solar panels, and circular materials will be employed.

Reykjavik, Iceland is funded to transform the city into a sustainable energy-positive and carbon-zero community (SPARCS). Reykjavik currently meets its energy demands from 100% renewable and circular sources, such as geothermal and hydrogen power. Its goal is to become carbon-neutral by 2040, with a focus on replacing fossil fuels with sustainable alternatives and reducing emissions from road transportation. Its climate plan embraces elements of the triple bottom line, emphasizing eco-friendly planning, CE principles, and low-carbon materials.

4.1.2. Neighborhood-level (micro-level) case studies

All the following neighborhoods represent different sizes and building densities making them good cases for comparisons. Both L'innesto, Milan and the Circle House, Lisbjerg, Denmark represent smaller neighborhoods, whereas Augustenborg, Sweden represents larger-scale neighborhoods with apartments and houses.

Augustenborg, a Swedish neighborhood in Malmo, transitioned into a circular community after its inception in 2001, initially focused on flood prevention. Residents played a vital role in upholding circularity by improving energy efficiency, creating green roofs, and setting a 90% waste recycling target. Augustenborg's transformation led to a 50% decrease in tenancy turnover, remarkable improvements in recycling, energy efficiency, and stormwater management, and a 25% reduction in heat and water consumption.

L'innesto, Milan is set to provide 400 apartments, 300 student accommodations, and innovative collaborative living spaces within a human adaptive zone. The project is guided by three main objectives: creating Italy's first zero-carbon social housing district, fostering a human adaptive zone, and implementing a responsible and resilient long-term management approach. Four key measures facilitate these objectives: a 4th generation renewable energy heating system, hybrid timber for reduced carbon impact during construction, bioremediation and urban forestry, and the promotion of active mobility and efficient transportation systems.

The Circle House, a groundbreaking social housing project in Denmark, embraces CE principles, focusing on sustainability and social welfare. Designed with three core principles, namely design for disassembly, material passports, and CE, it encourages easy reuse of components and a lightweight façade that can be disassembled for future use. The aim of the project is to lead the way in circular construction practices. It targets a 90% material reuse rate, emphasizing "design for disassembly".

4.2. Cross-case analysis

This section conducts cross-case analysis in terms of city-level and neighborhood-level, focusing on CE initiatives, solutions towards net zero buildings, and other sustainability initiatives, as shown in Table 4.

4.3. Pathway to success for South Wales

The Welsh Government is committed to achieve net zero by 2050 (Welsh Goverment, 2023a,b). In pursuit of this goal, Wales has implemented a range of initiatives to foster sustainability and integrate CE principles across various industries. A map developed by the Cardiff Circular Economy Framework shows the specific regions within Wales where these CE initiatives are being implemented (see: https://www.walescirculareconomy.com/). Additionally, WRAP Cymru, a CE non-governmental organization, has been established with a mission to reduce waste, optimize resource, promote job creation, and develop economy (WRAP Cymru). To further advance zero-waste strategy and boost local supply chains, the Welsh Government is in the process of establishing a £6.5 million Welsh Circular Economy fund, with the objective of achieving 100% recycling by 2050 (Welsh Goverment, 2019).

Recognizing the crucial role in reaching emissions reduction goals, the Welsh Government acknowledges the need to improve building standards and invest in energy-efficient measures and low carbon heating by providing grants and loans (The CCC, 2023). However, while these initiatives represent substantial progress, they may not suffice to transform buildings in NZN.

Consequently, the applicability to Wales and South Wales is analyzed using the adapted urban transformative capacity model (see Appendix A). This adapted model serves as a filtering system to identify most relevant initiatives from previously mentioned cases (see Section 4.2). Four key initiatives related to technology, construction, transportation, and waste management, are proposed for South Wales to integrate into cities and neighborhoods, thereby reaching their goal of net zero by 2050 (Welsh Goverment, 2023a,b).

4.3.1. Technological initiative

Technological advancements can play a crucial role in addressing traceability and energy challenges in the construction industry, particularly in the adoption of CE practices (Hossain et al., 2020).

Material passports - Material passports, as digital tools, have the capacity to capture both qualitative and quantitative data on material composition, providing real-time information to stakeholders about availability, location, condition and tracking (Antikainen et al., 2018). The objectives of material passports include maintaining material value over time, facilitating the reverse supply chain, and simplifying the selection of sustainable and circular materials (BAMB, 2020). Moreover, they have the potential to bolster the already strong recycling efforts of

[2] See more details here. https://smart-cities-marketplace.ec.europa.eu/scalable-cities.

Table 4
City-level and neighborhood-level cross-case analysis.

Cases	CE initiatives	Initiatives for net zero buildings	Other sustainability initiatives
City-level case studies			
Evora	- Pay-As-You-Throw waste production scheme - Reuse residential batteries, including used electric vehicles (EV) batteries - EV sharing scheme	- Adoption of various photovoltaic technologies in compliance with building codes - Integration of bi-directional smart inverters, power electronic energy routers, and advanced building management systems - Retrofitting for positive energy districts - Implementation of a smart distribution management system - Introduction of a peer-to-peer energy trading platform - Innovative freezing storage solutions for natural cooling - Market-orientated building flexibility services and solutions	- Peer-to-peer energy trading platform - Energy management platforms for EV charging - Use of bidirectional smart inverters for smart EV charging and vehicle-to-grid (V2G) applications - Solar-powered smart lampposts with 5G capabilities and EV charging - Support for social innovations
Alkmaar	- Circular materials in house reconstruction - Reusing wood, concrete, and steel from demolition in new construction - Use of material passports to track construction materials - Waste separation at homes - EV sharing program	- Triple-glazed windows and circular insulation materials - Local electricity production via building-integrated photovoltaics - Solar roofs on apartment blocks - Implementation of thermoacoustic heat pumps - Home energy management systems for monitoring - Retrofitting for positive energy districts - Aquifer thermal energy storage with heat pumps - City management systems for demand measurement - Peer-to-peer energy trading platform - Integration of reflex software for future flexibility - Hydrogen fuel cells for heat and power during low renewable availability - Stationary batteries for storing solar-generated electricity	- Smart solar charging stations with optimized control algorithm - Installation of bidirectional chargers for cars and buses - Lampposts integrated EV charging stations - Hydrogen powered garbage van - EV sharing program - Photovoltaics noise barriers along the ring road
Reykjavik	- Zero waste policy - Experimental district vegetable market - Evaluating food production emissions in the city's carbon footprint - Establishing a waste venue for the construction industry - Incorporating industry emission reduction commitments into zoning plans - Supporting repair services for electrical equipment and tools - Collecting with universities and high-emission enterprises to convert gas into stone	- Mandate for all city construction projects to be fossil fuel-free - The city's sustainable design to serve as a model for future construction projects - Inclusion of emissions from construction material production in carbon footprint assessments - Environmental certification for new districts - Plan for rental cottages and huts with small garden plots - BREEAM certification for new buildings and city properties maintenance - Rooftop gardens and vertical gardens	- Extensive citywide cycle paths - Charging solutions for cycles in covered car parks - Car restrictions in specific areas - Greenhouse gas-free public transport - New policy for water and electricity usage - Promotion of eco-friendly sources - Reduction in the number of petrol stations - Transformation into a walkable city - Become a world class cycling city
Neighborhood-level case studies			
Augustenborg	- Carpooling scheme - Improved recycling facilities - Stormwater management system for neighborhood water recycling - Recycling and reuse of 90% of collected waste through 13 disposal huts - Conversion of food waste into compost and biogas for cars and gardens - Installation of a nearby wind power plant at a school	- Development of 9500 square meters of green roofs, including botanical gardens and moss roofs - Implementation of a stormwater management system that collects 90% of rainwater from roofs, roads, and parking lots - Installation of 450 square meters of solar panels connected to a heating system and photovoltaic systems in the industrial area - Retrofitting existing buildings to meet high environmental standards	- Diverse transportation options, including biking, electric car-pooling, and a light transit system - Development of green open spaces - Economic opportunities through local business - Decrease in emigration rates - Community-driven enterprises reducing unemployment by 15% - Establishment of blue infrastructure
L'innesto	- Shared communal spaces - Buildings designed for disassembly and material recycling - Sustainable soil treatment and minimal excavation for landscaping - CE community shop with zero waste - Urban wastewater recovery system - Soil regeneration practices - Conversion of organic waste into compost for garden areas - Effective water management	- Using 4th generation renewable energy heating systems - Establishing a Zero Carbon Fund - Offering voluntary carbon credits for residents - Innovative construction methods involving bioremediation and urban forestation - Using hybrid timber, a low-carbon material - Incorporating green seeded rooftops for agriculture - Providing 100% renewable air conditioning power - Employing prefabricated construction technology during construction phase	- Establishment of walking and cycling paths connecting to the rail network - Promotion of sustainable transport system - Dedication of 72% of land for green spaces - Limited parking (100 spaces for 700 residents) to encourage alternative transportation - Provision of a 1200 m^2 bike garage and 10 electric car chargers - Creation of outdoor public spaces and agricultural areas - Reduction in fuel consumption
Circle House	- Buildings designed for easy disassembly, enabling material reuse - Extensive use of recycled materials, such as Cork, eelgrass, granules, old newspapers, and upcycled plastic - Simplified construction with only 6 structural components for easy disassembly - RFID-chipped material passports. - A take-back system for composting construction site waste, including offcuts	- Minimal cement usage - Customizable interior features integrated into the design - LED lighting installation in existing light fixtures - Carbon reduction through the use of low-carbon materials with documented life cycles, including Mosa carpet tiles (66% recyclable), Gyproc Ergolite pasteboard walls (45% recyclable), easily recyclable and demountable acoustic ceilings (65%), clay shingles for façades (45%), and precast concrete structures (45% dissemble and reusable)	- Nonprofit social housing with social impact - Renewable energy sources utilization - Use of Internet of Things (IoT) - Prefabricated concreate construction - Sustainable manufacturing - Prioritizes local transportation of raw materials - Hazard-free acoustic panels - Maintenance-free green energy heating - Leasing heating services for low maintenance - Innovative roofing system using olivine for rainwater CO_2 conversion into eco-friendly materials

South Wales and reduce the demand for raw materials (Welsh Government, 2020). Material passports also facilitate data collection for stakeholders and improve communication on sustainability to clients.

Currently, there is no evidence of material passports in Wales or any significant development towards their adoption. However, the Queen Elizabeth Olympic Park in London implemented material passports post-games to ensure materials are repurposed and sold for reuse (Hoosain et al., 2021). Additionally, Circuland, a platform that has been tested in a trial conducted in London, presents an opportunity for collaboration with South Wales and paves the way for the creation of material passports (Circuland). Such collaboration could potentially lead to cost savings by reducing waste creation (2019 Heinrich and Lang, 2019). A decrease in construction waste would significantly accelerate South Wales' progress towards achieving their net zero target by 2050, by minimizing landfill waste and reducing the carbon footprint.

Integrating blockchain technology into material passports can enhance transparency and trust by providing immutable records of material ownership (Ledger Insights, 2022). However, material passports pose several challenges, including addressing confidentiality and intellectual property concerns (Bianchini et al., 2019), potential implementation complexities (Götz et al., 2022), the need for stakeholder engagement for reliable data collection, cost implications, adherence to government policies, defining product passport criteria, and the challenge of data transparency for businesses (Munaro and Tavares, 2021). To further mitigate these challenges and create a successful material passport, Hoosain et al. (2021) outline an eight-step guide to developing a successful model that can be used by developers in the South Wales Region.

Furthermore, to enhance the strategic engagement of community stakeholders within the material passport system, it is essential to establish clear communication channels that ensure all parties are well-informed and can contribute effectively. It is also crucial to develop engagement strategies tailored to the specific interests and concerns of different groups, including government bodies, construction companies, and environmental organizations. Additionally, creating incentives for stakeholder participation will encourage active involvement and investment in the material passport system, furthering its effectiveness and reach.

Photovoltaic panels - As renewable energy sources, photovoltaic panels are known for their low maintenance requirements, reliability, and reduced grid dependence. Although they may exhibit lower efficiency compared to some other renewable energy technologies (Shafique et al., 2020), the potential for photovoltaic installations in England is substantial. For instance, projections indicate that photovoltaics could generate 40–50 GW by 2030, and with further investment, rooftop installations alone could contribute up to 117 GW by 2050 (The countryside charity, 2023).

Notably, South Wales has actively incorporated photovoltaics panels into various infrastructure, schools, public buildings, and especially along its ring road (GreenMatch, 2023). The main benefit to using them on ring roads is that they also maintain biodiversity by blocking out sound and exhaust emissions from green spaces and wildlife. Additionally, solar energy from photovoltaic applications has the potential to fulfill a significant portion for the electricity requirements of a neighborhood, ranging from 36% to 100% (Hachem-Vermette, 2022). To advance the objective of achieving net-zero status in South Wales, it is necessary to expand the integration of photovoltaic panels in the neighborhood construction.

4.3.2. Construction initiatives

As a construction strategy, the integration of design for disassembly and sustainable retrofitting can significantly benefit South Wales by contributing to construction initiatives. In 2019, the construction and demolition sector in Wales generated 3.43 million tons of waste (Natural Resources Wales). Additionally, with plans for a substantial number of new dwellings and an annual increase in construction, implementing this strategy could minimize demolition and promote the recycling and reuse of building components when structures are deconstructed (Stats Wales, 2023). Although Wales has expressed interest in this area, funding research projects aimed at minimizing construction waste and maximizing material reuse (Construction Excelence Wales, 2014), there is limited evidence of implementation of this design strategy in Wales.

Design for disassembly - Designing for disassembly, recognized as the most efficient way to address environmental impacts at the design stage, enhances building flexibility and adaptability to environmental changes (Rios et al., 2015). The ability of manufacturers to design products for easy disassembly not only benefits their revenue but also aligns with environmental and social responsibility goals (Salama, 2017). Furthermore, material selection, a key aspect of the design for disassembly strategy, is increasingly crucial for reducing reliance on finite resources (European Parliament, 2023). Sustainable materials are characterized by low embodied energy, waste reduction, simplified maintenance, recycled and reusable materials, ease of disassembly, and freedom from toxins (PlanRadar, 2023).

Sustainable retrofitting - As an effective strategy to enhance the sustainability of pre-existing buildings, sustainable retrofitting allows the buildings to maintain their original features while installing environmentally friendly solutions to upgrade older buildings to modern standards (Jagarajan et al., 2017). Often a more cost-effective option than demolition (Bullen, 2007), sustainable retrofitting presents opportunities for long-term savings, prolongs the lifecycle of building, and reinforces its resilience to weather-related challenges (Construct Update, 2021). Moreover, it contributes to the preservation of cultural assets embodied in existing structures, which is particularly crucial in Wales, known for its numerous historical and listed buildings (Llywodreath Cymru, 2023).

Wales plans to build between 6200 and 8300 new dwellings each year, and by implementing this initiative, a significant number of new dwellings could adopt circular principles (Master Builders, 2022). However, a major challenge is the need for traceability and detailed information about each item once it is disassembled or deconstructed, necessitating a platform like material passports, as discussed earlier. Additionally, challenges such as time constraints, the need for additional planning, a lack of experienced building professionals, and labor-intensive deconstruction processes should be considered (Jagarajan et al., 2017). While these challenges may entail extra costs, they also offer opportunities for job creation (Rios et al., 2015). To implement these initiatives, some key principles are highlighted for design for disassembly that South Wales could adopt, including documenting materials and deconstruction plans, selecting materials with high future value, designing connections, minimizing chemical bonds like glues and sealants, using mechanical connections such as bolts, screws, and nails, separating electrical, mechanical, and plumbing work for ease of disassembly, designing for worker and labor efficiency, simplifying structures to facilitate deconstruction, using interchangeable products to enhance reuse, and ensuring the safety and efficiency of disassembly to protect workers and reduce risks (Life Cycle Building).

4.3.3. Transportation initiatives

Transportation is a significant source of greenhouse gas emissions, account for 25% of the European Union's emissions (European Environment Agency, 2023). Within the context of Wales, car sharing represents an underutilized avenue. This prospect is particularly noteworthy considering that South Wales exhibits the highest prevalence of individual car usage in the UK, with 75–80% of the population relying on personal vehicles for their transportation needs (Welsh Government, 2023a).

Car-sharing schemes can provide a variety of vehicles in multiple areas, allowing individuals to book them through smartphones. Users can conveniently return vehicles to designated parking locations after completing their trips, thereby enhancing flexibility and encouraging the transition from personal vehicle ownership to shared transportation.

Shared cars can replace 4–15 privately owned cars (Namazu and Dowlatabadi, 2018). The adoption of car sharing can lead to notable cost savings, including potential tax benefits associate with purchasing car for both employers and employees (Shaheen et al., 2018),[3] decreased journey costs, reduced fuel consumption (Fellows and Pitfield, 2000), and lowered parking fees (NI Direct). However, shifting from public transport to shared transport may increase CO_2 emissions (Jung and Koo, 2018).

Addressing the issue requires the introduction of EVs and the establishment of intelligent charging infrastructure, often powered by photovoltaics systems. EVs have lower CO_2 emissions than fossil-fueled cars in use (depending upon the carbon intensity of the electricity supply), offering potential for NZN in South Wales (Transport and Environment, 2022). Moreover, their relatively simplified and fewer engine components translate into cost-effectiveness in maintenance and potential improvements in their reliability (Sanguesa et al., 2021). Nonetheless, it is essential to acknowledge that EVs do present certain challenges, such as limited driving range, slow charging times, and limited charging infrastructure availability. Additionally, souring raw materials, particularly cobalt, nickel and lithium, incurs environmental and social costs, while effectively managing the recycling end-of-life batteries can be difficult. Moreover, it is essential to consider that EVs require more energy to manufacture than internal combustion engine vehicles, largely depending on the carbon intensity of the electricity grid used throughout the supply chain, from mineral mining to refining.

As a transportation strategy, the integration of car sharing schemes and electric vehicles (EVs) powered by photovoltaic systems would benefit South Wales, as this region has a high percentage of car users and significant greenhouse gas emissions. In South Wales, several car-sharing initiatives like Wales Lift Share (Wales LiftShare), Travel Line Cymru (2014)'s cost and time-saving initiative from 2014, and TrydaNI's plan to introduce 100 electric cars by 2025 are promoting sustainable transportation (TrydaNi). Enterprise Car Clubs (Enterprise Car Club) and ZipCar (ZipCar), the UK's largest car-sharing club, also contribute but are currently limited to larger cities outside of Wales.

To effectively expand car-sharing, the Welsh government should incentivize companies with grants for free initial use to encourage adoption and invest significantly in infrastructure like charging stations to support electric vehicles and larger networks. Enhancing public awareness through social media, implementing robust safety measures, and integrating car-sharing with public transport are essential. Continuous monitoring and evaluation are necessary to refine strategies and improve the system. Furthermore, to implement this initiative, South Wales should prioritize enhancing licensing and app registration processes to address safety and ethical concerns. The region should enhance active travel options and improve EV battery supply chain management with innovative techniques such as material passports. Additionally, boosting infrastructure to support car-sharing enterprises and offering grants to facilitate a cost-free initial experience for users can stimulate interest and promote behavioral change.

4.3.4. Waste management initiatives

Globally, an annual production of 11.2 billion tonnes of waste presents a pressing concern, but this challenge can be mitigated through effective recycling and waste management systems (United Nations). Recycling is a core component of the CE in the built environment, while recycling rates remain an area of concern within the construction industry. South Wales should thus explore various strategies to effectively manage waste.

The Pay-As-You-Throw (PAYT) scheme, is a waste management approach in which users are charged based on the quantity of mixed waste delivered to the designated PAYT locations (European Commission, Pay-as-you-throw). This scheme primarily seeks to influence consumer behaviors and habits related to waste management (European Commission, Pay-as-you-throw). Benefits of the PAYT scheme include community engagement, waste reduction, cost savings, quick implementation, and job creation (Elia et al., 2015). It also promotes home composting (Dahlén and Lagerkvist, 2010). Since fully implementing the PAYT system in 2014, Treviso, Italy, now calculates waste fees for its 85,000 residents based 60% on household size and 40% on the quantity of mixed waste collected, leading to a 25% increase in the separate collection rate from 55% to 80% within just over a year. In 2015, the average waste fee per household in Treviso was €186, compared to the Italian average of €305, demonstrating that the PAYT system, alongside other initiatives like door-to-door collection, significantly reduces waste fees for households.[4] Nevertheless, significant challenges include its appropriateness for larger families and poor households, potentially leading to an increase in illegal waste disposal, such as fly-tipping. In a region like Wales, where poverty rates are prominent, the issue of fly-tipping becomes particularly pertinent (Stats Wales Recorded). High operational costs are another challenge, but incentives can help address these (Elia et al., 2015).

Wales is adopting circular recycling methods, including a new deposit scheme for single-use materials where customers pay a deposit refunded upon item return, proving successful in improving recycling rates (Keep Wales Tidy). Additionally, food waste is converted into biogas through anaerobic digestion and used to power homes (BBC, 2022; WRAP, 2023). The Pay-As-You-Throw scheme has led to increased community engagement, reduced waste and service costs, and job creation, and it promotes home composting (Dahlén and Lagerkvist, 2010; Elia et al., 2015; Skumatz, 2008). However, it poses challenges for larger and low-income families who may struggle with the costs, potentially leading to illegal disposal practices such as fly-tipping, which is already a significant issue in South Wales (Welsh Goverment, 2023b; Welsh Goverment, 2023b). High operational costs are another concern, although incentives might mitigate these issues (Dahlén and Lagerkvist, 2010; Elia et al., 2015). Additionally, other initiatives, such as storm water waste management and turning gas into stone, may prove to be more effective alternatives for South Wales.

5. Discussion

This research initially defines NZN and proposes a conceptual framework for achieving NZN. This framework, integrating multiple case studies design with the urban transformative capacity model, represents the first application of a multi-level urban transformative capacity model in transforming existing neighborhoods into NZN within a specific region. Supported by technological advancements and CE principles, this research conducts a comprehensive investigation of NZN transformation, encompassing aspects such as raw materials, construction practices, transportation, and waste management.

To validate the feasibility of the proposed model, we selected three city-level and three neighborhood-level cases, employing specific criteria outlined in Table 2, for a detailed cross-case analysis. This research offers valuable insights into the implementation of initiatives fostering environmentally sustainable cities and NZN in these six cases. A notable finding from cross-case analysis is the widespread adoption of sharing economy initiatives, which involve the communal use of spaces such as kitchens, living areas and recycling units. Sharing economy promotes a culture of favoring access over ownership, referring to the practice of using a communal or shared approach to access and utilize resources efficiently, reducing waste and promoting sustainability

[3] Several US states have introduced state-level commuter tax benefits and tax credits for carpooling. For instance, Maryland provides a tax credit covering 50% of the eligible costs associated with offering commuter benefits (Shaheen et al., 2018).

[4] More details of the Treviso example can be found here: https://greenbestpractice.jrc.ec.europa.eu/node/158.

(Dabbous and Tarhini, 2021). Additionally, community participation and engagement as well as technology innovation emerge as key drivers in effectively implementing waste management systems and promoting CE in the built environment.

South Wales is selected as a case study as it represents a microcosm of broader industrial transition challenges and opportunities seen globally, thus providing valuable insights into the feasibility and impact of CE initiatives in similar contexts. Its mixture of rural expanses and post-industrial urban centers, alongside a commitment to renewable energy and waste reduction, reflects conditions applicable to many regions undergoing economic restructuring. The primary findings indicate that four key initiatives encompassing technology, construction, transportation, and waste management have the potential to drive successful transformations towards NZN in South Wales. The benefits associated with these initiatives outweigh the challenges, making them an attractive option for the region. Overall, design for disassembly and material passports are considered most suitable for NZN in South Wales, facilitating CE and addressing the need for decarbonization and enhanced sustainability in the built environment and its supply chain. These initiatives also address traceability and transparency issues in the construction industry, inherent obstacles in implementing CE practices, while offering numerous additional benefits.

However, generalizing these findings poses challenges due to significant variations in demographic and economic differences, cultural and policy variability, technological and environmental considerations, as well as regulatory and material challenges in construction. More specifically, the smaller population size of South Wales means that data and proposals derived from these cases may not be applicable to more densely populated metropolitan areas. In larger cities or those with different economic structures, the implementation of these CE initiatives may face different economic challenges and cultural barriers. For example, the success of waste management strategies in South Wales, which leverages its high poverty rates to promote recycling and reusing as economic benefits to the community, might not directly translate to wealthier urban centers where consumer behavior is different. Additionally, the implementation of photovoltaic initiatives in South Wales, supported by government incentives and favorable geographic conditions for solar energy, may face obstacles in regions with less sunlight or without supportive renewable energy policies. Furthermore, transportation solutions based on South Wales' reliance on personal vehicles might not be suitable for cities with advanced public transport systems and different urban mobility patterns. As for the construction initiatives, since South Wales has a large amount of construction and demolition waste and numerous historically significant buildings that need to be preserved, the building proposals are tailored specifically to the conditions in South Wales. In regions with modern urban landscapes, different construction technologies and materials might be prevalent, and the historical preservation priorities that dictate sustainable reuse and renovation in South Wales might not be as pressing. For example, applying these building practices in rapidly developing cities in Asia might require adjustments to accommodate different building standards and a faster pace of construction, alongside varying levels of public awareness and regulatory support for conservation practices.

The proposed sustainable practices for South Wales also advance sustainability from a social perspective. These include enhancing community engagement, providing social benefits through sharing economy initiatives, and creating green jobs. Practices that encourage community participation and engagement not only support environmental initiatives but also community ties, enhance local governance, and improve the quality of life for residents. Shared spaces can promote community bonds, culture exchange, and social cohesion. Furthermore, sustainable practices in construction, technology, and waste management are likely to generate green job opportunities, providing education and training prospects. These initiatives are expected to balance economic growth with environmental protection and provide upward mobility for diverse social and economic groups, especially benefiting low-income and marginalized communities.

However, there are certain limitations in this research. Firstly, the data collection process utilizes a cross-sectional time strategy, rather than continuous monitoring over time. This choice introduces certain drawbacks, such as the limited time for in-depth assessment of each case and potential bias (Zainal, 2007). Second, the absence of specific indicators for each case precludes drawing accurate conclusions on the case displaying the most sustainable development and best-case practice. Additionally, this study relies heavily on conceptual frameworks and case study analysis but lacks empirical data from actual implementations to support the effectiveness of the proposed initiatives, limiting the ability to validate the findings quantitatively or qualitatively. Finally, the findings and the proposed model are specific to South Wales and might not be directly applicable to other regions without adjustments that consider their unique socio-economic, cultural, and environmental contexts.

6. Conclusion

The concept of net zero neighborhoods, deeply rooted in circular economy principles, is gaining increasingly recognition as a pivotal solution for enhancing sustainability in the construction industry. Supported by technological advancements and the foundational principles of circular economy, this research introduces an innovative conceptual framework.

The proposed framework, known as the multi-level urban transformative capacity model, has been specifically validated with a focus on South Wales. It highlights four key initiatives in technology, construction, transportation, and waste management. These initiatives offer significant benefits, including fostering a more sustainable and environmentally friendly construction industry through enhanced traceability and efficiency, and simultaneously promoting social sustainability by bolstering community engagement, providing social benefits through sharing economy initiatives, and creating new green job opportunities.

This research paves the way for transforming existing neighborhoods into net zero neighborhoods, contributing significantly to the goal of achieving energy self-sufficiency and net-zero status by 2050. By applying this framework to specific regions, a tailored set of initiatives can be developed, enabling a thorough exploration of transformational strategies specific to NZN contexts. Moreover, this research plays an important role in combating climate change and is instrumental in facilitating the achievement of the objectives of the SDGs, marking a significant step forward in sustainable development.

Future research should focus on conducting longitudinal studies to track the performance of NZN initiatives over time, providing valuable insights into their long-term sustainability and effectiveness. Furthermore, expanding surveys and interviews with a broader range of stakeholders, including community members, local authorities, and organizations involved in NZN projects, will help gather more comprehensive qualitative data on the social and economic impacts of NZN initiatives. Collaborating with local authorities and organizations to gain access to detailed quantitative data on energy usage, waste management, and transportation metrics is also essential, as it provides a stronger empirical basis for evaluating the effectiveness of NZN initiatives. Moreover, defining assessment indicators for drawing conclusions from the quantitative aspects would provide a deeper understanding.

CRediT authorship contribution statement

Jacob Edwards: Writing – original draft, Validation, Software, Methodology. **Hanbing Xia:** Writing – original draft, Visualization, Validation, Investigation, Conceptualization. **Qian Jan Li:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Data curation. **Peter Wells:** Supervision, Funding acquisition, Formal analysis. **Jelena Milisavljevic-Syed:** Writing – review &

editing, Supervision. **Alberto Gallotta:** Resources, Data curation. **Konstantinos Salonitis:** Writing – review & editing, Supervision.

Declaration of competing interest

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

Data availability

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

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Appendix A. Applicability to Wales and South Wales using Urban transformative capacity model

Technology initiatives - Materials passports [C2 Transformative leadership] & Photovoltaics panels [C7 Effective sustainability innovations]
Materials passports - Despite the absence of blockchain-enabled material passports in current practices in Wales, they are showing significant potential that completes 6200–8300 new dwellings each year, making material passports a worthwhile investment (Federation of Master Builders). Furthermore, a recent trial in London, focusing on material passports in Edenica office developments, may generate interest across the UK (New Civil Engineering, 2023). The Edenica project uses the Circuland platform to host material passports, with the aim of linking them to building information modelling (BIM) (Circuland). The platform can serve as a reference for South Wales, providing a comprehensive inventory of construction materials while enhancing transparency and traceability. Photovoltaics panels - South Wales is actively embracing photovoltaic panels by applying them to schools, public buildings. Wales benefits from abundant sunshine making photovoltaics panels highly effective through summer months but almost defective in October–January (GreenMatch, 2023). The extensive greenland in Wales can facilitate photovoltaics panels over the need for them on ring roads and roofs.
Building initiatives - Design for dissembling & Sustainable retrofitting *[C5 Sustainability foresight]*
Designing for disassembly and sustainable retrofitting could be beneficial to South Wales and Wales to reach net zero by 2050 and help them adopt new circular methods. Given the annual construction of new dwellings in Wales, with plans to build between 6200 and 8300 each year (Stats Wales Recorded), this initiative could hold significant benefits for South Wales.
Transportation initiatives - Car sharing schemes [C6 Community experimentation, C8 Social learning]
Wales exhibits the highest prevalence of privately owned cars and the greatest reliance on automobiles for transportation. It is estimated that 75–80% of Welsh commuters heavily depend on their personal vehicles as the predominant mode of transportation. This proportion surpasses the figures observed in both England and Scotland, and exceeds the British average of 68% (Welsh Government, Llwybr Newydd). Consequently, the transition to more sustainable modes of transportation in South Wales holds the potential to significantly contribute to the attainment of net-zero emissions targets. Currently, the transportation options available in Wales are predominantly limited to bus and train services, with the ongoing development of a Metro system poised to enhance public transport offerings (ITV News, 2023). Additionally, South Wales has a limited history of car-sharing initiatives, exemplified by efforts such as Wales Liftshare (Wales LiftShare). These endeavors have been trialed in locations like Powys (Rhys, 2020). The introduction of a car-sharing scheme in South Wales has the potential to yield substantial advantages, including cost savings, reduced CO_2 emissions, and alleviation of commuter stress.
Waste management initiatives - Pay-as-you-throw (PAYT) [C3 Empowered communities practice, C6 Community experimentation] & Turning food waste into Biogas [C7 Effective sustainability innovations] & Storm water waste management [C5 Sustainability foresight] & Turning gas into stone [C7 Effective sustainability innovations]
PATY - Wales is a global recycling exemplar, ranking 1st in the UK, 2nd in Europe, and 3rd worldwide (Welsh Government, 2020). This achievement is attributed to various strategies like statutory recycling targets, weekly food waste collection, improved recycling facilities, reduced general rubbish collections, and banning single-use plastics (Housing Europe, 2022). However, this high recycling rate might reduce the need to further enhance PATY scheme. Instead, the focus should shift towards other sustainability measures to reach net-zero. Food waste to Biogas - Wales has implemented an effective plan for managing food waste, where it is converted into energy to power homes. While this initiative has powered 10,000 homes across Wales, it's noteworthy that the ineffective recycling of food waste has resulted in a missed opportunity to power an additional 7500 homes (WRAP, 2023). Considering the missed potential for recycling almost 100,000 tonnes of additional food waste, Wales could benefit from a food waste initiative, and a PATY system might prove beneficial (WRAP, 2023). Stormwater management - South Wales could greatly benefit from a rainwater/stormwater management system to efficiently redistribute water resources. Initiatives by Dwr Cymru, a non-profit organization, demonstrate the water-saving options available in Wales, with the potential to abstract 3% of annual rainfall (Welsh Water). Implementing a system similar to what Augustenborg offers in local neighborhoods could enhance water redistribution in Wales. Turning gas into stone - A highly innovative approach to combat greenhouse gas emissions involves turning gas into stone. The Carbfix project in Iceland, in collaboration with a university, has proposed the worldwide potential of this initiative (Sky News, 2023). The process involves dissolving CO_2 into water and injecting it underground into rock formations, where it mineralizes and becomes a solid form of rock. While South Wales could benefit from this concept, it is essential to note that the operation would entail high costs, as the necessary facilities are not currently in place in Wales.

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