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The Zero-Energy Idea in Districts: Application of a Methodological Approach to a Case Study of Epinlieu (Mons)

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Abstract: Rapidly increasing global energy demand has raised concerns about the exhaustion of energy resources and the consequent heavy environmental impact. Improving energy efficiency in cities comprises an initial measure for addressing these phenomena. Within the current context of globalization, EU initiatives and policy targets have been proposed in order to revise urban development strategies and motivate its member states (MSes) toward “zero-energy objectives”. Providing a methodological approach with a simulation district analysis, the present article summarizes how this challenge was analyzed in an existing district in Belgium. This study contributes to the scientific discussion by analyzing the applicability of a holistic approach to zero-energy objectives on a larger scale.

Keywords: case study; district; energy; structure; zero

1. Introduction

In the aftermath of the first two energy crises in 1973 and 1978, Europe intensified the effort to become gradually independent of fossil fuels [1]. During the last two decades, primary energy has grown by over 40% and CO_2 emissions by 43% [2]. Over 60% of global energy demand is consumed in contemporary cities [3]. Lhendup et al. [4] have explained the importance of this demand as a critical factor for the economic and sustainable development of modern cities [5].

A major part of the world’s population lives in cities, where economic, social, and environmental processes affect human societies with a significant impact. The implications of this urbanization, both in terms of resources and living conditions, are numerous. Cities, as living organisms with dynamic and continuously changing processes in their systems, increase their demand in energy progressively, which constitutes a threat of resource exhaustion [6,7].

Transformations of modern cities in order to “mitigate” the disastrous consequences of climate change require a combination of initiatives and policy targets in existing environments and create numerous challenges [3]. Through a static interpretation of modern phenomena in urban development, planning “smartly” demands allocative decisions to ensure the livability of modern cities.

To this end, European directives and initiatives have pertained to the energy performance of buildings and targets to identify the characteristics of their corresponding demand ([8,9]). Already in 2008, policy targets regarding the 2020 climate energy objectives had been introduced (20 20 20): a 20% reduction in Greenhouse Gases (GHG) emissions compared to 90s levels by increasing the share of EU energy performance derived from renewable resources at 20% with a parallel improvement of 20% in the EU's overall energy efficiency [10].

1.1. Objectives of the Research

In particular, the objectives of this research were the following:

- To expand the zero-energy concept from buildings and investigate its applicability to larger territorial scales;
- To simulate the analysis and modeling of Net-Zero Energy District(s) (NZED) models, testing various indicators and interconnections between them;
- To introduce and apply a methodological approach in a real case study and consider the perspectives for its future transition within the zero-energy objectives.

1.2. Structure of the Paper

The paper is structured as follows: Section 1 introduces and describes the problem as well as the objectives of the research. Section 2 highlights the importance of the urban structure for the reduction of the energy demand/consumption of its users. Section 3 presents the main issues of the methodological approach (Urban – Zero Energy District) (U-ZED). Section 4 provides the main findings and results of the U-ZED methodology application in the district of Epinlieu in Belgium. Section 5 summarizes the main conclusions of the work.

2. Energy and Urban Structure: A State-of-the-Art Analysis

2.1. Literature Review and Previous Works

Girarbet [1] highlighted "energy management" as a priority in future urban development. Große et al. [2] cited the interrelation between urban structure and energy as a key perception in climate policies. Owens [3], Salat [4], and Ewing and Rong [5] analyzed the influence of density, architecture, and urban structure in energy consumption. One of the first in-depth studies in this field was conducted by S. Owens [3], with an identification of the energy-efficient attributes in a spatial structure (Figure 1). Owens argued that factors of the energy inventory (resources) and the geometry determine requirements and final energy consumption.

Owens [11] further attempted to quantify the magnitude of the KPIs of the urban structure (Figure 2) and their potential and implications for energy consumption.

Newman and Kenworthy [10], in their work "Gasoline Consumption and Cities: A Comparison of U.S. Cities with a Global Survey" (1989), explained how geographical factors influence energy consumption. In this work, the authors suggested that in world cities, the index of per capita fuel use is inversely related to GDP, expressed by an exponential function. Urquizo et al. [6] explained the reasons why we search for energy use, considering cities as a significant proportion of the world's energy consumption. Baker and Steemers [7] considered the overall impacts of the urban form on building energy. Miller [8], referring to "building morphology", reflected the geometry of a building related to its consumption [9].

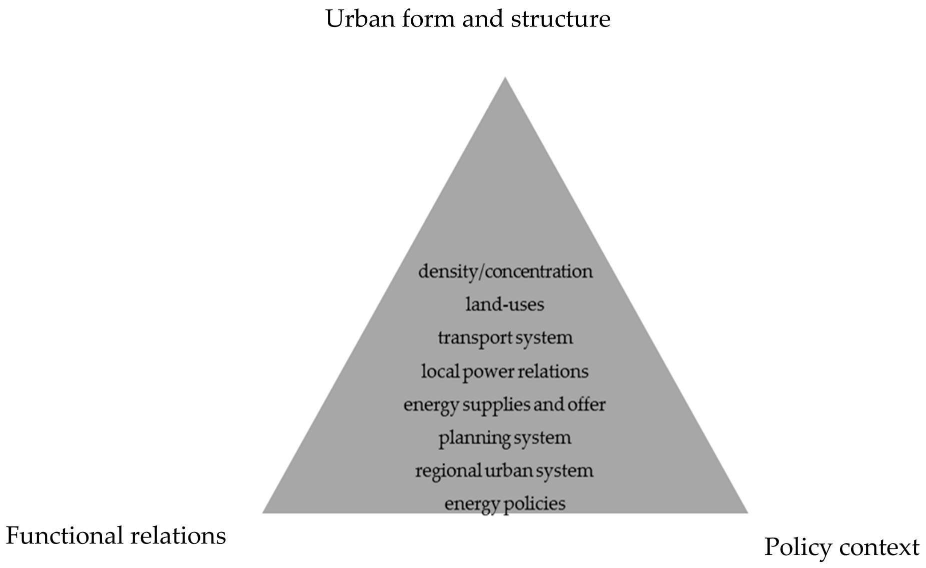
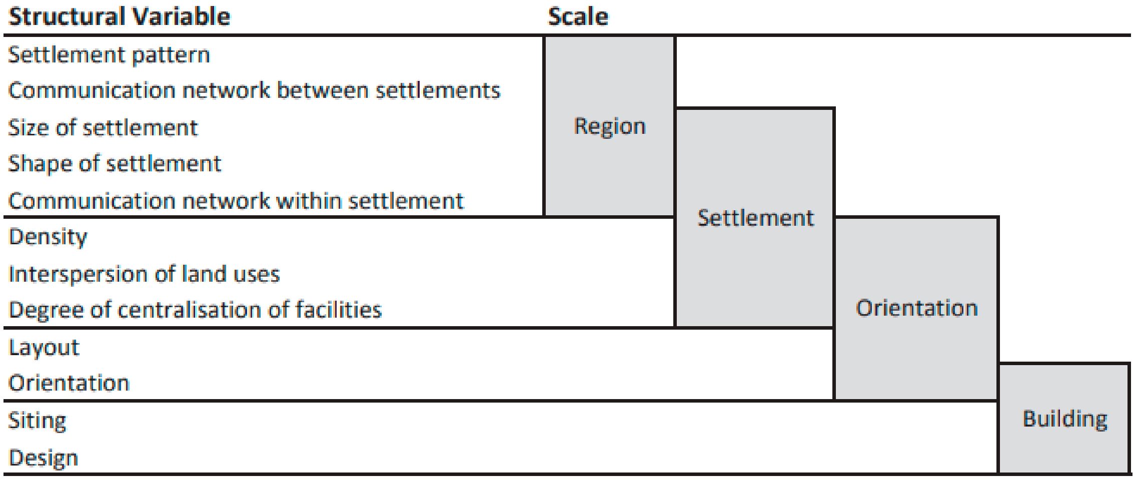


Figure 1. Urban form/spatial structure, functional relations, and policy context as interrelated dimensions.



Structural Variable	Scale
Settlement pattern Communication network between settlements Size of settlement Shape of settlement Communication network within settlement	Region
Density Interspersion of land uses Degree of centralisation of facilities	Settlement
Layout Orientation	Orientation
Siting Design	Building

Figure 2. Urban structure variables affecting energy at diverse urban scales.

On the other hand, the relation of "building density" and "energy consumption" is represented in various illustrations across academic manuscripts. Steemers [10] stated a potential of 50% reduction in heating requirements by increasing building density. Ewing and Rong [5] concluded that households living in low-density areas consume more than 50% of their energy for space heating and more than 20% for cooling compared to multifamily households in high-density zones. Generally speaking, their literature review investigated energy issues at a district scale by focusing on the impacts of urban structure on energy consumption in buildings [7].

3. Methodological Approach

3.1. The "Zero-Energy" Concept

In literature and academic manuscripts, the "zero-energy" objective has mostly been considered on a building scale. Broadly, the Zero Energy Building ("ZEB") is presented as *"a general concept* *including autonomous buildings not connected to energy grids"* [11]. The term Net Zero Energy Building (NZEB) underlines *"the fact that there is a balance between the energy taken from and supplied back to the grids over a period of time (nominally a year)"* [11].

The deployment of the concept has attracted the attention of scholars and the research community because of its mandatory performance from 2020 onwards [12]. Significant work has been done on providing a definition ([11], [13], [14]). The concept assesses the application of the zero-energy concept on larger scales essentially related to the reduction of the energy demand to almost "zero" coupled to the energy supply from renewable resources [12].

A first proposal to define the zero-energy concept in communities, found in Carlislie et. al. [15] argued that "an NZED reduces the requirements in energy through efficiency gains, such as the balance of energy for vehicles, thermal and electrical energy within the renewable local resources". Marique et al. [16] adapted this definition to consider the energy produced in a district as the sum of the needs for every single building and mobility. An Energy Performance of Buildings Directive (EPBD) [17] assumed that a "Nearly Zero Energy District is a delimited part of a city having high energy performance with the zero or very low amount of energy covered to a great extent by local production". Amaral et al. [18] considered that NZEDs are not a sum of Net Zero Energy Buildings NZEBs but a group of buildings with different consumptions whose overall balance reach almost zero.

3.2. The Role of the District

Through the constructive elements of a city [19] the district identifies patterns of energy consumption and seeks concrete "planning" solutions. The district is regarded as an appropriate scale incorporating the components that facilitate the application of optimization tools, thereby improving the energy performance and the local energy production (by Renewable Energy Sources (RES) by minimizing the requirements and the cost for infrastructure [20]

Jenks and Dempsey [21] defined the "district" as an *"element of geographical boundaries and cultural attributes"*. Barton et al. [22] focused on spatial aspects, considering a "district" to be the area of distinctive identity of a city. Amaral et al. [18] referred to the "district" as "a representation of new interests and an intermediate scale in urban strategies towards the 'smart cities'.

Another advantage of a district level is the diversity in load in supplementary energy savings by creating opportunities for heat recovery. The district is a more advantageous scale than individual buildings for managing aggregate loads and interactions with the power grid [23].

For this study, the district is understood as an "urban block" and a complicated system with diverse key parameters of its "internal" and "external" environment, including mobility, human factors, exchanges of services between other districts in a city, etc. (Figure 3). Figure 3 introduces the "definition" and the understanding of a district for the application of the U-ZED methodology. In particular, the district is defined as in a 'systemic approach', in which the interrelations between its diverse elements exist in a dynamic process as a continuous process of energy consumption and CO_2 emissions. Each district is a "micrograph" and an "individual" component of a city and a complex system with interchanges in services, infrastructure, etc., with the other districts of the same city (× 2, × 3, etc.). A representation of this process is depicted in Figure 3. The systemic approach facilitates the comprehension of the idea in terms of "inputs" and "outputs" and the balance between them (annually).

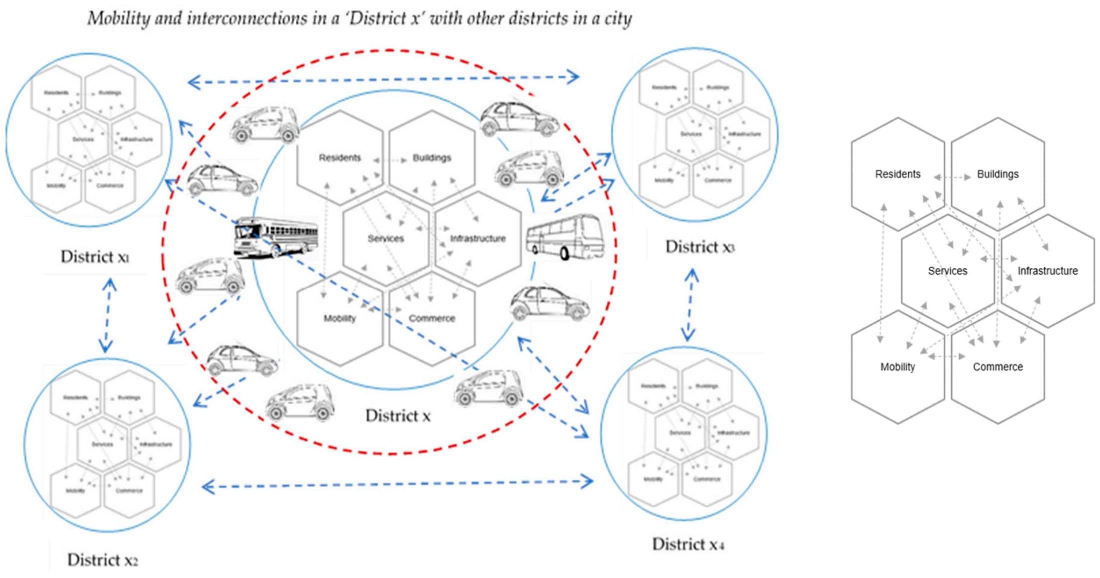
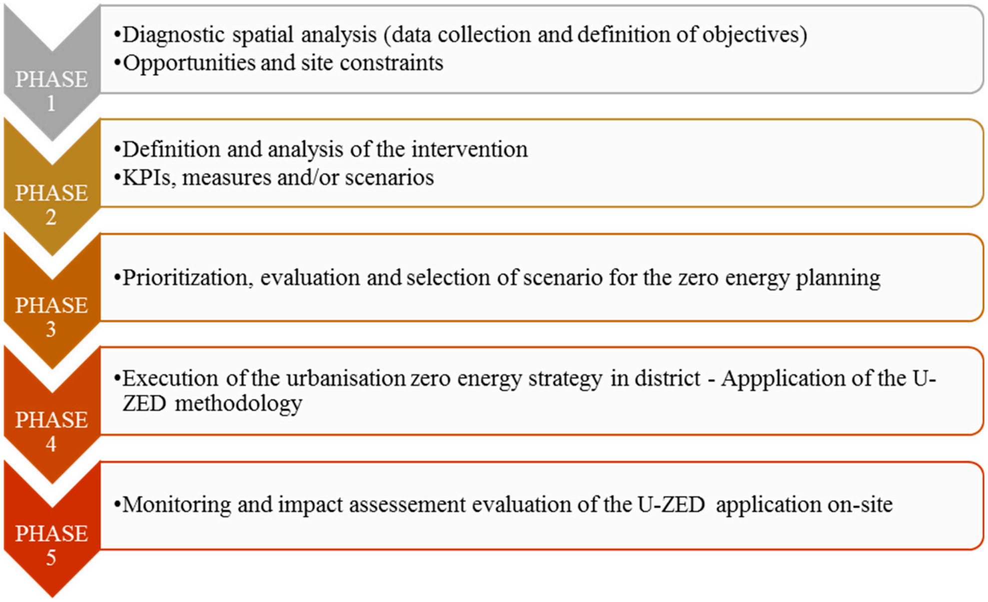


Figure 3. The understanding of the "district" in the U-ZED methodological approach.

3.3. Description of the Methodology and Steps

3.3.1. Development of a Theoretical Model

U-ZED is introduced as a decision-making supporting approach toward the strategies of a city for zero-energy planning in its districts. The methodology was deployed in several phases. Each phase ensured an effective dialogue among all of the city stakeholders and planners to strengthen confidence toward this direction (Figure 4).



- Diagnostic spatial analysis (data collection and definition of objectives)
- Opportunities and site constraints

- Definition and analysis of the intervention
- KPIs, measures and/or scenarios

- Prioritization, evaluation and selection of scenario for the zero energy planning

- Execution of the urbanisation zero energy strategy in district - Appplication of the U-ZED methodology

- Monitoring and impact assessement evaluation of the U-ZED application on-site

Figure 4. The U-ZED approach in phases.

The general idea of the methodology proposed is illustrated in Figure 5.

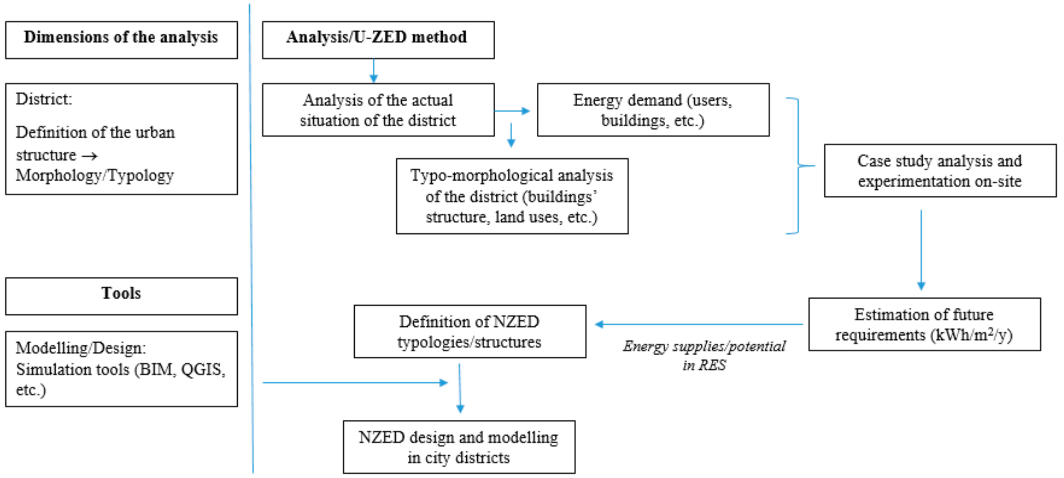


Figure 5. General description of the methodology.

The objective of the U-ZED approach is to develop a comprehensive local planning process in which the challenge of a zero-energy balance (energy demand ≤ energy offer/supply) is shifted from "individual buildings" to larger scales. U-ZED considers the districts as a system in which opportunities for the use of alternative resources are used in local production to balance the demand of its users. The methodology adopted to develop the theoretical and practical frame of the approach consisted of two phases (Figure 6):

A. **Theoretical approach.** This was a diagnostic phase of the current situation in the studied district (description of the parameters of the built and the urban environment, estimation and prognosis for the energy requirements of the users; etc.). For the U-ZED approach, the "problem" has been the outline of the "optimal typo-morphological definition of the district with zero-energy attributes";

B. **Experimental approach.** This was a validation of the criteria on-site and experimentation of the approach in real case studies. Assessing the current situation of the district was the initial phase of the experimentation approach of the case study application. Thus, we analyzed the potentialities with regard to energy, enhancement of mild mobility, etc., and the connection of the existing urban tissue of the city in accordance with the objectives of city planning as a whole.

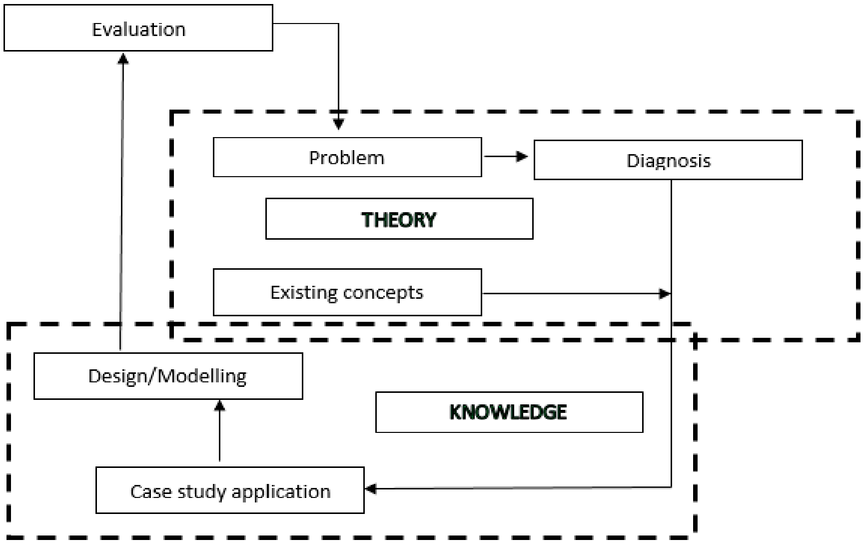


Figure 6. U-ZED concept.

The U-ZED approach focuses on a conception of the district from the early beginning within the zero-energy attributes. A territorial diagnosis, constraints and potentialities, the current situation at the geographical site, and also an analysis of energy requirements are the preliminary steps of the U-ZED approach (Figure 7).

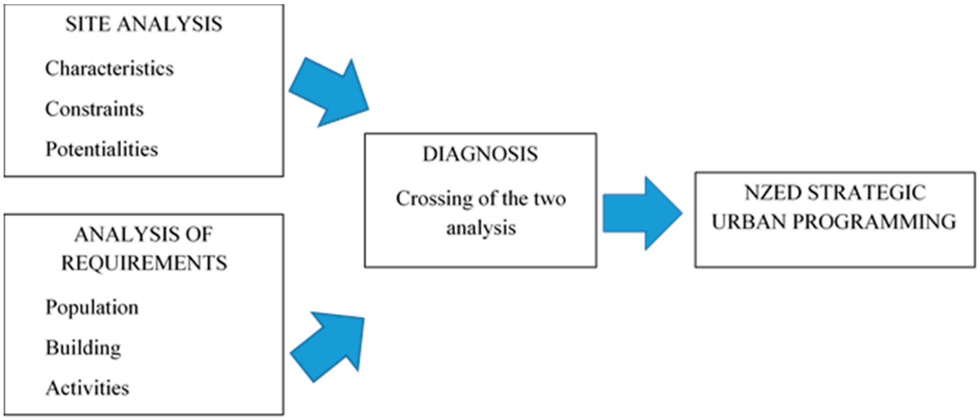


Figure 7. Diagnosis of the U-ZED approach.

The approach was developed in a theoretical frame. Table 1 presents a comparative screening of international scientific reviews, aiming to identify the originality and innovative actions that our approach provides.

Table 1. Methods and tools in the literature to support studies of districts and U-ZED novelty (adapted by [24])

Topic/Field	Objectives	Methods/Tools	Scale	Reference
NZED/ NZEB	Definition proposal for NZED	Hierarchical and qualitative approach	District	[15]
	Assessment of extending NZEB concept to district scale	Dynamic simulations	District	[25]
	Assessment of alternative scenarios for NZED construction	Multicriteria decision analysis	District	[26]
	Optimization of energy systems design toward NZED	Genetic algorithm	District	[27]
Sustainability assessment tools	Analysis of existing sustainability assessment tools	Comparative analysis and data	District	[28]
	Analysis of existing sustainability assessment tools	Comparative analysis and data	Urban	[29]
	Analysis of existing sustainability assessment tools	Top-down and bottom-up models	District	[30]
U-ZED	Development of a holistic theoretical methodological approach at the conception phase with a zero-energy context	Parametrical concept of the NZED with the use of a Geographical Information System (GIS) tool	District	[31]

Three concepts analyze the U-ZED approach in districts: “location”, “typology”, and “morphology” of the built stock (existing). Figure 8 recapitulates the main problems with the feasibility of zero-energy concepts in districts. Another important question is the identification of the building “types” and the land uses of an NZED, as well as other criteria (density, mixing, population, etc.) that will define the energy requirements of users.

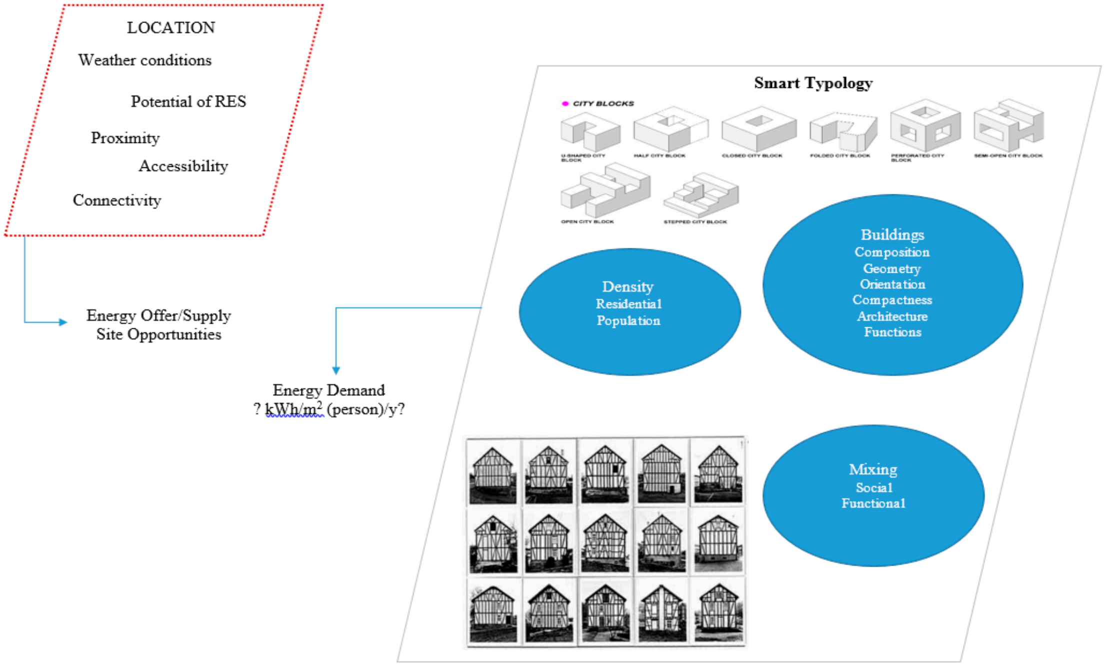


Figure 8. Criteria identification for NZEDs along the axis of "location" and "typology".

In this context, the U-ZED approach studies the possibility of developing a strategic future planning and targets the following:

1 The realization of a "state of place"/description of the actual situation in terms of energy requirements in districts (kWh) by its buildings and users. The first step is the determination of the energy requirements "on-site". To this end, diverse methods are developed with the intention of obtaining an approximation that is more realistic: for instance, real data use considering the real quantities of energy consumption or approximation methods;

2 The policy targets and measurements for urbanization strategies for zero-energy concepts in districts. The second step of the U-ZED approach is the development of scenarios to estimate the future energy requirements of the studied districts and assess the future needs of users related to the existing sources and supplies (Figure 9).

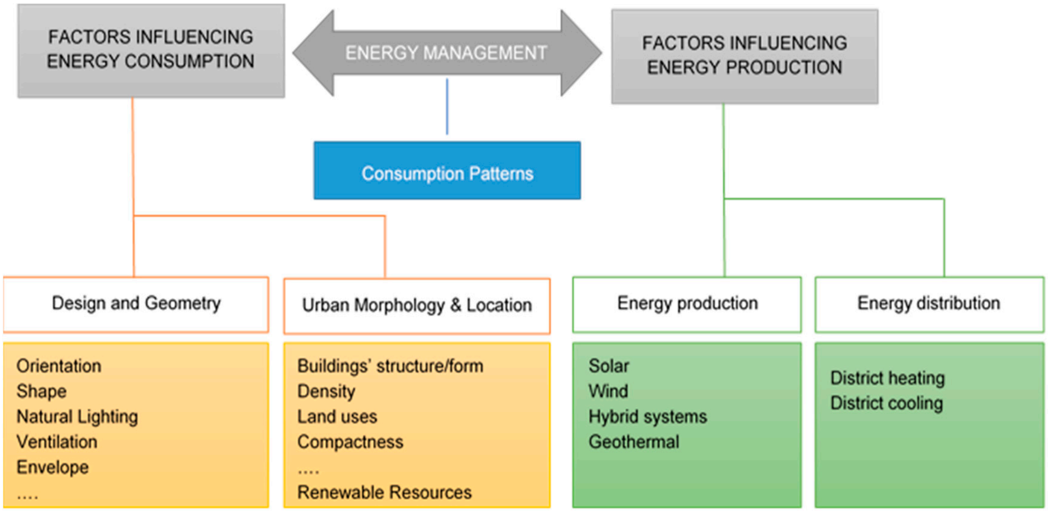


Figure 9. Overall key parameters and criteria influencing the zero-energy concept in districts.

3.4. Key Performance Indicators

KPIs are a concept originating from business administration with the aim to provide tools for measurement in business fields. In reality, they are quantifiable metrics reflecting the performance of achieving wider goals and help in the implementation of different strategies (in our case, the zero-energy planning in districts) [32].

3.4.1. Key Performance Indicators in the U-ZED Approach

Mitchell [9] underlined eight (8) KPIs for building energy consumption, including building consumption, users' activities, urban structure, etc., comparing them to the works of Salat et al. [33] and Ratti et al. [19] (Table 2). Sanaieian et al. [20] highlighted the difficulties in studying the impacts of surroundings on the performance of urban blocks, as they emphasized the complexity of including all conflicting aspects simultaneously.

Table 2. Factors influencing building energy consumption.

Mitchell [9]	**Salat et al.** [33]	**Ratti et al.** [19]
Urban geometry	Urban structure	Urban geometry
Building morphology	Building performance	Building design [7]
Thermal performance of materials	Equipment and system efficiency	System efficiency
Efficiency of internal systems	User/occupant behavior	Occupant behavior
Occupant activities and behavior	Type of energy use	
Internal and external temperatures		

For this study, we considered, as key aspects of the energy performance of NZEDs, site opportunities and attributes, the typo-morphology of the built environment, and the amenities and parameters of the eco-cycle (energy, water, waste). Table 3 lists the KPIs defined in the current study.

Table 3. Key performance indicators (KPIs) in NZEDs.

KPIs	**Criterion(a)**	**Description**	**U-ZED Approach**	**References**
Site opportunities	Location Site topography	Geographical site with a potential for energy resource proximity and city center accessibility	Climate conditions Distance from city center: 3–5 km Distance between the "stops": 200–500 m	[34]
	Mobility	Available public transport	1500 m from IC/IR or less than 1000 m from a local railway station	[25]
		Parking	0.2–0.5 places per dwelling, 500 places of parking in proximity to stations of means of transport	[25]
Resources	Natural resources	Production on-site	Local production by local resources at least 20%	[25]
Site attributes	Surface	Number of ha	-	[35]
	Population	Number of residents	≤5000 inhabitants	[25]
	Dwellings	Number of dwellings	500–2000	[25]
Typology/morphology	Compactness	A dwelling is considered to be semidetached if at least 80% of the area of two of its walls is in contact with a heated area	50% terraced, 30% terraced	[25]
	Density	Dwellings/ha	≥30 dwellings dwel/ha (poles) ≥40 dwel/ha (suburban)	[36]

KPIs	Criterion(a)	Description	U-ZED Approach	References
	Orientation (angle)	Southeast and southwest orientation	50% of the windows to the south, 20% of the windows to the east and west, 10% of the windows to north, forming “L”	[37]
	Functional and social mixing	Mixed-use land uses	15 different services/infrastructure in a perimeter of 1000 m 300 m in proximity to a commercial center 300 m in proximity to a primary school 500 m in proximity to an activity center	[38]
	Social mixing	Number of social dwellings/surface (ha)	15% in social dwellings, 10% of district’s dwellings accessible to “middle” revenues	[38]
	Mixing in Dwellings	Variety of dwellings/land uses in NZEDs	10% studios and/or dwellings of “one room”, 10% of dwellings “two rooms”, 10% of “three rooms” or more, 10% of public dwellings (Ground floor +1) to (Ground floor +5) (max)	[25]
Amenities	Connections to city center	Distances of the NZED from city center	Average distance between 2 and 3 km from the city center for the urban areas and 3 and 8 km from the city center for the suburban areas	[25]
	Green spaces	Expressed in m^2 spaces/number of inhabitants in NZEDs	30% to 50% of the site surface and 30% to 40% in suburban areas	[25]
	Collective spaces	Number of collective (public) spaces in NZEDs	700 m around the site’s limits	[25]
	Infrastructure/services for disable persons	Number of services provided for disabled persons	10% of dwellings accessible to disabled persons	[39]
Energy	Conception of districts with low energy consumption	-	Average consumption: ≤60 $kWh/m^2/y$ (heating) Electricity: ≤20 $kWh/m^2/y$	[40]
	Energy production by renewable energy resources	Maximization of the use of natural resources	Combination of the use of natural resources and the installation of various systems	[40]
Water	Recuperation of storm water	Valorization of storm water	100 lt/day/pers	[40,[41]
Waste	Waste reuse	Valorization of waste	60 m from residential dwellings, 100 kg/person/year	[25],[41]
Systems	“Smart” installation of systems for the reduction of energy consumption	Energy water waste	Heating: solar panels/captures Wind turbines Thermal solar panels Electricity: photovoltaic panels Cogeneration	[40]

3.5. Methods and Tools

In Figure 10, we schematize the general concept of the U-ZED approach. As analyzed above, at the second phase of the U-ZED method, we developed a roadmap toward zero-energy transition in districts with the use of tools and methods, as we will describe in this section.

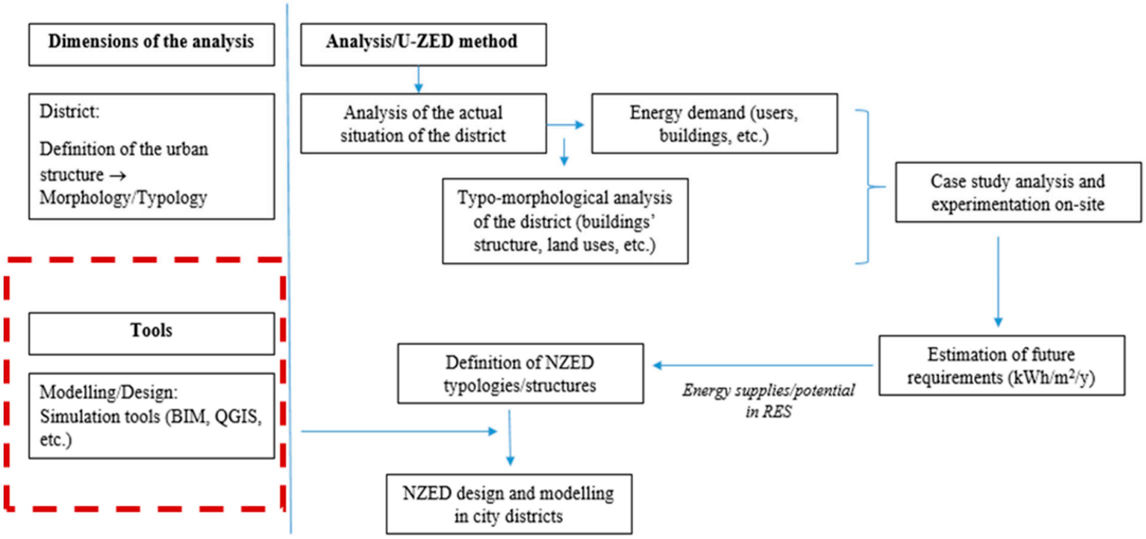


Figure 10. General description of the U-ZED approach.

3.5.1. Quantum Geographic Information System (QGIS) Tool

Chuvieco [42] argued that the association of the spatial optimization models with the use of GIS formulates and develops planning options. GIS is indispensable in a multicriteria decision analysis in providing technical inputs in the selection of planning options among diverse scenarios [43]. As a toolbox, GIS allow planners and architects to perform a spatial analysis with the use of different actions and the integration of diverse factors (Figure 11).

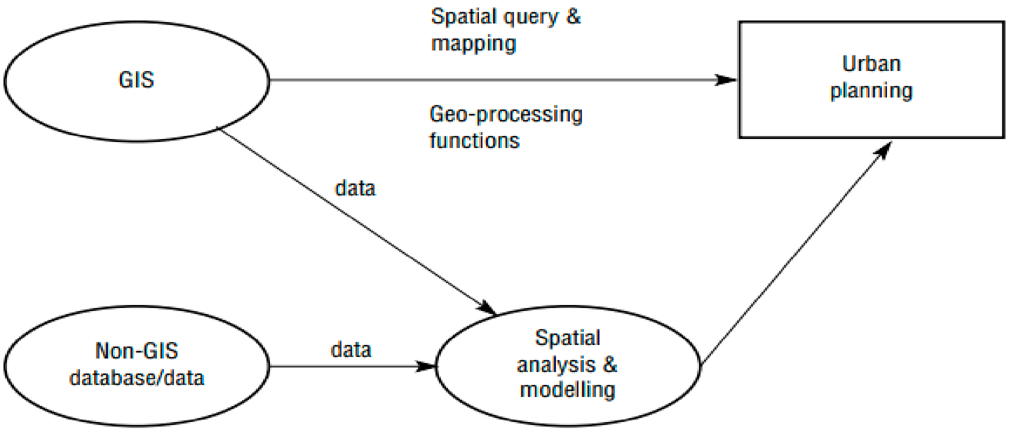


Figure 11. Urban planning and GIS use.

3.5.2. Hybrid Optimization Model for Electric Renewables (HOMER)

Bahramara et al. [44] claimed that HOMER is a powerful tool for energy planning in cities to determine the optimal size of its elements through a techno-economic analysis considering the components as grid-connected. HOMER requires six (6) types of data as input for simulations and optimizations, including meteorological data, load profiles, component attributes included in the design, spatial requirements, and economic and other technical data.

3.5.3. The Method of Degree Days

Karayiannis [45] explained in his work that the method of degree days is mainly used for estimating the heating energy demand in buildings over 70 years. It is expected that the method of degree days provides the smallest contribution of error, while it is important to quantify this contribution. Four main approaches are used for the calculation of degree days:

- Mean daily degree hours, including the integration or summation of hourly records;
- Mean daily temperature from daily maxima and minima;
- Meteorological office equations;
- Hitchin's formula.

For this study, we used the website of the degree days methodology, providing as input the meteorological data of the Uccle Station. The findings of the calculations are provided in Section 4 and Appendix A of this paper.

4. Case Study Analysis

4.1. The Case Study of Epinlieu in Mons: Diagnosis

The district of Epinlieu is situated 2.5 km from the center of Mons with a good proximity to services and infrastructure in its surroundings. In Epinlieu, most of the population is between the ages of 39 and 69, and an important fraction of young people are in the age group of 0–19 years.

4.2. Analysis of the Urban and Built Environment of the District in its Current Situation

Urbanization in the district is being developed along the following axis:a combination of building typologies, including single-family households, terraced houses and apartment blocks with accompanying infrastructure and various services for its residents (Figure 12; Figure 13):

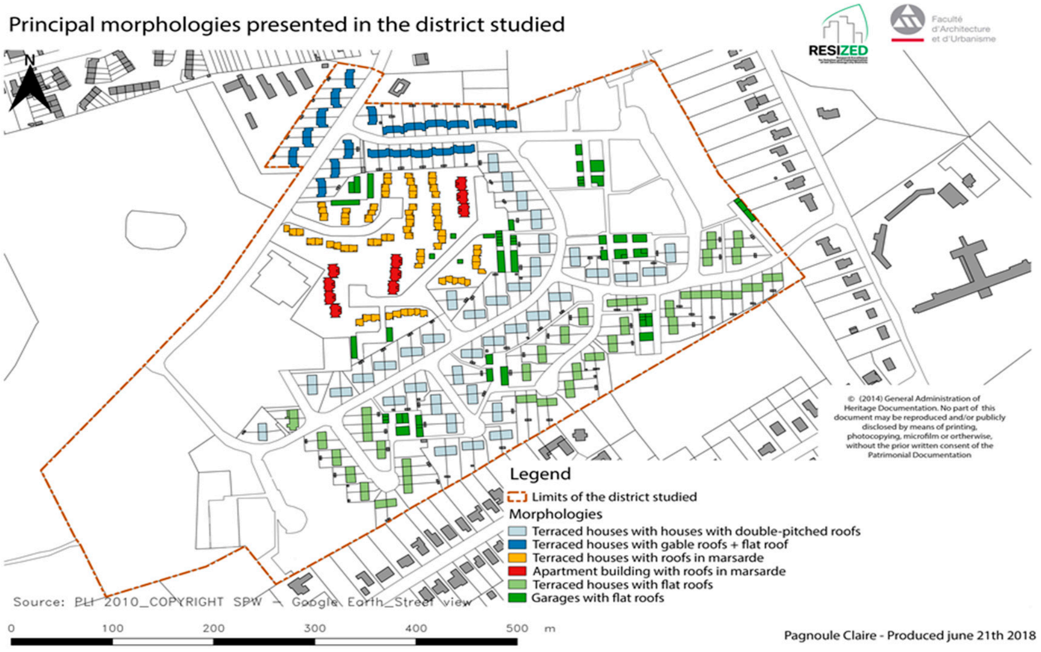


Figure 12. Principal morphologies in the district of Epinlieu (Mons).

The majority of the buildings in the district of Epinlieu were constructed in 1967 for military requirements, with a redevelopment proposed by a "Master Plan" during the 80s in line with Walloon regional directives.

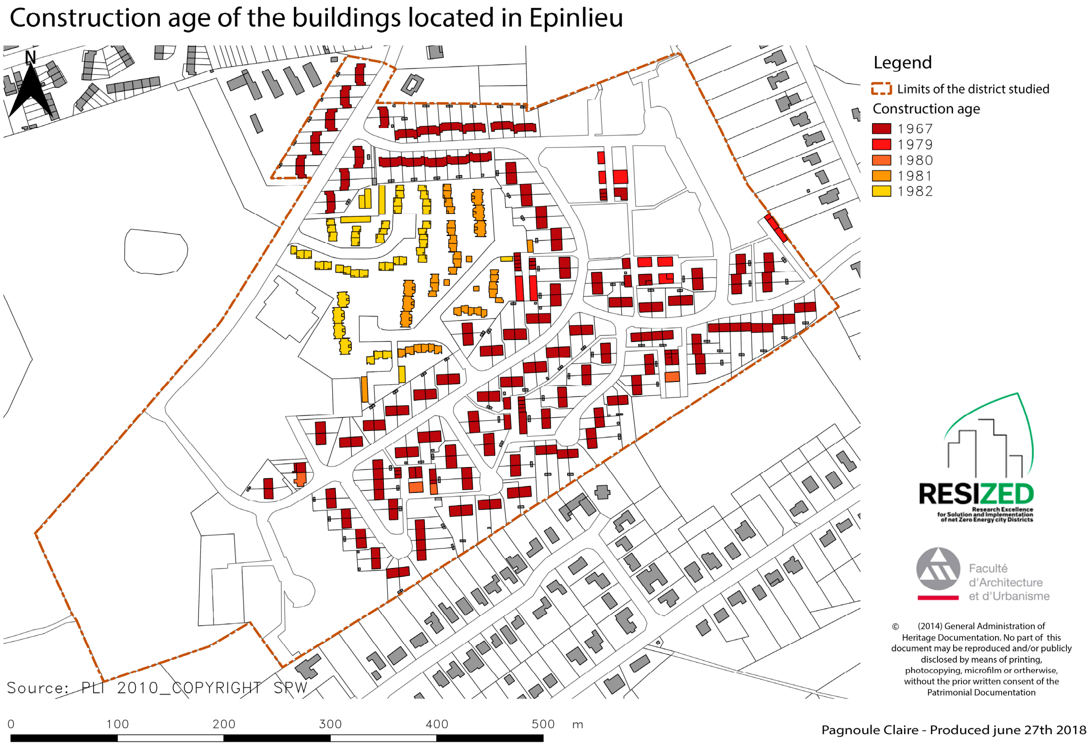


Figure 13. Analysis of the construction age of the built environment.

4.3. Transition toward the Zero-Energy Objectives: The Case Study of Epinlieu (A Focus on Energy Autonomy)

In this section, an estimation of the current space heating energy requirements per building typology in the district is performed based on the "degree days" method. Applying the method to a typical weather profile (meteorological data retrieved from the meteorological station of Uccle, Belgium), we estimated the "heating degree days" for the period 1 August 2017 to 1 August 2018 (Figure 14). For a standard weather profile attributed to the understudy region, a "heating degree days" demand was estimated on an upper and lower boundary. The defined interval accounted for variations of the U-value corresponding to the analyzed building typology, since U-values were imported from 'Typology Approach for Building Stock Energy Assessment' project (TABULA) and introduced to the calculations for the period 1 August 2017 to 1 August 2018. In this direction, it was possible to suggest interventions on the district level aiming to reduce the average heat consumption per dwelling.

Table 4 presents the calculations of the average energy requirements in the district of Epinlieu (kWh). In Appendix A, the authors present the analysis of the energy requirements per each building typology in Epinlieu. The typo-morphologies presented in the district are the following:

- **Type 1.** Terraced houses with gabled roofs (74 dwellings);
- **Type 2.** Terraced houses with flat roofs (70 dwellings);
- **Type 3.** Terraced houses with gabled roofs and parking (40 dwellings);
- **Type 4.** Terraced houses with mansard roofs (70 dwellings);
- **Type 5.** Apartments (10 blocks).

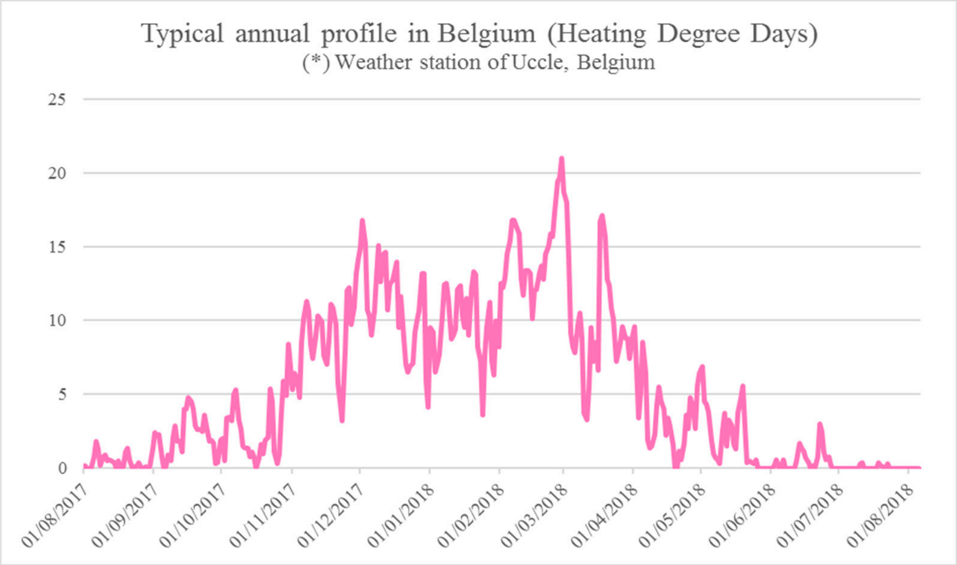


Figure 14. Typical annual profile of heating degree days in Belgium (period: 1 August 2017 to 1 August 2018).

Table 4. Calculations of average energy requirements in diverse typo-morphologies in Epinlieu.

Month	Type 1	Type 2	Type 3	Type 4	Type 5
January	8388.11	70,087.93	85,793.92	208,049.81	132,042.70
February	111,530.12	87,449.17	107,045.62	259,585.08	164,750.53
March	93,693.50	73,463.73	89,926.19	218,070.56	138,402.56
April	46,744.24	36,651.49	44,864.71	108,796.69	69,049.85
May	30,547.77	23,952.07	29,319.48	71,099.59	45,124.69
June	19,681.79	15,432.21	18,890.40	45,809.13	29,073.62
July	15,991.45	12,538.67	15,348.45	37,219.92	23,622.32
August	17,426.58	13,663.93	16,725.88	40,560.17	25,742.27
Sep	37,928.44	29,739.15	36,403.38	88,278.02	56,027.29
Oct	43,873.98	34,400.96	42,109.86	102,116.19	64,809.95
Nov	81,392.38	63,818.60	78,119.69	189,439.85	120,231.55
Dec	97,178.82	76,196.52	93,271.37	226,182.59	143,551.01
Total	**685,377.17**	**537,394.42**	**657,818.96**	**1,595,207.61**	**1,012,428.35**

Figure 15 presents the average calculated energy requirements in the diverse typo-morphologies studied in the district of Epinlieu.

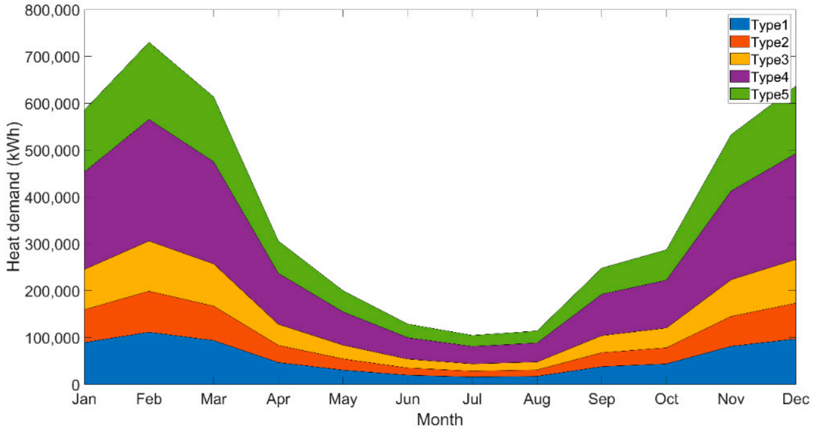


Figure 15. Average energy requirements in the diverse typo-morphologies of the district of Epinlieu.

4.4. Transition to the Zero-Energy Objectives

Following an analysis of the district's heating energy demands, an annual electricity consumption model per dwelling was devised, providing complementary input for sizing future renewable generation solutions. Due to local constraints, large centralized Renewable Energy Sources (RES) unit installations were omitted from this study, since district free construction space would be allocated for functional mixing. As a result, a solution with PV arrays integrated on building rooftops was proposed. Nonetheless, opting to efficiently allocate generated energy, the proposed household system was coupled with an electrical storage component, which counterbalanced intermittent factors in renewable generation, such as discrepancies in solar irradiation forecasted profiles. Furthermore, a criterion of rooftop orientation was set in order to assure an efficient PV generation profile. Hence, only west-, east-, and south-facing rooftops were considered. In turn, garages with flat roof typo-morphologies (as already defined) were excluded due to rooftop installation restrictions.

In the scope of sizing (the solar panel installation per typology), the study included indicators such as the temperature and solar irradiance. Three types of annual loads were calculated per typology based on the average consumption. Energy flow data were provided on an hourly basis for an average year. Specifically, terraced houses with flat roofs and houses with double-pitched roofs were considered as a common typology with respective 5566 kWh/yr consumptions. For types 3 and 46,123 kWh/yr, and finally the large apartment blocks had 22,264 kWh/yr. Figure 16 shows the estimated distribution of annual power consumption per typology in the district of Epinlieu.

Classification of the annual electricity consumption of dwellings per typology

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Figure 16. Analysis of profile of the electricity requirements in Epinlieu.

With the completion of the preprocessing of inputs, the corresponding systems per dwelling category were optimized in terms of net present cost and renewable generation components as well as storage capacity on a 10-year project lifetime. All system configurations considered a grid connectivity option in cases of unmet demand due to generation shortages, in the meantime permitting transactions with the grid operator (i.e., selling stored excess energy).. The NPC (or value) of the system is the present value of all the costs it incurs over its lifetime minus the present value of all the revenue it earns over its lifetime. Discount and inflation rates were set at 2% and 1%, respectively, accounting for a 0.99% real discount rate over the project lifetime. Cost of Energy (CoE) represented the cost of the system per kWh over the project lifetime. Other costs considered were capital costs, replacement costs, and operation and maintenance costs, while cashflows included salvage value in the final year. The rates per kWh were set at 0.275 €/kWh and 0.0116 €/kWh according to the defined tariff policy of Belgium [46]. HOMER ranked all system configurations by the NPC in the optimization results with the PV production per typo-morphology detailed in Figure 17. Thus, it was decided that we should compare the annual nonrenewable electrical consumption per house to the annual generation profile of the proposed renewable generation system. Consequently, the energy saving per household alongside the necessary costs for retrofitting concluded the analysis.

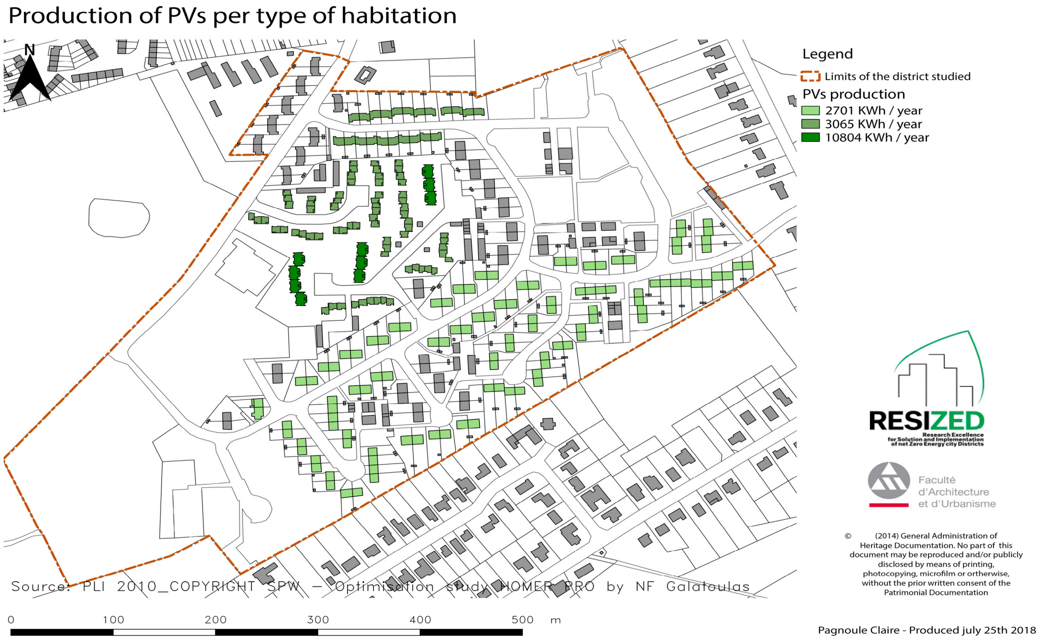

Figure 17. Analysis of PV production per typo-morphology in the district of Epinlieu.

The area size of a 16.7% efficiency PV module (325-W rated capacity) is equivalent to 1.951 m^2 with a 42-g CO_2/kWh carbon footprint attributed to upstream manufacturing processes [47]. It was observed that in the cases of small and average buildings (Table 5), the percentage of annual energy savings was lower than the expected percentage from the simulated PV output. This demonstrated the effect of enabling grid sales on the NPC optimization, which in turn oversized the investigated system as well as the effects of the load following strategies for serving electric loads. Moreover, renewable generation was not aligned with demand (peaks in generation were in the summer, contrary to demand peaks), and therefore the excess energy was either stored in the battery module, with certain losses present, or if a maximum SoC was reached, depleted. Nonetheless, these results yielded the lowest grid purchases in the meantime, maximizing the renewable fraction per system, while similar results occurred when the grid sales option was disabled and a storage module was used, which was in agreement with the relevant KPI defined. Importantly, the retrofitting costs per type of dwelling in terms of initial capital cost were recorded as follows: 9886 € for the small typology, 10,032 € for the medium typology, and 15,454 € for the apartment buildings.

Table 5. Summary of PV installation specifications per building typology.

Household Type	Estimated Annual Electricity Consumption (kWh/yr)	Calculated PV Output (kWh/yr)	PV Installation Surface Area (m^2) Module Size (Peimar SG325P)	Levelized Cost of Energy (€/kWh)	Annual Energy Savings (%)
Small	5566	5763	35.118 (5.72 kW)	0.294	72.2%
Average	6123	5474	33.167 (5.42 kW)	0.290	67.3%
Large block	22,264	14,999	89.746 (14 kW)	0.230	47.2%

Further improvements regarding the sizing of the installations and retrofitting costs can be introduced by disseminating the average annual consumptions according to precise consumption data from smart meters along with detailed occupancy information, extending market research on more efficient and lower cost PV modules and the consideration of switching to energy distributors that provide energy produced from renewable sources [48]. Last, the selection of an efficient electric storage component would raise annual savings and reduce grid dependency.

In Figure 18, the projected amenities of the U-ZED application in Epinlieu are presented. The diagnostic site analysis revealed a dysfunctional district without attractive equipment and with excessive energy requirements. In our proposal, the urban rearrangement of the agglomeration focuses on its functions with new facilities (for instance, an entertainment zone, etc.) with zero-energy standards.

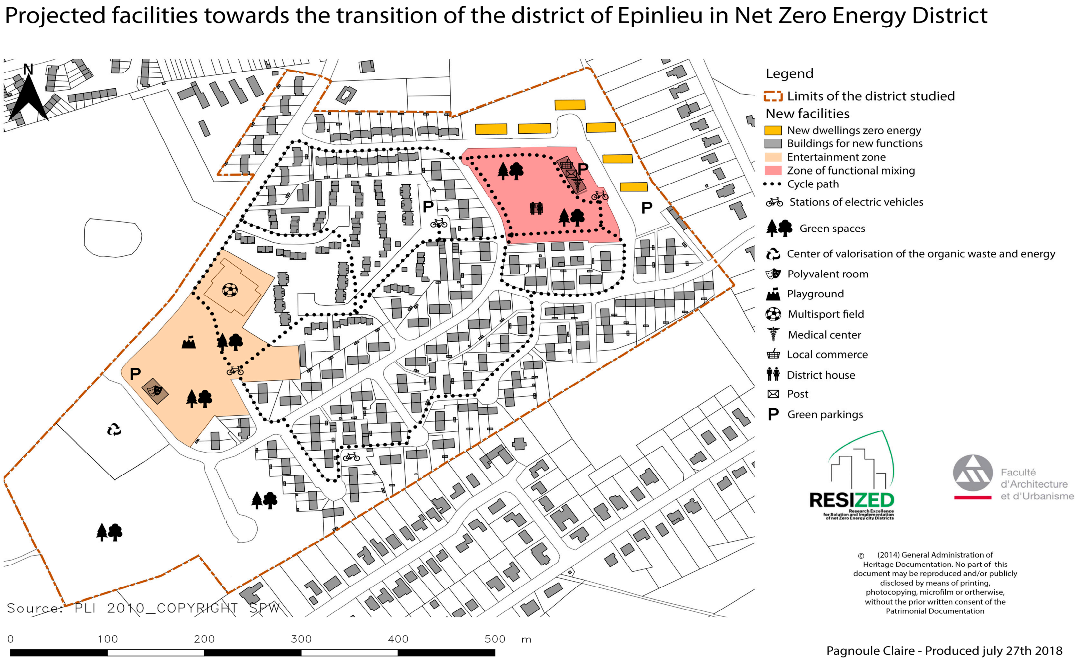

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Figure 18. Projected amenities and facilities for the transition of the district of Epinlieu into a zero-energy concept.

5. Conclusions

Rapidly growing world energy use has already raised concerns over supply difficulties, the exhaustion of energy resources, and the heavy environmental impacts of climate change. Undoubtedly, reducing energy demand has proven to be more difficult than is commonly assumed. Complex systems require necessarily large flows. In this paper, we assumed a correlation between energy consumption and typo-morphological structure in the district of Epinlieu for its transition to a multifunctional and autonomous district.

Various effects and mechanisms of the urbanization process show substantial impacts on urban structures and energy consumption. The current research study investigated the opportunity to extend the "zero-energy" concept to larger territorial scales by proposing a theoretical approach with spatial dimensions for the "optimal" structure of a district. Although the idea can be conceptualized in a district with an approach similar to individual buildings by articulating the main energy uses, the concept remains complicated and challenging for contemporary cities. This implies innovative approaches to interdisciplinary planning that highlight the importance of the zero-energy concept and aid city stakeholders and planners to define these particular structures. Indeed, the interrelation between urban structure and energy is a key aspect of this path. Related to this, a "well-structured" area is a key point that increases sustainable transport and the share of renewable resources

In this study, we analyzed the district of Epinlieu (Mons, Belgium) as a demonstration of our methodological approach. We simulated the analysis and modeling of NZED models, testing various indicators and interconnections between them in the case study of Epinlieu and recommending a planning strategy for the transition to zero-energy objectives.

Addressing the U-ZED research questions, we developed different phases in our analysis: (1) a diagnostic study with an assessment of the actual situation with respect to the indicators and (2) a transition phase toward zero-energy application. The study can be summarized as three phases:

- **Phase 1.** Diagnosis and assessment of the current (actual) situation: We defined the geographical location of the district (perimeter of the district/research limits, location with regard to its surroundings in the city of Mons and in other districts, etc.). At this phase, we defined the spatial organization of the existing district and studied the site opportunities with respect to the potential energy inventory, the weather conditions, the natural resources for its "transition" to the zero-energy objectives, etc.;
- **Phase 2.** The problem of "geographical location": Is Epinlieu "smartly" located or not? The district is situated 2.5 km from the center of Mons with a good proximity to services in its surroundings, and it is well connected by sustainable means of transport. The study of the district's transition recommends improvements in bus frequency as well as the introduction of bicycles as a soft mobility measure by constructing cycle paths, which would also support electric bicycles and the installation of stations serving the district. The district was developed for military service requirements with limited functional mixing (residential), but its strategic location is a key factor for the enhancement of its future attractiveness;
- **Phase 3.** This was the analysis of the three pillars of action via the U-ZED approach: the core of the U-ZED analysis with the study of the actual situation with respect to the current energy demand (users' requirements), taking into account the site opportunities and the possibilities for energy storage. In the case of Epinlieu, the analysis revealed a lack of valid data, e.g., for the approximations of the energy produced on-site. To solve this, we developed methodological assumptions and scenarios with the use of existing tools to identify the energy demand (method of degree days; etc.). With regard to the district's offerings and opportunities for energy inventory, we were limited only in solar energy: this is the main reason why we propose (at the phase of the district's transition) technologies and systems around the exploitation of solar energy, e.g., photovoltaic panels.

The application of the U-ZED approach for an existing district, as in the case of Epinlieu, included an identification of the actual situation in a multicriteria context (with a focus on "smart typology"), as presented previously, in particular the following:

- **Building typology.** This was a typo-morphological analysis of the existing building stock in the district of Epinlieu. As presented previously, five typologies are "met" in the district, with an interesting diversity in architectural and construction design and physical composition. The analysis also included the criterion of roof orientation to define the possibilities of the angles maximizing solar gain for the possibility of installing PVs. The criterion of compactness was not studied in an in-depth analysis, but only with respect to the diverse typologies in the district;
- **Functions.** The criterion of functional mixing was part of the analysis of the current situation in the district of Epinlieu. The analysis revealed the problems of a residential district without diversity in complementary activities for its users, e.g., in commerce, offices, or other services or infrastructure;
- **Density.** The criterion of density was not studied in the current analysis.

This study contributes to the scientific discussion on the linkage between energy and urban structure to increase the energy efficiency in districts. Notwithstanding this, limitations mainly concerning the lack of data and the complexity of the applicability of the zero-energy concept at larger scales were restrictions and weaknesses for this study. The human factor and public awareness as well as the participation process are significant for successful policies and for the zero-energy concept in districts. Further research and works are required in the future on this particular and major issue for the longevity of modern cities and the achievement of their sustainable objectives.

Author Contributions: S.K., C.P., N.-F.G., and A.B. conceived of the methodology on the transition of the district to the zero-energy objectives; C.P. performed the cartographical analysis of the district in its diagnostic and projected situation. T.W. provided explanations for the QGIS tool and its use for the study. V.B. and C.S.I. provided suggestions and supervised the study. S.K. and N.-F.G. wrote the paper.

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Conflicts of Interest: The authors declare no conflicts of interest.

Nomenclature

EU	European Union
MS	Member state
GHGs (emissions)	Greenhouse gases (emissions)
NZED	Net-zero-energy district
U-ZED	Urban zero-energy district
KPIs	Key performance indicators
GDP	Gross domestic product
CERTU	Centre d’Etudes sur les Réseaux, les Transports, l’Urbanisme, et les Constructions Publiques
ZEB	Zero-energy building
NZEB	Net-zero-energy building
EPBD	European Performance of Buildings Directive
GIS	Geographical information system
HOMER	Hybrid optimization model for electric renewables
NPC	Net present cost
CoE	Cost of energy

Appendix A. Analysis of Heating Energy Requirements in the District of Epinlieu

This study included calculations for five (5) building typologies of the district by month to define the annual profile of the energy demand in the district of Epinlieu. The figures below provide the generated data per building/typo-morphology and the heat loss through conductive elements for each of the categories defined previously. In this paper, the degree days method was used to calculate the conductive heat loss by assuming a constant indoor temperature of 20 °C in dwellings throughout the whole year [1]. In the rest of the paper, we use the term heat demand to describe the results for conductive heat loss calculations.

Appendix A1. Typo-Morphology 1: Terraced Houses with Gabled Roofs (74 Units)

Table A1. Calculations of energy requirements for terraced unit(s) with gabled roofs.

Month	**Degree Days**	**Area of Losses(m^2)**	**U (W/m^2K)**	**UAmin (W/K)**	**Energy Demand for One Building (D_{1min}) (KWh)**	**Energy Demand for All Buildings (D_{tmin}) (KWh)**	**UAmax (W/K)**	**Energy Demand for One Building (D_{1max}) (KWh)**	**Energy Demand for All Buildings (D_{tmax}) (KWh)**
January	436	262.6	0.44	92.36	966.36	71510.49	138.53	1449.54	107265.73
February	544				1205.73	89224.09		1808.60	133836.14
March	457				1012.90	74954.80		1519.35	112432.20
April	228				505.34	37395.39		758.01	56093.09
May	149				330.25	24438.22		495.37	36657.33
June	96				212.78	15745.43		319.16	23618.14
July	78				172.88	12793.16		259.32	19189.74
August	85				188.40	13941.26		282.59	20911.90
September	185				410.04	30342.75		615.06	45514.13
October	214				474.31	35099.18		711.47	52648.78
November	397				879.92	65113.91		1319.88	97670.86
December	474				1050.58	77743.05		1575.87	116614.58
				Total	**7409.48**	**548301.74**		**11114.22**	**822452.61**

Explanations
$UA_{min} = 0.8 * U * S$
$UA_{max} = 1.2 * U * S$
$D_{1min} = (UA_{min} * \text{Degree Days} * 24)/1000$
$D_{1tmin} = \text{Number of units} * D_{1min}$
$D_{1max} = (UA_{max} * \text{Degree Days} * 24)/1000$
$D_{1tmax} = \text{Number of units} * D_{1max}$

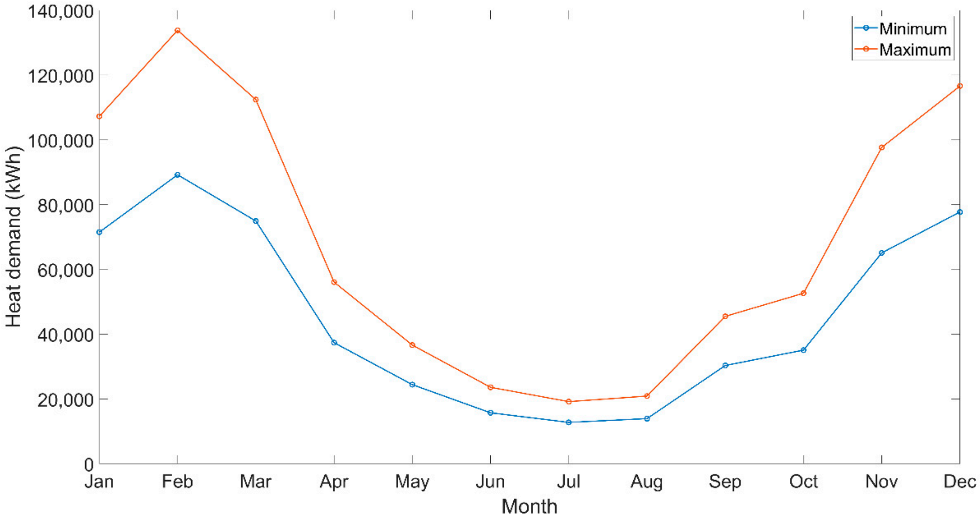


Figure A1. Energy demand of terraced houses with gabled roofs in Epinlieu per month (kWh).

Appendix A2. Typo-Morphology 2: Terraced Houses with Flat Roofs (70 Units)

Table A2. Calculations of energy requirements for terraced unit(s) with flat roofs.

Month	Degree Days	Area of Losses (m^2)	U (W/m^2K)	UAmin (W/K)	Energy Demand for One Building (D_{1min}) (KWh)	Energy Demand for All Buildings (D_{tmin}) (KWh)	UAmax (W/K)	Energy Demand for One Building (D_{1max}) (KWh)	Energy Demand for All Buildings (D_{tmax}) (KWh)
January	436	233.38	0.41	76.55	801.00	56070.35	114.82	1201.51	84105.52
February	544				999.42	69959.33		1499.13	104939.00
March	457				839.59	58770.98		1259.38	88156.48
April	228				418.87	29321.19		628.31	43981.79
May	149				273.74	19161.66		410.61	28742.48
June	96				176.37	12345.76		264.55	18518.65
July	78				143.30	10030.93		214.95	15046.40
August	85				156.16	10931.15		234.24	16396.72
September	185				339.88	23791.32		509.81	35686.98
October	214				393.15	27520.77		589.73	41281.15
November	397				729.36	51054.88		1094.03	76582.32
December	474				870.82	60957.21		1306.23	91435.82
				Total	**6141.65**	**429915.53**		**9212.48**	**644873.30**

Explanations

UA_{min} = 0,8 * U * S

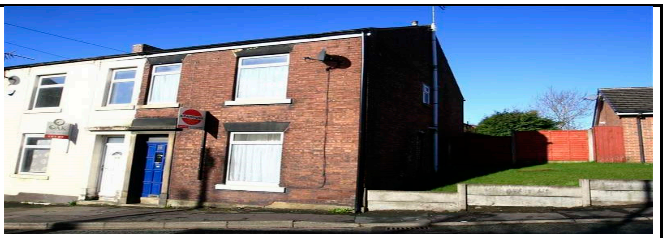
UA_{max} = 1,2 * U * S

D_{1min} = (UA_{min} X Degree Days * 24)/1000

D_{1tmin} = Number of units * D_{1min}

D_{1max} = (UA_{max} *Degree Days * 24)/1000

D_{1tmax} = Number of units * D_{1max}



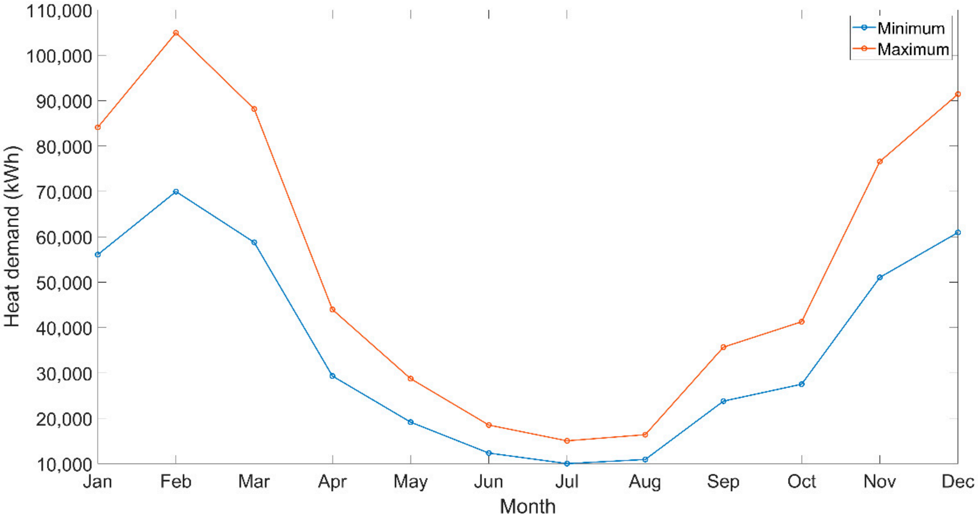


Figure A2. Energy demand of terraced houses with a flat roof in Epinlieu per month (kWh).

Appendix A3. Typo-Morphology 3: Terraced Houses with Gabled Roofs and Parking (40 Units)

Table A3. Calculations of energy requirements for terraced unit(s) with gabled roofs and parking.

Month	Degree Days	Area of Losses (m^2)	U (W/m^2K)	UAmin (W/K)	Energy Demand for One Building (D_{1min}) (KWh)	Energy Demand for All Buildings (D_{tmin}) (KWh)	UAmax (W/K)	Energy Demand for One Building (D_{1max}) (KWh)	Energy Demand for One Building (D_{tmax}) (KWh)
January	436	266.2	0.77	163,98	1715.88	68635.13	245.97	2573.82	102952.70
February	544				2140.91	85636.50		3211.37	128454.75
March	457				1798.52	71940.95		2697.79	107911.43
April	228				897.29	35891.77		1345.94	53837.65
May	149				586.39	23455.58		879.58	35183.38
June	96				377.81	15112.32		566.71	22668.48
July	78				306.97	12278.76		460.45	18418.14
August	85				334.52	13380.70		501.78	20071.05
September	185				728.07	29122.71		1092.10	43684.06
October	214				842.20	33687.89		1263.30	50531.83
November	397				1562.39	62495.75		2343.59	93743.63
December	474				1865.43	74617.10		2798.14	111925.64
				Total	**13156.38**	**526255.17**		**19734.57**	**789382.75**

Explanations

UA_{min} = 0,8 * U * S

UA_{max} = 1,2 * U * S

D_{1min} = (UA_{min} X Degree Days * 24)/1000

D_{1tmin} = Number of units * D_{1min}

D_{1max} = (UA_{max} * Degree Days * 24)/1000

D_{1tmax} = Number of units * D_{1max}

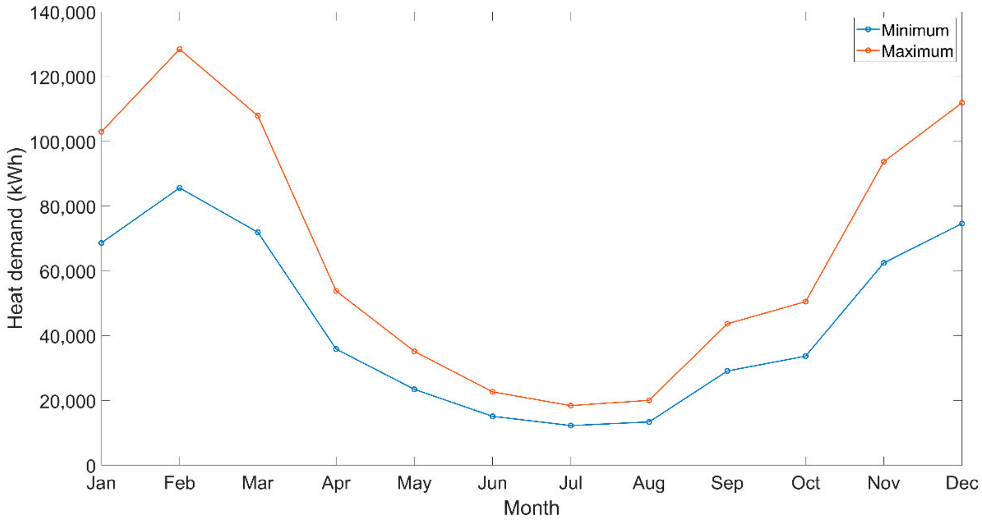


Figure A3. Energy demand of terraced houses with gabled roofs and parking in Epinlieu per month (kWh).

Appendix A4. Typo-Morphology 4: Terraced Houses with Mansard Roofs (70 units)

Table A4. Calculations of energy requirements for terraced unit(s) with mansard roofs.

Month	Degree Days	Area of Losses (m²)	U (W/m²K)	UAmin (W/K)	Energy Demand for One Building (D_{1min}) (KWh)	Energy Demand for All Buildings (D_{tmin}) (KWh)	UAmax (W/K)	Energy Demand for 1 Building (D_{1max}) (KWh)	Energy Demand for All Buildings (D_{tmax}) (KWh)
January	436	213.56	1.33	227.23	2377.71	166439.85	340.84	3566.57	249659.77
February	544				2966.69	207668.07		4450.03	311502.10
March	457				2492.23	174456.45		3738.35	261684.67
April	228				1243.39	87037.35		1865.09	130556.03
May	149				812.57	56879.67		1218.85	85319.51
June	96				523.53	36647.31		785.30	54970.96
July	78				425.37	29775.94		638.06	44,663.90
August	85				463.54	32448.14		695.32	48672.20
September	185				1008.89	70622.41		1513.34	105933.62
October	214				1167.04	81692.95		1750.56	122539.43
November	397				2165.03	151551.88		3247.54	227327.82
December	474				2584.94	180946.07		3877.42	271419.11
				Total	**18230.94**	**1276166.08**		**27346.42**	**1914249.13**

Explanations

$\mathbf{UA_{min}}$ = 0,8 * U * S

$\mathbf{UA_{max}}$ = 1,2 * U * S

$\mathbf{D_{1min}}$ = (UA_{min} * Degree Days * 24)/1000

$\mathbf{D_{1tmin}}$ = Number of units X D_{1min}

$\mathbf{D_{1max}}$ = (UA_{max} * Degree Days * 24)/1000

$\mathbf{D_{1tmax}}$ = Number of units * D_{1max}

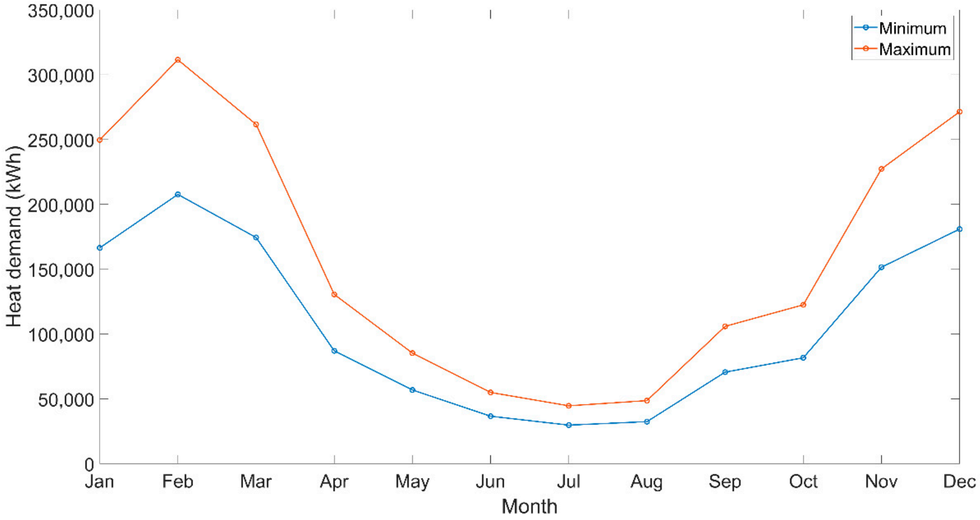


Figure A4. Energy demand of terraced houses with mansard roofs in Epinlieu per month (kWh).

Appendix A5. Typo-Morphology 5: Apartments (10 Units)

Table A5. Calculations of energy requirements for apartments.

Month	Degree Days	Area of Losses (m^2)	U (W/m^2K)	UAmin (W/K)	Energy Demand for One Building (D_{1min}) (KWh)	Energy Demand for One Building (D_{tmin}) (KWh)	UAmax (W/K)	Energy Demand for One Building (D_{1max}) (KWh)	Energy Demand for One Building (D_{tmax}) (KWh)
January	436	742.28	1.70	1009.5	10563.42	105634.16	1514.25	15845.12	158451.25
February	544				13180.04	131800.42		19770.06	197700.64
March	457				11072.20	110722.05		16608.31	166083.07
April	228				5523.99	55239.88		8285.98	82859.83
May	149				3609.97	36099.75		5414.96	54149.62
June	96				2325.89	23258.90		3488.83	34888.35
July	78				1889.79	18897.85		2834.68	28346.78
August	85				2059.38	20593.82		3089.07	30890.72
September	185				4482.18	44821.84		6723.28	67232.75
October	214				5184.80	51847.96		7777.19	77771.94
November	397				9618.52	96185.24		14427.79	144277.85
December	474				11484.08	114840.81		17226.12	172261.22
				Total	**80994.27**	**809942.68**		**121491.40**	**1214914.02**

Explanations

UA_{min} = 0,8 * U* S

UA_{max} = 1,2 * U* S

D_{1min} = (UA_{min} * Degree Days * 24)/1000

D_{1tmin} = Number of units * D_{1min}

D_{1max} = (UA_{max} * Degree Days * 24)/1000

D_{1tmax} = Number of units * D_{1max}

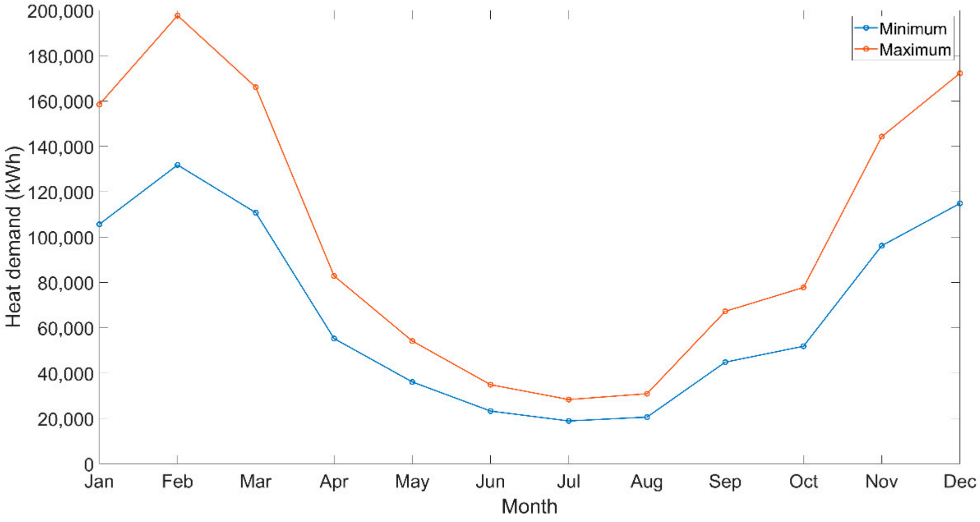


Figure A5. Energy demand of apartments block in Epinlieu per month (kWh).

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