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European Union 2050 vision on building nearly zero energy neighbourhoods for the future

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Abstract

Achieving Net Zero Energy at the district scale is a critical objective for enhancing urban resilience in the face of climate change. However, only a few experts globally master the complex technologies required, and vulnerable regions often lack tailored roadmaps. This study aims to address this gap by proposing a methodological framework for retrofitting existing urban districts to meet Net Zero Energy District (NZED) criteria, with a focus on the European Union context. A comprehensive life cycle assessment was conducted over a 100-year horizon, analysing three types of neighbourhoods—urban, sustainable, and rural—across various EU capitals. The study employed the Plaides LCA tool coupled with Meteonorm software to evaluate energy demand, carbon emissions, and environmental cost during construction, operation, renovation, and demolition phases. Key parameters such as local building materials, microclimate, national energy mixes, and transportation modes were integrated into the analysis. Results indicate that energy demand in urban districts is 14% and 30% higher than in sustainable and rural areas, respectively. A mixed scenario combining global warming adaptation, deep renovation of all buildings, full transition to electric vehicles, and widespread solar panel integration could reduce total energy demand by up to 95% by 2050 in EU countries. This study demonstrates the feasibility and environmental benefits of transitioning to NZEDs and emphasizes the urgent need to train regional experts and improve district-level data collection to support climate-resilient urban planning.

Keywords Nearly zero energy · Neighbourhoods · Roadmap · European Union, 2050

1 Introduction

In recent years, rapid population growth has substantially increased energy demands for heating and cooling in residential buildings, making this sector one of the most energy-intensive and responsible for significant carbon emissions (Beccali et al., 2013). As a result,

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buildings have become central to the global challenge of reducing greenhouse gas emissions. While high-performance housing demonstrates the feasibility of reducing energy consumption and carbon footprints while maintaining comfort (Chlela et al., 2009; Kalz et al., 2010), the sector remains a major consumer of natural resources, particularly fossil fuels. In regions like the European Union, buildings account for approximately 42% of final energy use (IEA, 2011), 35% of greenhouse gas emissions (Metz et al., 2007), and 50% of material extractions (European Commission, 2011). To address these environmental challenges, the European "Zero Energy Building" (ZEB) initiative envisions that all new buildings achieve net-zero annual energy consumption—generating as much energy locally as they consume over the course of a year (Brown & Vergragt, 2008; Yi et al., 2017). However, most regulations to date focus only on individual buildings and emphasize operational energy use, overlooking other critical life-cycle stages such as construction, transportation, and end-of-life phases (Nematchoua et al., 2020a, b, c, 2022). Consequently, a more holistic and multi-scale perspective is necessary to transition towards sustainable urban environments.

Numerous studies have proposed strategies for achieving net-zero energy buildings globally. For example, Brown and Vergragt (2008) emphasized the role of behavioral aspects and socio-technical interactions in the success of zero-fossil-fuel housing. Yi et al. (2017) revealed that early-stage "zero-energy" buildings often relied heavily on non-renewables, transitioning gradually to greener energy sources. Other researchers, such as Szalay and Zöld (2014), have explored how building shape influences energy needs, while Zhou et al. (2016) stressed the importance of aligning energy simulations with actual performance in the face of variable weather conditions. Studies by Srinivasan et al. (2012) and Chastas et al. (2016) also examined how factors such as orientation, material choice, and embodied energy significantly impact energy efficiency and overall sustainability. Energy demand and CO_2 emissions are closely correlated. Rising temperatures have led to increased cooling needs (Reyna & Chester, 2016), while occupant behavior has proven to be a key variable in energy use and emissions. At a broader level, the sustainability of neighborhoods is influenced by climate, building design, materials, and geographic location (Trigaux et al., 2014). Recent concepts such as Net Zero Energy Buildings (NZEBs) and nearly Zero Energy Buildings (nZEBs) stress the importance of energy efficiency in conjunction with renewable energy integration (Shirinbakhsh & Harvey, 2021). In practice, NZEBs often combine low-energy design principles with technologies like heat pumps, solar thermal systems, and PV panels (Musall et al., 2021), and most studies confirm that PV systems remain indispensable for achieving net-zero status.

Despite these innovations, challenges persist. Krarti and Ihm (2016) found that sustainable construction materials can halve annual energy consumption. Galvin (2022), examining older German apartments, concluded that achieving net-zero energy may require oversized PV systems and additional efforts to reduce carbon emissions. However, global guidelines for achieving net-zero energy remain difficult to standardize due to diverse regional contexts, behaviors, and construction typologies. This raises several crucial questions: What are the main technological obstacles in retrofitting existing urban districts to meet Net Zero Energy District (NZED) standards? How can renewable energy be reliably integrated at the district scale? What lessons can be learned from EU initiatives and applied globally? And how do NZEDs perform in EU regions compared to non-EU regions? This study aims to address these questions by developing a unified methodology for achieving net-zero energy at the neighborhood scale within the European Union. The objective is to promote sustainable urban development by reducing energy demand and maximizing renewable energy use. Despite the growing momentum for nearly zero-energy neighborhoods, the literature often overlooks the socio-economic and technical complexities that vary across

EU regions. A more comprehensive analysis is required—one that integrates technological, economic, and policy dimensions to guide local strategies for NZED implementation. This research expands the focus from individual buildings to entire neighborhoods, adopting a life-cycle approach that considers construction, operational use, transportation, and end-of-life stages. An initial experimental study was conducted in various neighborhoods in Belgium to collect the data needed for advanced modeling. Three representative districts in different EU countries were then simulated, incorporating country-specific energy mixes, climates, building materials, and transportation habits. The study assessed current energy demand and costs, then used the IPCC RCP 4.5 scenario to predict future energy needs and expenditures by 2050. PV systems were integrated to evaluate their effects, and further scenarios included comprehensive retrofitting measures, full electrification, and the exclusive use of electric vehicles. The results were analyzed comparatively to identify optimal strategies for achieving NZEDs. Through this holistic and systematic approach, the study contributes to a deeper understanding of how to implement nearly zero-energy neighborhoods effectively and equitably across diverse EU contexts.

2 Methodology

This section presents the methodological approach adopted in this study to assess the potential for achieving net-zero energy in residential neighbourhoods across the European Union. The methodology is illustrated in Fig. 1, which summarizes the key phases of the research process. These include the selection of representative case studies, data collection related to building energy performance and mobility, the definition of scenarios based on climate, materials, and energy sources, followed by energy modelling, life-cycle assessment, and comparative evaluation. Finally, policy recommendations were developed based on the outcomes. Each step of this process was guided by replicable criteria to ensure the reliability and relevance of the findings.

The methodology comprises the following steps:

i) **Baseline Model Creation**: A district was modeled as the initial case to analyze energy demand using the LCA method, serving as the foundation for comparative analysis.
ii) **Use of Simulation Tools**: Specialized software for dynamic thermal analyses and LCAs at the building and neighborhood scale was utilized to conduct this study.
iii) **Scenario Definition**: Various scenarios were defined by altering specific parameters to explore the impact on energy demand and sustainability outcomes.
iv) **Comparative Analysis**: The scenarios were analyzed and compared to the initial model to draw comprehensive conclusions.

2.1 District selection

Selecting representative neighborhoods was essential to ensure the validity and generalizability of the results. The authors modeled three existing neighborhoods based on precise plans and developed a series of virtual parameters. All selected districts are located in the Liège region of Belgium, within the Walloon area, characterized by a temperate climate with long cold periods spanning 8–10 months annually.

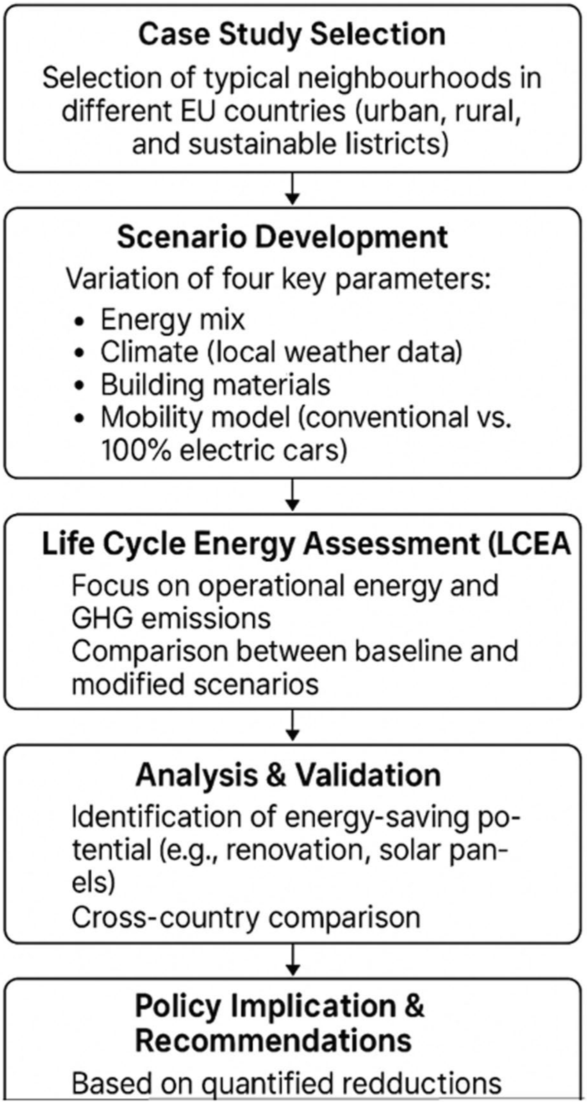

Fig. 1 Overall method for Net Zero energy district Assessment

The neighborhoods selected for the study are:

a) Eco-District of Sart-Tilman: A sustainable neighborhood in the southern part of Liège City near the university.This eco-district was chosen due to its accessibility, recent construction, and adherence to sustainable urban planning principles; b) Urban Block –"District of Maghin": Located in the Saint Leonard district of Liège, specifically on Rue Maghin. The area represents an urban block within a densely built environment. C) Rural Block –"district of Neupre": Situated in Neupre, a rural area within the province of Liege. This neighborhood showcases the characteristics of a low-density rural settlement.

These districts represent a range of typologies—sustainable, urban, and rural—to provide a comprehensive understanding of varying neighborhood dynamics in energy and environmental performance.

2.1.1 Sustainable district

This district combines residential and commercial functions with a diverse range of building types, including: Building Typologies: Forty compact flats, forty-five spacious dwellings, eleven semi-detached houses, and six retail or business premises for shops and businesses (see Fig. 2). The area features a housing density of 40 units per hectare, with more than half of them being terraced or connected homes.Outdoor spaces include more than 30% "green" or "blue" areas (e.g., vegetative surfaces and water management features). Separate systems are implemented for managing rainwater and wastewater.Private parking spaces are available near buildings, and ground-floor accommodations include private gardens.

The neighborhood aligns closely with the sustainable neighborhood benchmark published by the University of Liège, making it an ideal candidate for analysis (Nematchoua et al., 2020a, b, c).

2.1.2 Functional unit

The choice of the functional unit is critical to the scope and accuracy of this study. The authors limited the analysis to the residential segment of the neighborhood under consideration. Environmental impacts were systematically calculated using three functional units. The primary functional unit for gross results was defined as:Total surface area:3.5 hectares, comprising:1 hectare allocated to roads, access routes, and parking areas; 17,800 m^2 dedicated to vegetation and green zones; 6,580 m^2 of constructed floor area; 13,160 m^2 of habitable interior space; Roughly 220 inhabitants; Estimated lifespan: 100 years; Located in the outskirts of the capital city of each country analyzed, beginning with a case study

Fig. 2 Eco-District of Sart-Tilman

near Liège, Belgium (Nematchoua et al., 2020a, b, c). In designing the sustainable neighborhood, several advanced technologies and environmental strategies were employed to optimize energy use and minimize ecological impact. Firstly, the buildings were compact and thoughtfully oriented to align with the sun's path, thereby maximizing natural lighting and solar heat gain. Additionally, enhanced thermal insulation—featuring thick walls and airtight construction—played a vital role in reducing heat loss. High-performance windows with double or triple glazing were installed to improve thermal efficiency. Moreover, passive cooling strategies such as solar shading, the use of high thermal mass materials, and night ventilation were integrated to maintain indoor comfort without relying on active cooling systems. Complementing these efforts, energy-efficient mechanical ventilation and smart heating systems with programmable thermostats were adopted to ensure both comfort and energy savings. Finally, the integration of photovoltaic panels allowed for local electricity generation, further contributing to the neighborhood's sustainability goals.

In parallel, the urban district selected for comparison, known as"Quartier Maghin,"was located in the heart of Liège and represented a traditional urban block from the pre-20 th-century era. This site, covering 8,726 m^2, was characterized by a dense arrangement of residential units surrounding commercial and office spaces. Architecturally, the buildings varied in form, comprising two to four façades and multiple stories, with diverse internal dimensions. Notably, the configuration and uniformity of the structures reflect the historic urban growth pattern of the time. To ensure consistency across the analysis, this neighborhood was virtually placed in the central districts of each capital city studied, allowing for a fair and uniform evaluation of the proposed sustainable strategies (see Fig. 3).

2.1.3 Rural neighbourhood

The rural neighbourhood covered a total area of19, 457 m^2. It was essentially constituted of residential buildings with a total number of accommodations three times lower than that of the urban district. There was no highway and the mode of public transport was only by bus. The authors observed on both sides of the street, the aging buildings, for the most part, built between the seventeenth and nineteenth centuries. In this study, the author has modelled this district in the far north of the capital in each of the countries studied, see Fig. 4.

Fig. 3 Urban district assessed

Fig. 4 Rural neighbourhood (Nematchoua, 2021)

In this study, the author adapted the built space occupied by each district in each European Union country. In a sensitivity process, taking into account one of the recent reports of the Bank World, the living area varied from 30 to 50 m^2 per inhabitant in these countries. The main characteristics of the three neighbourhoods studied are shown in Table 1. As shown in Table 1, The authors see that in the rural district, the number of occupants is lower than in other districts. The authors noticed 40 buildings available, and occupied by only 30 people, so, buildings were unoccupied.

2.2 Modelling assumptions

The representation of the various types of neighborhoods analyzed in this research is illustrated in Fig. 5. A suitable location was determined for implementing these three residential models in each country, aiming to assess and compare environmental impacts—such as energy consumption and greenhouse gas emissions—in a fair and standardized manner, using an appropriate functional unit. It is important to note that only the capital cities and their surrounding areas were selected as locations for these neighborhood types. The simulations placed urban districts in the downtown area of each capital, sustainable neighborhoods in the suburban zones, and rural communities on the outskirts. This focus on capital

Table 1 Main reference characteristics of the three neighbourhoods studied

Category of Residential Zone	Eco-Friendly	City Center	Countryside
Surface (m^2)	35,480.0	8,726.1	19,457.0
Number of Residents	220	100	30
Total Constructions	20	30	40
Individual Homes	10.0%	7.0%	75.0%
Paired Houses	60.0%	17.0%	19.0%
Row Houses	25.0%	75.0%	4.0%
Flats	5.1%	1.0%	2.0%
Residential Density	6.0 units/ha	35.0 units/ha	20.1 units/ha
Percentage of Usable Area	18.0%	44.0%	10.0%

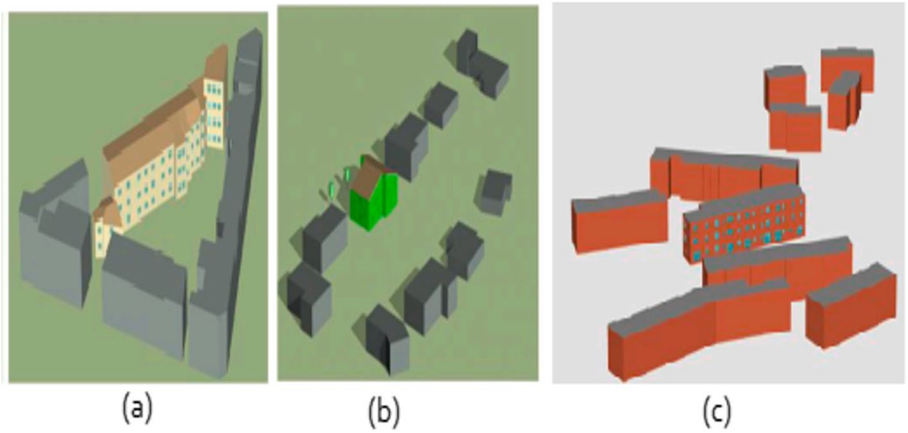

Fig. 5 Modelling of three neighbourhoods in the Pleiades LCA software((**a**) Urban district, (**b**) Rural, and (**c**) Sustainable district)(Nematchoua, 2021)

cities was intentional; numerous studies have highlighted that capitals are often the most populated cities within a country and tend to exhibit high levels of energy consumption and carbon output. For each case study, the researchers considered key factors that influence energy use and emissions, including the construction materials, national energy mix, regional climate conditions, socioeconomic development levels, average living space per person, and the cultural practices of occupants regarding energy use and lifestyle habits.

(a) I am aware that the situation of each country in times of war was not the same as during times of peace. This could have a significant impact on carbon emissions. To resolve this issue, I have assumed that all the countries studied were living in a time of peace and that there were no wars between nations (Nematchoua, 2020).
(b) The different values of the local climatic parameters of each country were evaluated with the most recent version of the American Meteonorm software. With this software and knowing the geographic coordinates of each city, it was possible to connect to an American satellite and download the climatic data specific to each city. The data provided by the Meteonorm software were reliable and have already contributed to several valuable publications from researchers all over the world. The database of this tool contained more than 6,200 cities and more than 8,325 weather stations worldwide.
(c) Data on commonly used construction materials in each country were gathered through analysis of national thermal building codes from 2018 to 2020, resources available on the UN-Habitat platform, and insights drawn from multiple scholarly publications.

The standard data regarding the daily transportation of occupants was suggested by the simulator based on the geo-localization of each country. All the different weekly journeys of inhabitants depended on the types of neighbourhoods. Generally, all the data related to transportation was standard and offered by the tool applied. We fixed the daily mobility concentration of occupants at least 80% in all the countries. Setting, the distance of the weekly journey between the house-shop at 1000 m; distance from the public transport network at 500 m; distance from home to work, between 5,000 m and 20,000 m. Noticed that the trip was made during 5 days per week and for 47 weeks per year. The principal means of public transport are tram, bus and metro. The occupant's activity was considered in most cases, standard in the different categories of neighbourhoods. I guess that all the occupants were in good health. The yield of water system was set at 80% in all the districts; Hot water usage was estimated at 40 L per person per day, while cold water consumption was assumed to be 100 L per person daily.

I assumed that the waste quantity per day per person is between 0.8 to 1.2 kg. It's important to notice that the Embodied energy (quantity of non-renewable energy per unit of building material, component or system), was automatically calculated by the software.

2.3 Database

In this study, environmental data used to evaluate the two primary environmental indicators were sourced from the Swiss-based Ecoinvent database, a globally recognized platform for environmental impact data. Ecoinvent is particularly noted for its methodological transparency (Ecoinvent LCI Database, 2021). The data for each material included a comprehensive life-cycle inventory detailing all input and output flows of materials and energy within the system boundaries, following the approach of Peuportier et al. (2006). These datasets covered: (i) resource usage (e.g., energy, water); (ii) emissions released into natural media such as air (e.g., CO_2), water (e.g., ammonia), and soil (e.g., heavy metals); and (iii) waste production (whether inert, hazardous, or radioactive). The study utilized a recent version of the database, Ecoinvent 3.5. The analysis focused on two key environmental indicators—life-cycle energy consumption and life-cycle greenhouse gas emissions—across three different neighborhood typologies. However, the same methodology could be applied to other environmental performance metrics (Goedkoop & Spriensma, 2000). The software tools employed for simulation are presented in the following section.

2.4 Simulation software

The different components of tool are show in this paragraph.

2.4.1 Process

All the analyzed neighborhoods were simulated over several weeks. In particular, the simulation period for applying the modeled neighborhoods within various European Union case studies was set to three weeks.

2.4.2 Components

In this study, the primary simulation tool employed was the Pleiades LCA software (developed by Izuba Energies, France), version 4.19.1.0. This platform comprises six core modules: BIM, LCA, Library, Modeller, Publisher, and Results—each serving a distinct function. Pleiades is widely recognized for its effectiveness in assessing life-cycle environmental impacts at the neighborhood scale and has been extensively applied in related academic research (Lotteau et al., 2015). The Modeller module serves as a visual input interface, enabling the user to define building geometries, incorporate solar obstructions, and configure the structural composition of walls, windows, roofs, and other elements. Meanwhile, the Editor module facilitates dynamic thermal simulations (Colombert et al., 2011). The LCA module then utilizes these simulation outcomes to evaluate various environmental indicators at both the building and neighborhood levels.

Meteonorm is a global meteorological database that provides climatological data tailored for solar energy applications at any geographical location (Nick et al., 2016; Wati et al., 2015). Over the past decade, this software has been widely utilized in numerous studies focused on evaluating outdoor climatic conditions (Ciobanu et al., 2014). In the present research, the latest release—Meteonorm 8.2—was employed. This version features updated datasets on weather and atmospheric turbidity, along with enhanced functionalities. In terms of data reliability, key variables such as temperature and solar radiation were validated through multiple testing procedures. The interpolation accuracy for monthly radiation and temperature data demonstrated a root mean square error (RMSE) of approximately 7% and 1.2 °C, respectively (Nematchoua & Reiter, 2019).

2.5 Scenarios

Given that the main objective of this study is to achieve carbon neutrality and net-zero energy consumption by 2050, several scenarios were proposed:

(1) Baseline Scenario: It was assumed that building occupancy levels varied throughout the day. During daytime hours (7:00 a.m. to 6:00 p.m.), the occupancy rate was estimated at 25%, while during nighttime (7:00 p.m. to 6:00 a.m.), it increased to approximately 100%. Based on experimental data, the occupancy density was set at 4 persons per 100 m^2 for the Maghin neighborhood (urban context) and 2 persons per 100 m^2 for the Neupre area (rural setting). In all neighborhoods, the occupants'activity level was considered sedentary (1 met).

To streamline the dynamic thermal simulations, various thermal zones and their respective occupancy schedules were defined. Three primary thermal zones were established, since modeling each room individually was impractical. Apartments were divided into a *day zone* and a *night zone* (Nematchoua et al., 2020a, b, c). An additional zone was created to represent common areas such as corridors or halls.

Analysis of meteorological data supported the following heating setpoints: in the day zone, temperatures were set to 16 °C between 10:00 p.m. and 7:00 a.m., and 19 °C during daytime. Conversely, in the night zone, heating was maintained at 18 °C at night and reduced to 16 °C during the day. Occupancy was assumed to alternate between zones depending on the time of day—day zones being used during daylight hours and night zones at night. A temperature of 18 °C was deemed sufficient for sleeping areas. The internal heat gains from electrical devices, which contribute to the building's energy performance, were also considered. These gains were higher during peak usage hours, particularly from 7:00 a.m. to 10:00 a.m. and from 6:00 p.m. to 9:00 p.m., during which an average internal load of 5.7 W/m^2 was recorded (Nematchoua et al., 2020a, b, c).

In terms of illumination, the lighting level was set below 100 lx between 10:00 p.m. and 5:00 a.m., aligning with typical sleeping hours, while values exceeded 250 lx from 6:00 a.m. to 10:00 p.m., matching peak activity periods during working hours. These thresholds were established in accordance with existing lighting standards. Moreover, it was considered that the *day zone* of the dwelling would be active during daylight hours and unoccupied at night, with the reverse pattern applied to the *night zone*. A setpoint temperature of 18 °C was deemed appropriate for bedrooms during sleeping hours (Nematchoua et al., 2020a, b, c). Internal heat gains were primarily attributed to electrical appliances, whose usage increased during periods of higher occupant activity. This contributed significantly to the building's internal thermal load. Based on an analysis of collected data, the average residential density in the simulated dwellings was set to 0.033 occupants per square meter, equivalent to one resident for every 30 m^2 (Nematchoua et al., 2020a, b, c).

For each designated thermal zone, ventilation parameters were determined based on the assumed level of building airtightness. A very low infiltration rate of 0.25 air changes per hour (ACH) was selected, reflecting the high-performance envelope typical of passive house standards (Nematchoua et al., 2020a, b, c). While most building codes permit up to 0.6 ACH for newly constructed buildings, this study adopted stricter criteria, emphasizing airtight construction practices implemented throughout the design and execution stages (Nematchoua et al., 2020a, b, c). The ventilation strategy employed a balanced mechanical system with heat recovery, set to operate at 0.3 ACH and delivering a recovery efficiency of 85%. Notably, the heat exchanger function was disabled from mid-June to early September to reflect seasonal operational adjustments. Domestic hot water and space heating were supplied by a condensing gas boiler with an efficiency of 92% (lower heating value). Heat distribution was provided by underfloor heating on the ground floor and radiators on the upper floor. Some input parameters were based on default settings in the simulation software due to consistency with system specifications. **(2) Photovoltaic Integration Scenario:** This scenario retained the initial conditions but introduced mono-crystalline photovoltaic (PV) panels, covering one-third of each building's roof surface. The panels were oriented based on the country's geographic location. In the Northern Hemisphere, for instance, the PV modules faced south with an optimal tilt angle between 35° and 37°. A new round of simulations was conducted to reflect the impact of this solar integration. **(3) Deep Renovation Scenario:** In this scenario, extensive retrofitting measures were applied to both urban and rural neighborhoods. Existing buildings were upgraded using sustainable construction materials. Insulation was added to walls, roofs, and floors, and attics were thermally reinforced. More efficient heating technologies, including condensing boilers and heat pumps, were introduced in countries with temperate climates. Additionally, all rooftops were equipped with PV panels, and both private and shared modes of transportation within the neighborhood were assumed to be electric or environmentally friendly. A new simulation run provided updated results. **(4) Mixed Scenario:** This scenario combined multiple strategies: a 100% transition to electric vehicles, complete renovation of all buildings (100%), and widespread use of renewable energy, particularly PV systems. Furthermore, the environmental impact of global warming was integrated into the analysis, as outlined in Nematchoua et al., (2021a, b). The comprehensive approach allowed a holistic assessment of decarbonization and sustainability strategies at the neighborhood scale.

2.6 Environmental cost calculation method

Ecological effect was converted into ecological expenses, which allows for their comparison. The calculation of costs is based on the"Monetization of the MMG"method (Global Method Monetisation), updated in 2017 by De Nocker et al., which draws on earlier methodologies developed by Allacker et al. (2014) and De Nocker et al. (2011). This technique assigns financial values to each environmental indicator for three regions: Western Europe, Belgium, and the rest of the globe, as stated by De Nocker & Debacker (2018). The error margin linked to these financial values is minimal. Table 2 presents the conversion rates for translating ecological impacts into economic costs. The operational stage plays a major role in the overall ecological expenses, contributing 71.1%, whereas the upkeep phase constitutes only 3.7%. These findings align with those of Trigaux et al. (2017).

3 Results

This section presents the main results of the study, organized into several subsections.

3.1 Validation of results

We will assess the scale of our findings by comparing them with those available in the academic literature. Lotteau et al. (2015) conducted an extensive review of the current research on Life Cycle Assessment (LCA) at the district level, as presented in Table 3.

They observed a range in primary energy usage from 20.5 to 461.2 kWh/m^2 of floor area annually. In comparison, in this research, we measured primary energy consumption between 39.4 and 120.2 kWh/m^2 of floor area per year. When we compare each of the values above (see Table 1), we find that our results are generally within the ranges suggested by Lotteau et al. (2015). Therefore, we can affirm that our outcomes are of an acceptable magnitude.

3.2 Current state of neighbourhoods

The LCA of energy demand was detailed in this section.

3.2.1 Environmental impact analysis

As shown in Fig. (6a, b, and c), the energy demand was approximately 1,140,048.01–3413596.7kWh.year, 1,316,874.7–2,835,933.8kWh.year, and 860,748.5–2,278,065.2kWh.year, in Sustainable, urban, and rural neighbourhoods, respectively. Globally, the results showed that the energy demand is 14% higher in urban than sustainable neighbourhoods; and 30% higher in urban than rural neighbourhoods.

In rural districts, energy demand is the highest in Lithuania, and the lowest in Cyprus; in Urban districts, energy demand is the highest, in Lithuania, and the lowest, in Portugal; and in eco-districts, the energy demand is the highest, in Poland, the lowest, in Spain. Table 4 gives the quantity of carbon and energy per living and floor area in the three districts.

3.2.2 Environmental cost analysis

As shown in Figs. (7 and 8), the average energy demand cost is 267,949.5€ in sustainable neighbourhood, 427,567.9€in urban neighbourhood, and to 298,257.5€ in rural neighbourhood.

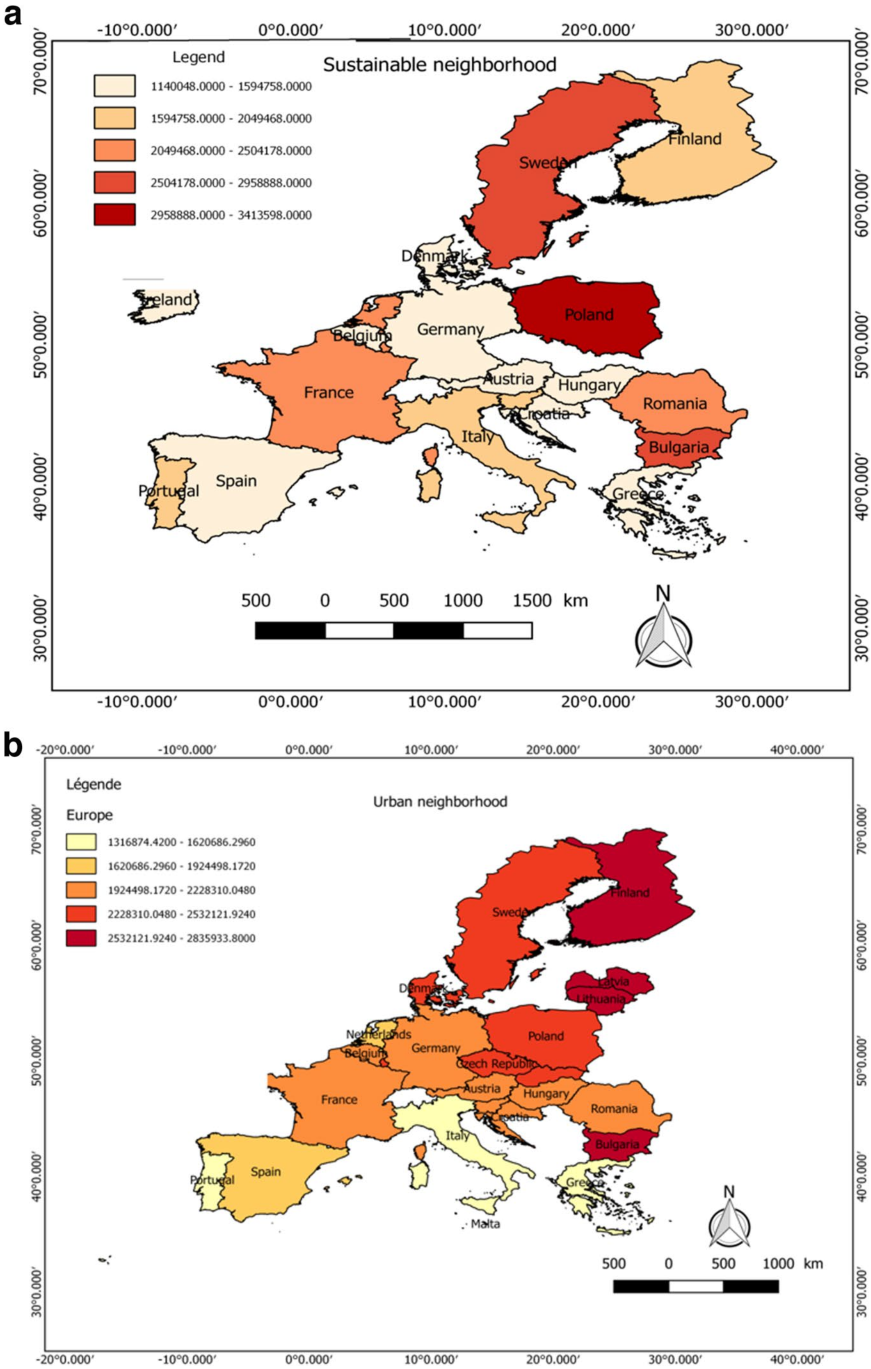

Fig. 6 **a** Distribution of primary energy demand per year in sustainable neighbourhood in some countries in the European Union. **b** Distribution of primary energy demand per year in urban neighbourhood in some countries in the European Union. **c** Distribution of primary energy demand per year in rural neighbourhood in some countries in the European Union

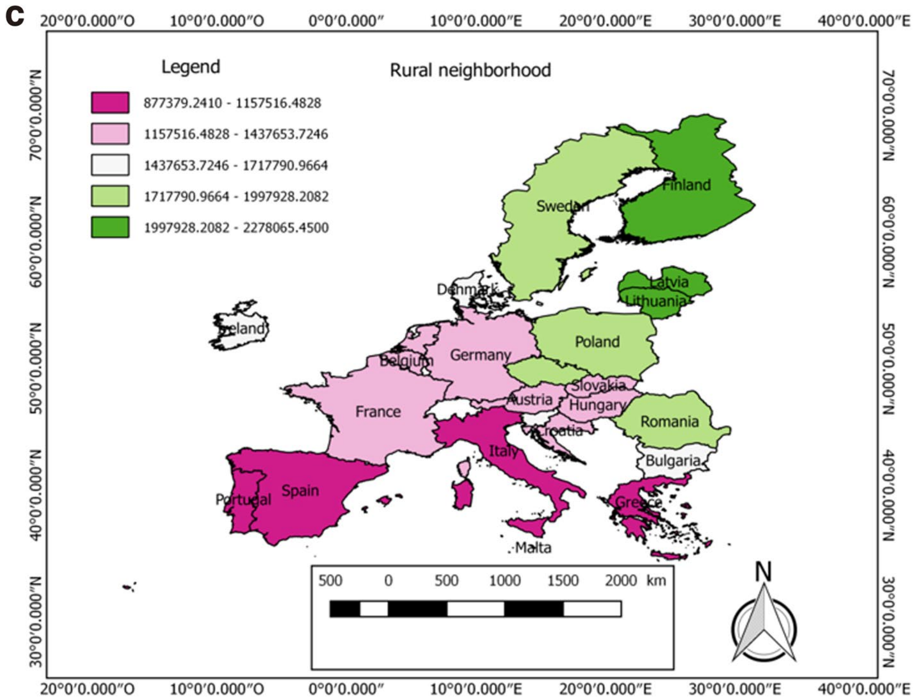

Fig. 6 (continued)

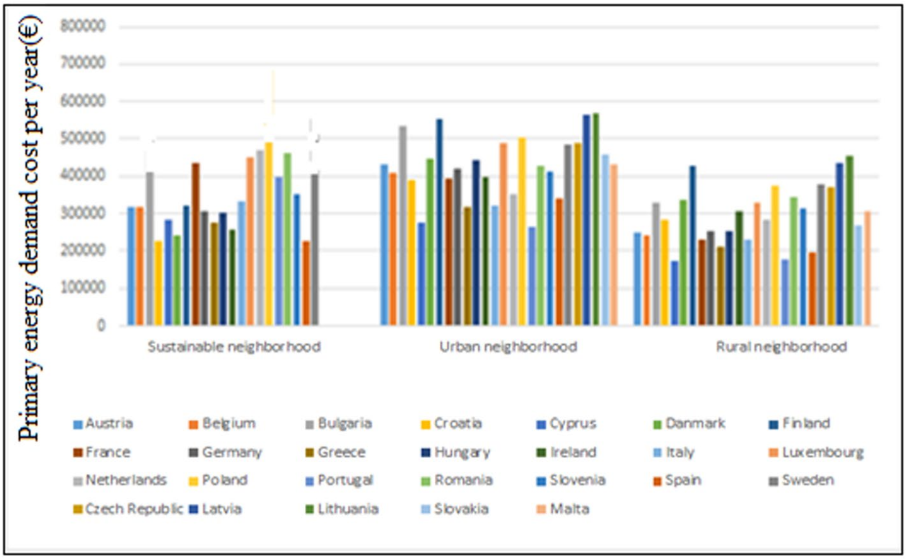

Fig. 7 Primary energy cost per year in the different districts in the EU (€)

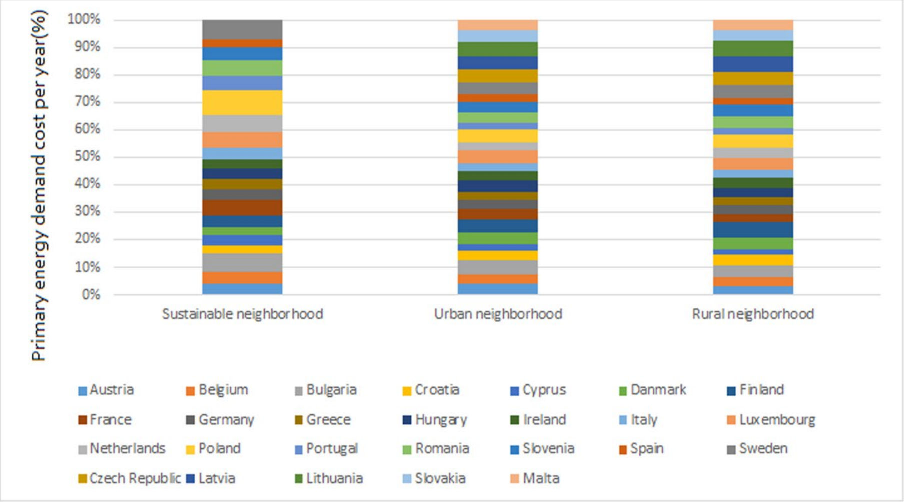

Fig. 8 Primary energy cost per year in the different districts in the EU (%)

Table 2 Monetary indicators (De Nocker et al., 2011)

Ecological parameter	Measurement unit	Cost (€/unit)
Energy consumption	kWh	0.20

CEN (European Committee for Standardization); ECC (*European Consumer Centres); PDF* (potentially disappeared fraction)

Table 3 Comparison of the Findings from this Study with Existing Literature

Environmental impacts	Lotteau et al. (2015)	This research
Primary energy consumption (kWh/m^2/year)	20.5- 461.2	39.4- 120.2

It was noticed that the energy consumption cost was weak in Cyrus, Portugal, France, but high in Poland, Lithuania etc. The energy consumption cost is 30% higher in Urban than rural neighbourhoods.

3.3 Prediction in 2050

State of environmental impact by 2050 are showed in this subsection.

3.3.1 Environmental impact analysis

Figure 9 shows the prediction in 2050 of the energy demand of the two studied neighbourhoods.

Table 4 Concentration of energy demand per area in some countries

Countries	Sustainable neighbourhood Energy demand (kWh/year/m^2)		Rural neighbourhood Energy demand (kWh/year/m^2)		Urban neighbourhood Energy demand (kWh/year/m^2)	
	living area	Floor area	living area	Floor area	living area	Floor area
Austria	241.6	55.0	505.5	-	719.4	70.5
Belgium	166.6	55.1	483.3	-	697.2	68.4
Bulgaria	394.4	89.7	630.6	-	950.0	93.0
Croatia	172.2	39.4	461.1	-	819.4	80.2
Cyprus	216.7	49.1	322.2		494.4	48.6
Denmark	183.3	41.8	525.0	-	972.2	95.3
Finland	244.4	55.4	650.0	-	1224.3	120.2
France	330.5	75.1	463.9	-	666.7	65.3
Germany	252.8	52.8	491.7	-	727.8	71.4
Greece	211.1	47.8	375.0	-	605.6	59.3
Hungary	230.5	52.2	522.2	-	727.8	71.3
Ireland	194.4	44.3	469.4	-	877.8	86.1
Italy	252.7	57.5	377.8	-	663.9	65.1
Luxembourg	341.6	77.9	572.2	-	944.4	92.5
Netherlands	358.3	81.3	416.7	-	816.7	80.05
Poland	519.4	118.1	594.4	-	1075.0	105.2
Portugal	300.0	68.4	311.1	-	505.5	49.5
Romania	350.0	79.61	502.8	-	988.89	96.9
Slovenia	266.7	60.9	538.9	-	905.6	88.77
Spain	172.2	39.4	400.0	-	563.9	55.3
Sweden	419.4	95.58	572.2	-	1088.9	106.7

We can see that energy demand is expected to be over the mean in France, Bulgaria, Poland, Romania and Lithuania in Urban neighbourhoods. An increase of 34% in urban than sustainable districts is noticed in 2050.

3.3.2 Environmental cost analysis

In Fig. 10, it can be observed that energy demand cost varied between185771.4€ and410814, 3€ in sustainable districts; and, from 204,446, 6€ to 511,460, 2€ in urban districts. The average energy demand cost is estimated to be 290,500.9 €, and 387,514, 8 €, in sustainable, and urban neighbourhoods, respectively. This means that, if nothing were done to limit the evolution of the climate, in 2050 the energy cost is expected to be 33.3% higher in urban than sustainable districts.

The energy cost should increase to 21.0% in sustainable districts, and 9.3% in urban districts in the next decade (2050), compared to the concentration obtained currently.

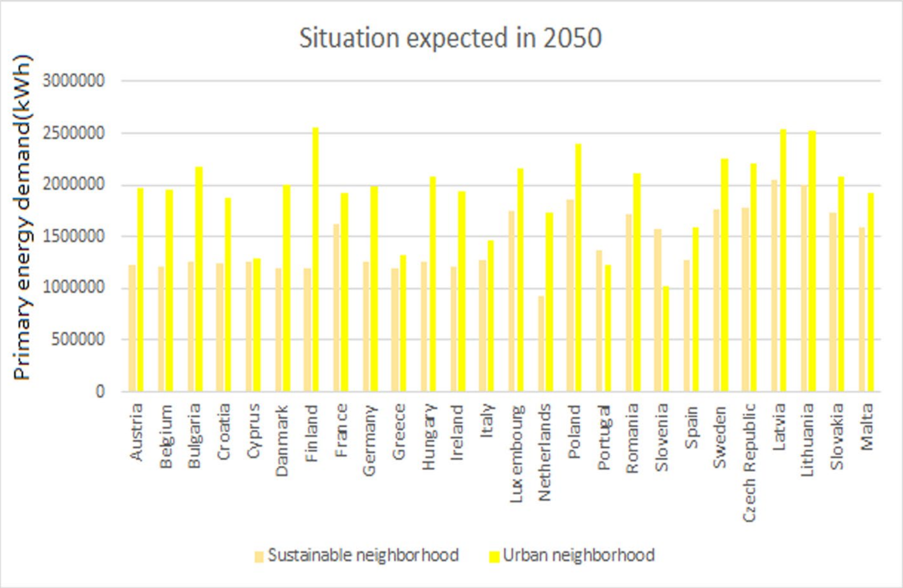

Fig. 9 Energy demand in sustainable and urban neighbourhoods in 2050

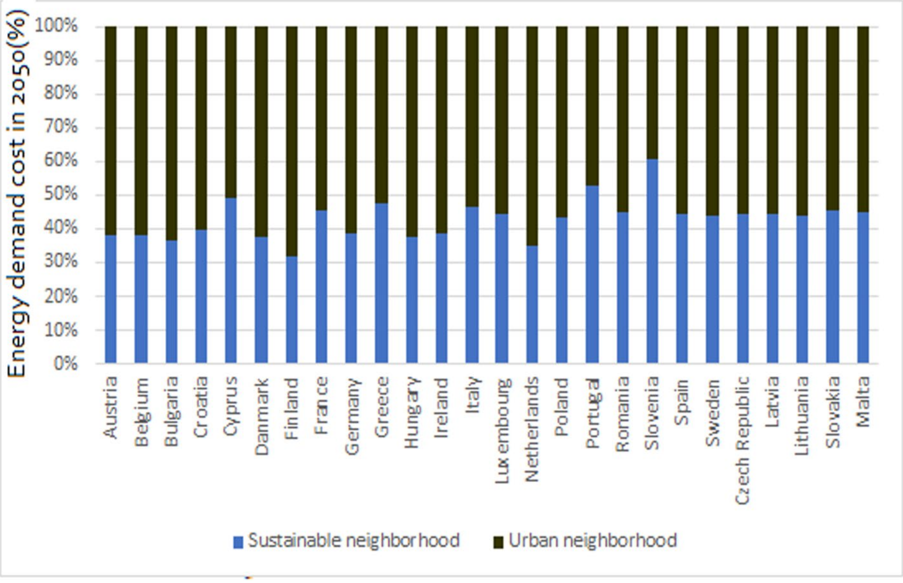

Fig. 10 Variation of energy emission cost in 2050 in different countries of the EU

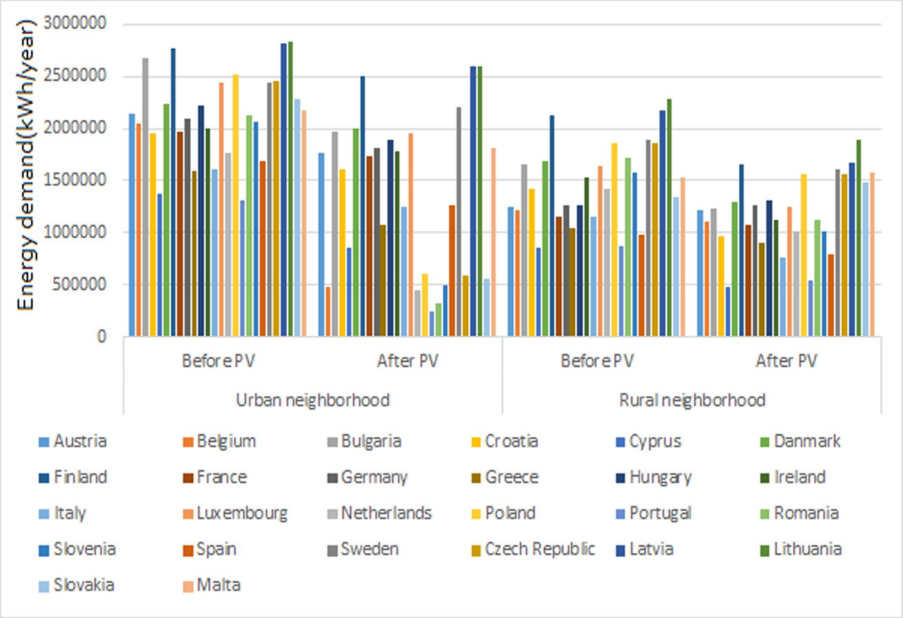

Fig. 11 Variation of energy demand after installing PV in urban and rural districts in EU countries

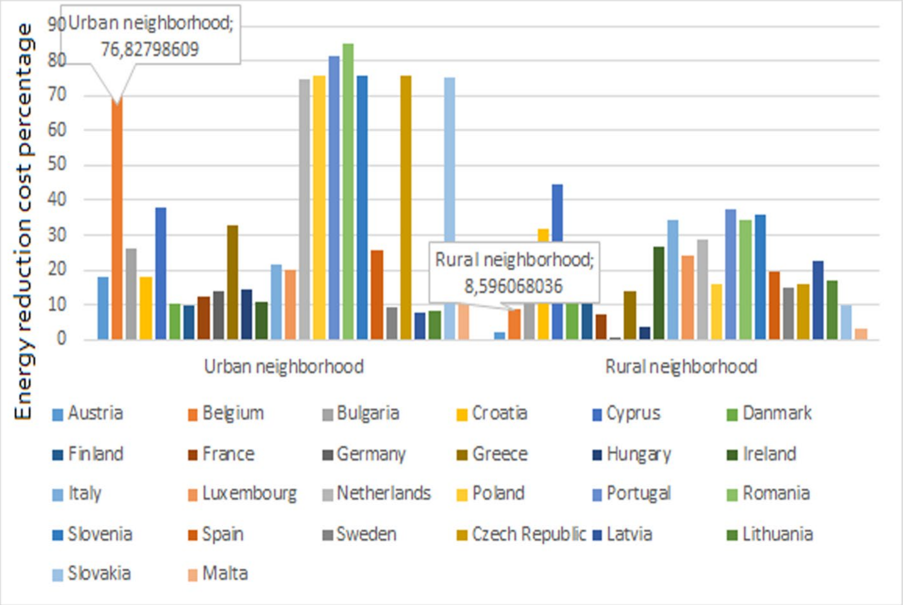

Fig. 12 Energy reduction cost in different countries (%)

3.4 Mitigation strategies: Impacts of Photovoltaic panel

This subsection analyzes how photovoltaic (PV) systems influence the overall energy demand within the district.

3.4.1 Environmental impact analysis

In addition, after installing PV, the energy demand decreased by average of 26.7% in both districts, either, only 18.8% in the rural districts, and, up to 34.5% in the urban neighbourhoods as shown in Fig. 11.

3.4.2 Environmental cost analysis

The cost of energy demand decreased on average to 28% in both districts, either a distribution relative to 35.9%, and 20.1%, in urban and rural neighbourhoods, respectively (see Fig. 12).

Globally, the cost of the reduction of the energy demand after using PV was 10.3% (in Austria), 42.7% (in Belgium),16.9%(Denmark), 16.1%(Finland),9.7%(France), 7.2%(Germany), 23.3%(Greece), 28.0%(Italy), 45.9%(in Poland) etc.

3.5 Mitigation strategies: mixed scenario

In this section, we applied a mixed scenario, which mean:(Global warming + heavy renovation of all buildings (100%) + 100% electric cars – solar panels). As detailed in Fig. 13, the implementation of a mixed scenario will allow2050 to reduce on average 92.6% of total

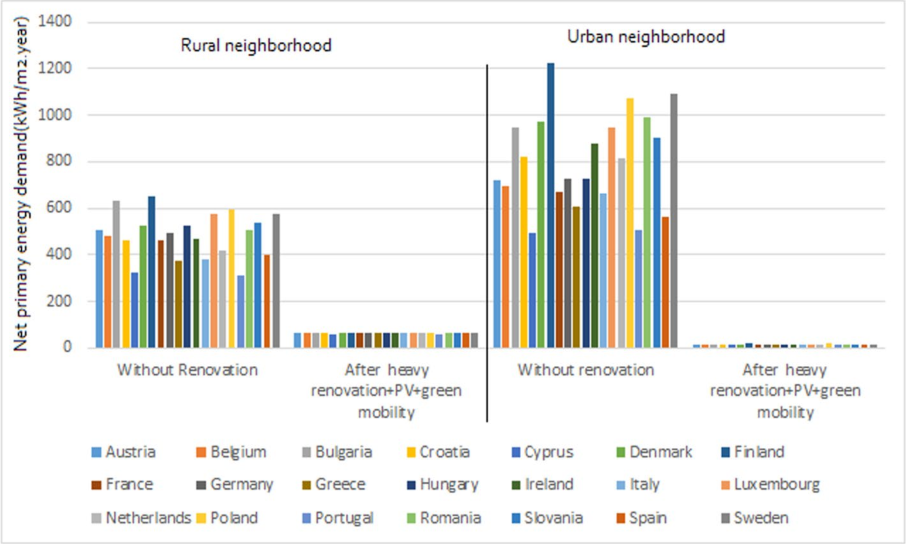

Fig. 13 Variation of energy demand after applying mixed scenario in urban and rural districts

Table 5 Reduction (in percentage) in total energy consumption cost (buildings + transport – local renewable energy) based on mixed scenario applied in some EU countries in 2050

Countries	Rate of reduction of total energy consumption cost(buildings + transport – new local renewable energy)
Austria	92.7%
Belgium	92.5%
Bulgaria	94.0%
Croatia	92.3%
Cyprus	89.4%
Denmark	93.1%
Finland	94.1%
France	92.3%
Germany	92.7%
Greece	90.8%
Hungary	93.0%
Ireland	92.5%
Italy	90.9%
Luxembourg	93.6%
Netherland	91.6%
Poland	93.8%
Portugal	89.1%
Romania	92.9%
Slovenia	93.2%
Spain	91.1

energy consumption (in both districts), either, 98.3%in urban, and, 87.1% in rural districts, compared to the reference year.

The mixed scenario allows to achievement of nearly zero-energy in 2050 at the neighbourhood scale, considering energy consumption by buildings and daily mobility. This scenario should be recommended and applied in our different urban and rural neighbourhoods located in European Union countries to stabilize the temperature around 1.5 °C. Table 5 summarises the percentage of cost reduction of energy consumption in some European Union countries.

More than 90% of environmental cost is expected to be reduced in 2050 by applying this scenario in urban and rural neighbourhoods (see Table 5).

4 Discussions

This section is organized into three subsections, each corresponding to a specific scenario examined in the study.

4.1 Confrontation between environmental impacts from initial districts

The authors noticed the very strong participation of the mobility component and the household waste management component in LCA at the neighbourhood level. In addition, the average energy consumption (in living area) is estimated to be 277.1kWh/m^2.year in the

Table 6 Variation of concentration of energy and cost in the three neighbourhoods located in some European Union countries

Countries	Sustainable neighbourhood		Rural neighbourhood		Urban neighbourhood	
	Primary energy consumption (kWh/year)	Primary energy consumption-cost (€)	Primary energy consumption (kWh/year)	Primary energy consumption-cost (€)	Primary energy consumption (kWh/year)	Primary energy consumption-cost (€)
Austria	1,589,943.2	317,988.6	1,249,765.5	249,953.1	2,148,444.9	429,688.9
Belgium	1,593,462.7	318,692.5	1,212,418.0	242,483.6	2,047,541.3	409,508.2
Bulgaria	2,592,687.4	518,537.4	1,648,749.3	329,749.8	2,674,682.5	534,936.5
Croatia	1,140,214.6	228,042.9	1,421,616.9	284,323.3	1,956,618.4	391,323.6
Cyprus	1,420,450.2	284,090.0	860,748.5	172,149.7	1,374,127.6	274,825.5
Denmark	1,209,290.2	241,858.0	1,688,746.8	337,749.3	2,234,984.5	446,996.9
Finland	1,602,490.6	320,498.1	2,130,992.0	426,198.4	2,766,413.8	553,282.7
France	2,170,886.8	434,177.3	1,157,812.0	231,562.4	1,970,507.4	394,101.4
Germany	1,526,059.4	305,211.8	1,265,871.2	253,174.2	2,093,538.9	418,707.7
Greece	1,383,330.5	276,666.1	1,050,408.4	210,081.6	1,587,846.0	317,569.2
Hungary	1,508,839.8	301,767.9	1,263,665.6	252,733.1	2,214,864.9	442,972.9
Ireland	1,279,774.1	255,954.8	1,526,198.3	305,239.6	1,995,768.7	399,153.7
Italy	1,661,249.4	332,249.8	1,154,275.9	230,855.2	1,602,507.2	320,501.4
Luxembourg	2,252,926.3	450,585.2	1,640,315.9	328,063.2	2,435,838.9	487,167.7
Netherland	2,349,660.4	469,932.1	1,418,644.6	283,728.9	1,764,994.6	352,998.9
Poland	3,413,596.7	682,719.3	1,865,284.4	373,056.8	2,519,764.6	503,952.9
Portugal	1,976,901.9	395,380.4	877,379.2	175,475.8	1,316,874.4	263,374.8
Romania	2,300,776.7	460,155.3	1,717,972.1	343,594.4	2,132,105.9	426,421.1
Slovenia	1,759,580.7	351,916.1	1,573,215.4	314,643.0	2,068,238.7	413,647.7
Spain	1,140,048.0	228,009.6	979,671.7	195,934.3	1,694,577.4	338,915.4

sustainable district; 485.0 kWh/m^2.year in the rural district; and 811.2 kWh/m^2.year in the urban district. So, energy consumption was 65.8% and 40.2%, higher in urban than in sustainable and rural neighbourhoods. We deduce that such as carbon emission, the energy consumption concentration was the highest in urban and the lowest in sustainable districts. This result is not a surprise, in fact, since 2013 the (United Nations, 2013) in a report explained that currently over 50% of the world's population immigrates and lives in cities. This frequency is expected to increase up to 70% in the next decade. Table 6 shows different environmental impacts and costs.

4.1.1 Confrontation between environmental impacts from future districts

The building sector is recognized, to be one of the most consumer-intensive sectors in terms of natural resources, especially fossil fuels. It induces huge environmental impacts at the same period. With reasonably built densities and occupancy rates, the sustainable districts represented an interesting alternative to reach the net zero energy target because of the adaption of this type of neighbourhood to the new climate.

If nothing is done to limit the increase in air temperature, in 2050, energy demand is expected to increase between 30–45%, in sustainable and urban neighbourhoods. This study also explains how a shift in the energy mix towards renewable sources yields important reductions, without effect on daily energy consumption. Our research shows that the

Table 7 The cost increase in 2050 in some European Union countries

Countries	Sustainable neighbourhood	Urban neighbourhood
	Rate of increase oftotal Energy consumption cost in 2050 (%)	Rate of increase oftotal Energy consumption cost in 2050 (%)
Austria	8.6	23.0
Belgium	4.8	24.3
Bulgaria	22.7	51.4
Croatia	4.6	8.4
Cyprus	6.7	11.9
Denmark	11.8	1.6
Finland	8.2	25.1
France	2.1	25.1
Germany	5.3	17.9
Greece	20.0	13.4
Hungary	6.1	17.0
Ireland	2.5	5.1
Italy	9.7	23.7
Luxembourg	12.4	22.5
Netherland	1.4	60.4
Poland	4.9	45.6
Portugal	7.3	30.7
Romania	6.1	25.0
Slovenia	10.7	10.7
Spain	6.9	11.4

carbon emission rate is very high in Poland, Bulgaria, and Romania. These results were not a surprise, it is rather normal, knowing that over 70% of the energy consumed in these countries is generated by fossil fuels, such as oil, charcoal etc. In countries such as Denmark, Sweden, and Finland, the emission rate is low, which may be because of the large-scale of renewable energy installed to generate energy. In addition, in Germany, France, Italy, and Belgium, the greenhouse gas generated is slightly weak, maybe, because, heating and electricity are in the most case produced by gas, nuclear, and renewable energies. Table 7 shows the increase in carbon cost and energy costs in 2050.

4.1.2 Confrontation of environmental impacts after applying PV

As explained in the last chapter, after applying PV on the building roof in urban and rural neighbourhoods, the energy demand decreased by around 21.7%, in both districts. This result is very important; this means that we could reduce more than a quarter of energy consumption in some cities located in EU countries just by using PV. The implications are direct on environmental costs. In EU countries, the part of renewable energy in energy consumption increased between 9.6% by 2004 and 22.1% by 2020, thus exceeding the EU target which was to reach up to 20% of renewable energy mix in most of EU countries in 2020 (Nematchoua et al., 2020b) This result is appreciated, although a lot needs to be done to significantly reduce the rate of carbon emitted. The increase in the renewable energy mix in 2020 was partly prompted by the decrease in the consumption of fossil fuels because of the COVID-19 pandemic. So, the new EU target for 2030 is set to reach up to 32% of renewable energy.

It was noticed that in 2020, renewable energy represented up to 60.1% of the energy mix in Sweden, 43.8% in Finland, and 42.1% in Latvia. In contrast, only 10.7% in Malta, 11.07% in Luxembourg, and 13.0% in Belgium (Eurostat, 2023).The big difference comes from the endowment of natural resources such as the sun, Wind Sea etc. It was very interesting to notice that from 2004 to 2020, seventeen countries in the EU have at least doubled their share of renewable energy in the energy mix. The Table 8 shows the share decrease of dioxide carbon emission and energy consumption.

Table 8 Percentage of energy consumption after PV in urban and rural districts

Countries	Urban neighbourhood	Rural neighbourhood
	Rate of share decrease of total energy after PV(%)	Rate of share decrease of total energy after PV(%)
Austria	18.1%	2.2%
Belgium	7.6%	8.5%
Bulgaria	26.2%	25.6%
Croatia	17.8%	32.0%
Cyprus	37.7%	44.4%
Denmark	10.4%	23.3%
Finland	9.7%	22.2%
France	12.2%	7.0%
Germany	13.7%	4.9%
Greece	32.6%	13.8%

4.2 Synopsis of the scenario

By executing a hybrid scenario (climate change + comprehensive refurbishment of all structures (100%) + complete electrification of vehicles – photovoltaic integration), as outlined in the preceding section, an average decline of 92.6% in the overall energy requirement is anticipated by the year 2050. This outcome is particularly noteworthy, as it highlights a strategic pathway toward accomplishing the 2050 objective.

More than 90% of expenditures related to energy are projected to diminish by 2050 when this scenario is implemented across both metropolitan and countryside zones. Thorough upgrades of residential infrastructures represent the most impactful measure to significantly curtail energy usage. A similar inference was drawn by various authors (Reiter and Marique, 2012; Nematchoua et al., 2021a, b). Promoting eco-friendly transportation options along with incorporating decentralized renewable energy technologies remain among the most effective methods for realizing the Zero-Energy ambition and achieving carbon neutrality by 2050 (Attia et al., 2012; Nematchoua & Orosa, 2022; Nematchoua et al., 2020b, 2022) (Table 9).

As identified in previous research (Nematchoua, 2020, 2021; Nematchoua & Reiter, 2021), both major and minor retrofitting efforts, when applied at the existing renovation pace, can lead to an energy use decrease of up to 20%. In contrast, a full-scale refurbishment (100%) of housing units can result in a reduction in energy demand of up to 89%.

5 Policy implications

This study highlights several key policy implications derived directly from the simulation and comparative analysis of net-zero energy neighbourhoods in various EU countries. To effectively support the transition toward carbon neutrality by 2050 at the neighbourhood scale, the following evidence-based recommendations are proposed:

Table 9 illustrates in detail the percentage of energy savings under each scenario applied across various EU member states

Countries	Scenario (0') - (initial district): Energy consumption (EC) (kWh. year)	Scenario (1) Percentage of reduction of EC after PV	Scenario (2) Percentage of reduction of EC after (Global warming + heavy renovation of all buildings (100%) + 100% electric cars – solar panels)
Austria	1,699,105.2	10.1%	92.7%
Belgium	1,629,979.6	8.1%	92.5%
Bulgaria	2,161,715.9	25.9%	94.0%
Croatia	1,689,117.6	24.9%	92.3%
Cyprus	1,117,438.0	41.0%	89.4%
Denmark	1,961,865.6	16.8%	93.1%
Finland	2,448,702.9	15.9%	94.1%
France	1,564,159.7	9.6%	92.3%
Germany	1,679,705.1	9.3%	92.7%
Greece	1,319,127.2	23.2%	90.8%

- Urban Planning and Building Renovation: Implement large-scale renovation policies to improve building energy performance. Findings indicate that heavy renovation of all buildings can reduce total energy consumption by up to 93% over the neighbourhood life cycle. Prioritize building envelope improvements, insulation, and passive design strategies, particularly for heating, which accounts for over 45% of operational energy demand.
- Renewable Energy Deployment: Accelerate the deployment of rooftop solar photovoltaic systems, especially in urban areas where the productivity potential is estimated at 22.7%. Integrate renewable energy planning at the district level to maximize on-site generation and reduce dependence on fossil fuels.
- Sustainable Mobility Systems: Promote the full electrification of private and public transportation within neighbourhoods. The study demonstrates that using 100% electric vehicles significantly contributes to reducing emissions and energy demand. Redesign neighbourhood layouts to support soft mobility (cycling, walking) and reduce transport-related energy consumption, which comprises 60% of total energy demand when combined with waste management.
- Material Circularity and Green Infrastructure: Encourage the use of sustainable and recycled building materials as part of national construction standards. Foster urban greening strategies such as increasing green areas, green roofs, and walls, which contribute to passive cooling and improved microclimates.

Each of these policy actions is critical to ensure that EU countries can meet their net-zero energy and carbon neutrality targets efficiently and equitably. The results of this study provide a concrete basis for tailoring national and regional policy instruments that align with the EU Green Deal and climate resilience goals.

6 Conclusion

This research evaluates the potential to propose a unified roadmap toward net-zero energy neighbourhoods across European Union countries. The same reference neighbourhood was simulated in various EU countries by modifying four key parameters: energy mix, local climate, building materials, and mobility models. The results of this life-cycle assessment revealed the following key insights: The energy demand associated with transport and waste management during the use phase accounts for approximately 60% of the district's total life-cycle energy consumption. Heating represents more than 45% of the operational energy use, while over 80% of the total energy is consumed during the neighbourhood's use stage. Energy consumption in urban neighbourhoods is 65.8% higher than in sustainable ones, and 40.2% higher than in rural ones, confirming that urban areas demand the most energy, whereas sustainable districts consume the least. Sustainable neighbourhoods demonstrate between 30–45% lower energy consumption compared to conventional districts found across EU countries. The average photovoltaic panel productivity in urban districts is estimated at around 22.7%. A strategic combination of global warming mitigation policies, full-scale building renovation (100%), complete electrification of transportation, and widespread deployment of solar panels could potentially reduce total energy consumption by more than 93% at the neighbourhood level. These findings emphasize the urgent need for coordinated efforts across EU countries to adopt this comprehensive strategy over the next decade. In addition to the proposed scenario, complementary technologies and approaches such as energy efficiency measures, heat pump installation, sustainable construction materials, passive design strategies, wind turbines, green roofs and walls, circular economy principles, optimized building orientation, shading systems, and increased green spaces can further enhance sustainability and climate resilience at the neighbourhood scale. This study is limited to European countries with predominantly temperate climates. Future work will extend this research to examine the applicability of similar strategies in hot-climate regions such as Asia and Sub-Saharan Africa.

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Data availability The data can be available at the request of the reader.

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