

Article

Looking for the Optimal Location of an Eco-District within a Metropolitan Area: The Case of Tricity Metropolitan Area

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Abstract: Compact housing structures located in city centers are considered to be the most energy and environmentally effective, mainly due to the access to services, transport networks and municipal infrastructures. There is the question of why so many of the acknowledged ecological housing complexes are located on the outskirts of cities or suburbs. Numerous cities decide to introduce strategies either to densify city centers, hoping to improve energy efficiency. The Tricity metropolitan area is a special case undergoing dynamic transformation, and its development overlaps with the processes of both planned densification of the center as well as uncontrolled suburbanization. The goal of this study was to find the correlation between optimal location of an eco-district from the functional center of the Tricity metropolitan area, allowing for the most favorable energy and environmental parameters related both to the architectural and urban scale. The research was conducted in four different scenarios, concerning present and future development. In these scenarios, specific locations were examined, and the following were compared: total energy consumption, ecological footprint and CO₂ lifecycle emissions. This study shows the possibility for suburban housing complexes with appropriate parameters in an edge city model to have the same or better results than complexes situated closer to the functional center of the city. This is mainly due to the building's energy efficiency, sustainable mobility, municipal infrastructure and relevant service access. The research proves the importance of implementing sustainable energy-saving and environmentally oriented activities at both an architectural and urban scale planning process.

Keywords: suburbanization; urban sprawl; eco district; energy optimizations; urban planning; energy efficiency; carbon neutrality; energy transition; sustainable process index; sustainable development

1. Introduction

In the era of shrinking natural resources [1,2] and energy transformation [3–5], methods and countermeasures focusing on sustainable energy optimization [6], increasing energy efficiency and renewable energy applications [7] are being sought in all sectors.

In the context of the construction sector responsible for the largest percentage of total energy consumption in the EU [8], most of the remedial actions focus on minimizing energy consumption within building structures. Unfortunately, aspects of the building environment and related urban factors, such as access to urban infrastructure, distance from services and mobility issues, are often underestimated in optimization [9–15]. The above-cited numerous studies show, however, that urban aspects play the greatest role for housing development in the context of the overall final assessment of energy consumption and assessment of the negative impact of the building complex on the natural environment.

Dynamic global mega trends, such as energy transformation and climate protection measures, are accompanied by processes that are problematic for urban development. There is a constantly growing number of urban inhabitants [16] increasing housing demand and, as a result, often causing uncontrolled suburbanization [17–19]. The growing population means increased energy demand, the need to expand infrastructure (of which the efficiency decreases with distance) and transport—mainly increased individual mobility—generating pollution and using more and more energy. Therefore, initially uncontrolled suburbanization is rising with an unfavorable trend and there is a tendency to densify city centers, aimed at saving energy and resources, as well as increasing the efficiency of urban infrastructure. According to popular knowledge, compact housing structures located in city centers are considered the most energy and environmentally effective [20], mainly due to access to services, transport networks and municipal infrastructures, which results in reduced transfer losses.

In order to alleviate the aforementioned problems, there is an emerging trend of designing so-called eco-districts [21,22] around the world. They are adapted to the local context and the needs of residents and, at the same time, meet restrictive environmental parameters. Numerous eco-districts, however, are located distanced from the city center, for instance, Vauban in Freiburg [21], Jenfelder in Hamburg [23], BedZED in London [24] or Seestadt in Aspern [25], and many more.

There may be some wondering why most of the so-called ecological building complexes are located in suburbs or in areas distanced from the city center. Is it possible that ecological housing complexes in special conditions have more favorable parameters related to urban energy efficiency than those located in city centers? What conditions and parameters must, exactly, be met for this to happen in the case of suburban locations? This topic may become a particularly interesting concern due to the spatial policy of many contemporary cities in the world, aiming at densifying the city centers rather than supporting intensive development of the outskirts or suburbanization.

Optimizations in the field of urban energy efficiency are also important from the perspective of the growing problem of uncontrolled suburbanization [17,18]. Recognizing the uncontrolled urban sprawl as an unfavorable trend, countermeasures are taken to densify the city centers. Therefore, the research question for this article was: where is there a spatial border for the optimal distance between buildings and the city center, respecting the effective functioning of urban infrastructure and the saving of energy and resources?

*1.1. Urban Aspects in the Assessment of Energy Efficiency and Environmental Impact of Building Complexes **

There have been many recent developments around buildings' energy performance and energy efficiency, creating new perspectives for suburban eco-districts by developing their energy independency; to mention a few, renewable energy technologies [26], decentralized energy systems [27,28] and occupant-based smart technologies [29,30] enabling the effective usage and transmission of energy independent from the centralized system.

Thanks to the growing environmental and energy awareness of inhabitants [28], we can talk about greater environmental societal responsibility and expect changes in unfavorable life habits and non-ecological energy acquisition [30]. Therefore, there is a potential for residential areas to become 'co-managers' of energy in smart grids [31].

Growing needs along with energy transition paradigms force planners to seek the most ecologically, economically and socially beneficial housing solutions for the coming years. However, some severe improvements are still expected in already-functioning energy solutions and systems, especially in terms of building sector [29].

Several researchers [32–34] have already undertaken topics related to the search for the optimal distance between housing complexes and the city center, taking into account urban and energy aspects. It was research in the context of American city models with a specific type of suburbs (laissez-faire). These studies have demonstrated the theoretical possibility [35] for households in larger cities to consume more energy than those located in smaller cities or on their outskirts. Further research on American cities [32] proved that with certain parameters, the energy consumption per capita in

American cities does not change with increases in the size of the city. Households in larger US cities consume less housing reserves, but commuting takes longer and is slower, and their residents consume more numeraire goods. These results are compensated on American suburbs (laissez-faire type). Previous studies have been carried out only using theoretical [35] or statistical and mathematical methods [32]. The emerging method is empirical research [7,12,14,15,36] on a unit calculation of the urban energy efficiency of a building complex for a specific location, characterized by high precision, but having only local significance.

A special situation is characteristic for countries in transition where no such research has been carried out hitherto. Worldwide, there are countries that have undergone socio-political and economic transformations in the in the 1990s and are currently undergoing dynamic development and changes. Due to the specific functioning and development models of these cities, American research based on a specific type of suburb (laissez-faire) and central business district (CBD) may not be reflected in the case of the edge city model present in the countries in transition.

To answer this problem, the main aim of this research was the investigation of the relationship between the edge city model and urban energy efficiency in the context of the country in transition. Extended, detailed case-study research for the Tricity metropolitan area (TMA) in Poland was planned. TMA is characterized by a specific Polish edge city model [37] that includes a large number of locally-focused small and medium businesses. Due to the special morphology of the TMA, characterized by a distinct concentration of services and functions in the suburbs, there was a hypothesis that it may be possible to repeat the investigation results of American researchers, demonstrating that building complexes located in suburbs may have better end parameters than those located in city centers.

1.2. Subject of Research

The subject of research is focused around two main concepts: the central business district and edge city model at a regional level and strategies that emerged from the concepts of compact cities and suburbanization.

Energy transition and dynamic urbanization in cities of countries in transition require a change in the design workshop and further research in the field of comprehensive city planning, controlling negative suburbanization. Therefore, focus should be laid on interdisciplinary research in the field of urban energy efficiency and learning the morphological aspects of cities that have the greatest impact on environmental and energy aspects.

In the context of ecological and energy-saving cities, strategies related to the compact cities concepts [20,38] are widely used. Due to the concentration of building services and infrastructures in an ergonomic and compact way, they usually gain much more favorable energy and environmental parameters, and thanks to walkable distances, they ensure accessibility and a good quality of life for residents. The strategy of compact cities is concentrated, in many existing cities, on densifying city centers and inhibition of uncontrolled suburbanization (i.e., Helsinki [38]). Some of the cities, apart from densifying centers, decide on comprehensively planned and controlled expansion in the suburbs, such as in Vienna (Seestadt, Aspern) [25], through a development of eco-districts. Suburbanization is commonly associated with a negative phenomenon, however, with some comprehensive planning interventions, it is possible for carefully planned suburban eco-districts to achieve similar or even better ecological parameters than the districts in city centers. The factors that affect these conditions are, however, very specific to each location, hence they are usually impossible or difficult to achieve with a standard or universal design approach. Therefore, promising directions are individually conceptualized eco-districts, whose solutions fit into sustainable strategies evolving from different urban concepts, such as eco city, resilient city, zero emission city, smart city and future concept of self-sufficient city. These urban concepts, however, constitute only a general direction and set of design paradigms, therefore they always require an in-depth examination of local conditions and learning the relationship between urban energy efficiency and the morphology and functioning of individual cities.

One of the theoretical and empirical approaches is the concept of urban energy efficiency and integrated spatial and energy planning developed by Stoeglehner [12]. It is based on a system analysis of elements dealing with spatial structures, energy demand, energy supply and most effective regulatory elements. It allows the identification of key planning elements (Figure 1). On their basis, a tool called ELAS (Energetic Long-Term Assessment for Settlements and Structures [39]) was developed to perform empirical local energy and environmental simulations. In this research, it was planned to focus on the relationships occurring in connection with the location in the context of integrated spatial and energy planning and measuring urban energy efficiency both theoretically and empirically.

	Active elements	Passive elements	Buffering elements	Critical elements
LOCATION	<ul style="list-style-type: none"> • Density • Topography • Location • Exposition 	<ul style="list-style-type: none"> • Technological density • Sealing of soil • Open space design at specific locations • Residues 	<ul style="list-style-type: none"> • Preliminary land uses 	<ul style="list-style-type: none"> • Density of jobs • Building quality and form
TRANSPORT		<ul style="list-style-type: none"> • Means of transport • Distance covered • Travel time 	<ul style="list-style-type: none"> • Combination of routes 	<ul style="list-style-type: none"> • Nearness
RESOURCES, ENERGY	<ul style="list-style-type: none"> • Resource base 	<ul style="list-style-type: none"> • Dynamics of energy generation • Energy distribution technologies • Conflicts around energy supply • Demands on the location of energy supply facilities • Energy used for mobility • Dynamics of energy consumption 	<ul style="list-style-type: none"> • Density of resources • Energy cascades • Space heating and hot water demand • Process energy demand • Light and power demand 	<ul style="list-style-type: none"> • Environmental impacts • Used resources • Energy generation technologies • Formation of clusters
ECONOMY	<ul style="list-style-type: none"> • Mix of functions 	<ul style="list-style-type: none"> • Facilities 	<ul style="list-style-type: none"> • Mix of economic sectors 	



Figure 1. Graphical summary of elements of integrated spatial and energy planning. Author's elaboration based on [40].

1.3. The Edge City Model

The edge city model is a term in urban planning and social geography intended to describe a specific form of suburbanization [41]. (Other terms used to describe these areas include: suburban activity centers, mega centers, and suburban business districts). The edge city model describes suburban large centers that are multifunctional; they have all the characteristics of an independent city, such as a wide range of jobs, shopping, leisure, residential facilities, and a concentration of businesses, outside a traditional downtown or central business district, in former suburban residential or rural areas (Figure 2). Edge cities represent a kind of final form of a suburbanization process. The term originated in the United States, but these districts have now developed in many countries. On the

one hand, traditional edge cities are perceived as unsustainable due to a low-density housing area and the fact that they are mostly built at automobile scale, where pedestrian access and circulation is usually supposed to be unfeasible. Therefore, their densification is more difficult than in the traditional grid network that characterizes the traditional CBD model. However, in the 21st century, numerous edge cities have introduced plans for densification, that usually are concentrated around a walkable downtown-style core. An emerging direction for edge cities is increasing accessibility by public transit and bicycles along with integrating denser urban-style neighborhoods.

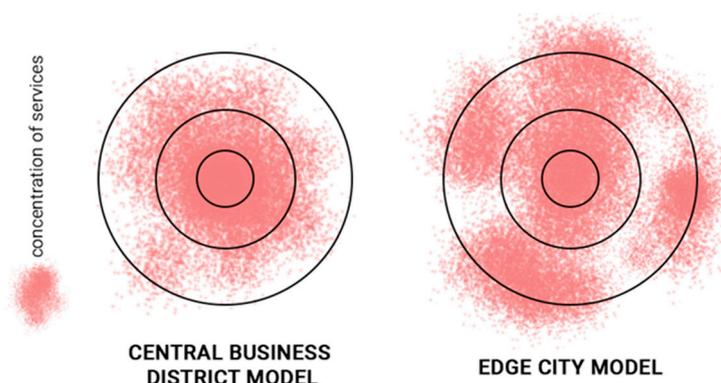


Figure 2. Authors' diagrammatic representation of service distribution within cities of different morphological models: in the American central business district model and in the Polish edge city model.

1.4. Situation of Poland and Tricity Metropolitan Area

There is a lack of complementary research on urban energy efficiency in the context of countries in transition and their suburbs, especially characterized by an edge city model. In this context, the Polish edge city model is a very interesting example because, apart from the predominant residential function, it is characterized by the occurrence, in the suburbs, of small and medium-sized enterprises (SMEs), as well as many other functions [42].

Moreover, these countries are characterized either by the lack of regulations in the respect of urban energy efficiency or having regulations focused solely on the shapes of buildings. However, these countries are undergoing dynamic changes driven by EU policy and socio-economic transformation and the situation is in constant alteration.

Out of such countries, Poland was selected as the scope of research work—specifically, the Pomeranian Voivodeship with Tricity metropolitan area (TMA) due to its special conditions and unique morphology (edge city model) (Figure 3).

Tricity metropolitan area, located in northern Poland, belongs to the MEGAs (Metropolitan European Growth Areas) as a one of the significant European metropolitan centers [43]. Its territorial coverage can be seen in Figure 3. TMA, as a metropolitan area, is characterized by all modern development processes, among others a compact city urban development policy [44]. At the same time, TMA is still experiencing urban sprawl because continuous investment in road infrastructure is triggering an uncontrolled suburbanization process. Therefore, Poland and TMA can be a good example from which lessons learned can be applied and compared to other locations in countries in transition.



Figure 3. Geographical location of the Tricity metropolitan area in Poland in relation to other EU metropolitan regions. Authors' graphic based on [43].

In Poland, as in other EU countries, there are legal regulations regarding building energy aspects [45]; however, they only apply to the scale of individual buildings and there is no reference to urban aspects.

In Tricity, in accordance with the regulations [45,46], the main interest in the context of energy efficiency is building forms. In accordance with applicable law, public buildings currently have priority in the context of improving energy efficiency in Poland. Residential buildings are subject to Technical Conditions regulation [46], which focuses mainly on the parameters of a building envelope rather than on a holistic assessment of its parameters, taking into account urban factors, e.g., infrastructure and transport.

TMA functions as a specific edge city [47], meaning there is an increased intensification of services and multifunctionality of areas located at the administrative border of the city and an associated theoretical possibility of occurrence, in the suburban areas of TMA, of areas with very good parameters for urban energy efficiency.

Earlier, only preliminary studies were conducted. The author's initial research included literature studies [48] in the context of the importance of integrated spatial and energy planning. They proved the need to deepen research and refer to the local context of TMA.

The purpose of preliminary empirical research (Julia Kurek and Martyniuk-Pęczek, 2019) was to check if it is possible for residential complexes located in the suburbs or outskirts of TMA to have, under special conditions, better urban energy efficiency parameters than those located closer to the center. This hypothesis was confirmed by preliminary research based on an empirical approach and computer simulations. They confirmed the theses of American city researchers on the possibility of occurrence, in the suburbs of TMA, of locations where total urban energy consumption and negative environmental impact per capita is lower than in the case of locations closer to the city center of TMA. The conducted research allowed for preliminary verification of urban energy parameters for five individual locations within TMA area.

Therefore, due to special conditions (including dynamics of suburbanization, environmental and energy problems), it was decided to conduct further research in the context of TMA and develop it in a comprehensive way under this study.

There is a hypothesis that in the case of the TMA, officially characterized as an edge city [48,49], it will be possible to achieve equally surprising results of urban energy efficiency as in some American cities, showing that building complexes located in the suburbs may have, in special conditions, better final parameters of urban energy efficiency than those located closer to the city centers. The Tricity metropolitan area is a special case undergoing dynamic urban transformation, and its development

overlaps with the processes of both planned densification of the center as well as uncontrolled suburbanization. The TMA edge city model may be perceived as untypical because of the Baltic Sea, which is a physical barrier to development from the north-east part. However, TMA represents all other characteristics of an edge city, so it can be treated as a representative sample of this city model for research. Tricity metropolitan area, thanks to its smaller scale compared to other edge cities, such as New York or Paris, has enabled effective empirical research.

The process of Polish suburbanization is the most dynamic among others in the Pomeranian Voivodeship, in the Tricity metropolitan area (cities Gdańsk, Sopot, Gdynia) [50]. The Pomeranian Voivodeship is also characterized by a unique phenomenon at a national scale—according to data from the Central Statistical Office [51], it is the only area in the country where, in 2050 (compared to 2013), the number of urban residents will decrease by 12.9 percent and residents of suburban areas and villages will increase by 20.4 percent.

Correspondingly, in the Tricity metropolitan area, there is a strategy to densify the city center. At the same time, areas on the outskirts are not subject to the main interest of cities in terms of both spatial and energy aspects. Nonetheless, TMA suburban areas are developing dynamically due to the migration of residents seeking affordable housing.

Due to the lack of energy masterplans and tools for comprehensively assessing urban and energy aspects, with the factors that affect them most, planning urban energy efficiency of dwelling complexes in TMA suburban areas is mainly intuitive or based only on theoretical research.

In the Pomeranian Voivodeship, optimizations in the field of urban energy efficiency are particularly important for both energy and low-emission policy as well as environmental reasons. The Pomeranian Voivodeship is able to satisfy its energy needs only in 30 percent. There is a need to import almost 70 percent of its energy from central and southern Poland through the National Power System [52]. Another serious problem is air pollution [53] caused by individual heating systems. Even in the city of Gdańsk, which has relatively good air quality compared to other regions in Poland, the PM_{2.5} and PM₁₀ dust concentration limits are regularly exceeded [53].

2. Materials and Methods

2.1. Aim of the Research and Research Hypothesis

The main aim of the research was to verify how the location from the functional center of the city of Gdańsk affects the urban energy efficiency end parameters of total energy demand and environmental footprint of the entire housing complex. One of the main purposes of this research was to find the answer for the question asked in the title of this article, whether, due to the unique conditions of the Polish Tricity metropolitan area (TMA) functioning as an edge city, it may be possible for housing complexes located in the suburbs or on the outskirts to have, under certain conditions, more favorable urban energy efficiency parameters than those located closer to the TMA center.

Additionally, several additional research questions were asked. Firstly, we tried to prove which location is most beneficial for an eco-housing complex within urban tissue of TMA in terms of urban energy efficiency—central or suburban. A further research question asked which urban aspects are most important in the final assessment of urban energy efficiency in specific areas of the edge city (TMA) suburbs.

An important question, associated generally with the most favorable ecological and energy distance of the housing complex from the center topic, was the final question posed in this research: whether the eco-districts can become a solution or remedy for chaotic suburbanization and should be included in the city's development policy.

2.2. Description of the Method

In the research, the empirical method of conducting a series of computer simulations using the ELAS tool [39] was adopted (Figure 4). Total energy consumption, ecological footprint and CO₂



lifecycle emissions were examined for identical test model housing complexes. The test model dwelling complex was placed in ten different locations within the TMA: in the center, on the outskirts and outside the administrative boundaries of the city. Afterwards, simulations were performed for each location in four different scenarios (Figure 4).

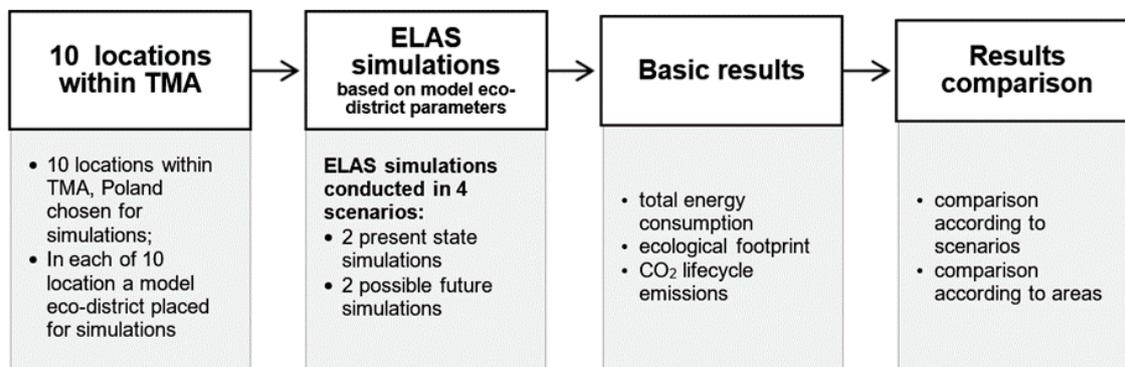


Figure 4. Authors' research method.

The criterion for choosing the ten test locations was the location within TMA at various distances from the functional center of the city. Another feature of the location selection was the presence of vacant areas that could potentially be used for the construction of a new ecological housing complex with the adopted parameters. These locations are schematically indicated in Figure 5.

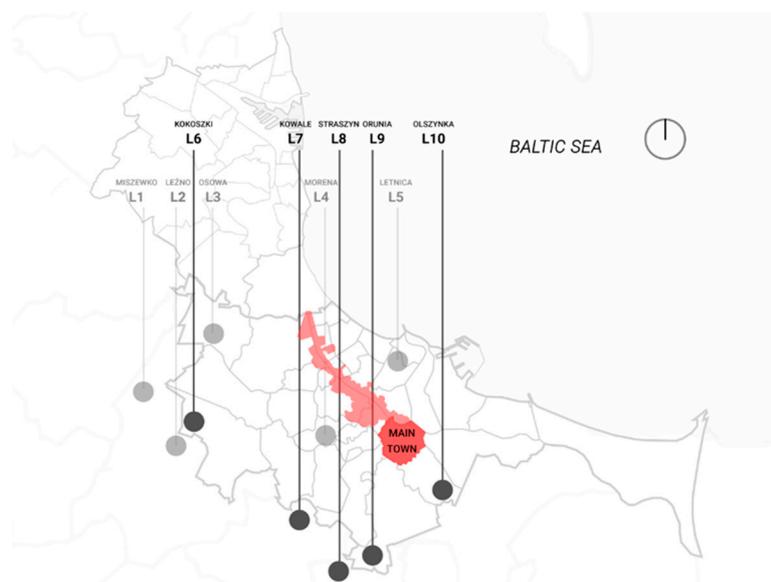


Figure 5. Ten locations within Tricity metropolitan area chosen for simulations in ELAS (Energetic Long-Term Assessment for Settlements and Structures). The functional center, according to study of conditions and directions of spatial development, of the city of Gdańsk [44] is marked with red color.

For each selected location, simulations were carried out in four different scenarios. The first scenario assumed only activities at an architectural scale. It assumed the energy efficiency improvement of all buildings in the test housing complex to an energy-saving standard with a building space heating energy rating of 40 kWh/m² year. The second scenario also assumed only activities at an architectural scale, improving energy efficiency to the passive building standard, with an energy rating of 15 kWh/m² year.

The third and fourth scenarios concerned the future development and functional model of a housing complex, with possible dependence on the lifestyle of residents, mobility and energy sources used.

Scenario three, called the green scenario, assumed improvement both at the architectural and urban scale, the so-called ecological lifestyle of inhabitants and the use of renewable energy sources at a larger scale.

The green scenario was grounded on responsible usage of energy and resources: the total energy consumption of the settlement was decreased by 33% and was covered 100% by eco-electricity (from renewable energy sources). The total kilometers were increased, as in the trend scenario, by 25%, car-operation was driven exclusively by biogas cars (70%) and electric cars (30%) and bus operation was only run on biogas.

The fourth scenario assumed activities regarding the improvement of buildings energy efficiency to the passive house standard—as in the second and third scenario—while maintaining negative trends with increased mobility, non-ecological lifestyle and reliance on non-renewable energy sources. The trend scenario was built on present predictions in the areas of energy and mobility: the energy consumption (electricity) rising yearly by 2.2% and the electricity provision changes. In the section of everyday mobility, the total kilometers were increased by 25% while the amount of biogas cars was elevated, by the year 2040, to 10%, and the number of electric cars to 15%.

Then, the results for individual locations were compared in the given scenarios, based on the Letnica [L5] test reference location. The reference location Letnica [L5] is located near (below 1 km) to the main functional center of Gdańsk and is characterized by a well-developed urban and technical infrastructure. It has a well-developed road and public transportation network; it is also characterized by multifunctionality and the 98 dominance of the residential function.

The results were compared in terms of main parameters addressed to whole housing complexes: total energy consumption, ecological footprint and CO₂ lifecycle emissions. Afterwards, the results were compared in terms of individual component categories for the above-mentioned parameters (total energy consumption, ecological footprint and CO₂ lifecycle emissions). Subsequently, the results within component categories were juxtaposed and compared with the percentages from the reference location Letnica [L5]. This allowed for drawing conclusions and obtaining answers to the research questions.

2.3. Further Concepts and Factors Adopted in the Research

In the article, several markings and factors were proposed either by the authors of this article, such as the concept of using a model eco-district for tests (Figure 6), or some factors indicated by the authors [12] of the ELAS calculator [39].

Model of Sustainable Eco-District (Housing Complex)

The selection of the eco-housing project for tests was inspired by the model Vauban district in Freiburg, Germany.

Freiburg can be comparable to Gdańsk, despite being twice as small. It is known that there is an eco-district in Freiburg, and we wanted to check if it would work over a larger area. The Freiburg model is a model of a medium-sized city, and here, we wanted to test it in a metropolitan area

It was decided that this district would be chosen because it has all the necessary features attributed to sustainable eco-districts. Vauban is characterized by an energy-efficient layout of the district (Figure 7), the occurrence of certified energy-saving facilities, the use of renewable energy sources and the emphasis on walking and cycling.

This eco-district, due to the typology of building dimensions, was possible to use at the Tricity metropolitan area scale. Potentially, it will be possible to use it for testing in other edge cities.



Figure 6. Location of Vauban eco-dwelling complex within Freiburg. Source of maps [54].



Figure 7. Plan of Vauban, Freiburg, eco-dwelling complex. Source [54].

Basic data regarding this building complex were adopted, based on source materials from the official website of the project [55,56].

The exact parameters and input data for this complex are provided in the following tables:

- Table 1: Input data for simulations with model test dwelling complex. Model calibration for ELAS.
- Table 2: Input data for simulations with model test dwelling complex. Model calibration for ELAS simulations: buildings and households' data.

The main parameters that constituted the remit of this research in each scenario were total energy consumption, ecological footprint (Sustainable Process Index) and CO₂ lifecycle emissions. The results in these categories were calculated for the same given building complex placed in one out of ten given locations. Energy consumption was understood as total energy consumption of a dwelling complex per year, including the consumption within given areas and was measured in kWh/m² a year.

In the composition of the results regarding total energy consumption, ecological footprint and CO₂ lifecycle emissions for individual areas and categories were identified.

Table 1. Input data for simulations with model test dwelling complex. Model calibration for ELAS simulations: Space heating and hot water supply.

Space Heating	Value
Energy rating (kWh/(m ² Year))	40
Total space heating demand (kWh/Year)	7,400,000
Hot water supply	value
Hot water demand per person (kWh/Year)	1000
Total water demand (kWh/Year)	5,661,000

Table 2. Input data for simulations with model test dwelling complex. Model calibration for ELAS simulations: buildings and households' data.

Input Data	Value
Building energy rating	Low energy house (VARIABLE)
Building construction	solid construction
Insulation	ecological insulation
Total living space	185,000 (m ²)
Building lot area	41,300 (m ²)
Number of households	2591
Number of residents	5661

3. Results

The results for individual locations in the given scenarios were compared with the results for the reference location Letnica (L5).

According to the original hypotheses, studies have shown that the most favorable scenario for each location tested is a combination of green scenario solutions with the passive house standard. This proves the importance of implementing energy-saving and environmentally friendly activities both at an architectural scale, in the form of restrictive energy standards, and an urban scale (green scenario); regarding the change in the method of energy generation, this would mean turning to renewable energy, sustainable mobility and the ecological lifestyle of residents.

The application of only a restrictive energy-saving (passive house) standard in the entire district with the lack of urban optimization and the lack of social commitment to an ecological lifestyle (trend scenario) caused the final results of energy demand to be similar or even worse than in the basic low energy scenario.

3.1. Present State Simulation: Low Energy Scenario

According to the initial hypothesis, if the given building complex is located further from the functional center of the city, its energy and environmental parameters will deteriorate (Table 3, Figure 8). These parameters were influenced by the distance from basic services and technical infrastructures as well as access to public transport and roads. As it is well known, increasing the distance from the aforementioned assets results in increased building and maintenance costs, enlarged transmission losses and, as a result, causes greater energy consumption.

The highest energy demand (total energy demand per year) compared to the reference location Letnica (L5) was from locations placed furthest from the functional center of Tricity: Miszewko (L1), Leżno (L2) and Kokoszki (L6). Their energy demand was respectively 146%, 137% and 119% in relation

to the results in Letnica (L5). These locations also had the least beneficial results in terms of ecological footprint, respectively 126%, 120% and 110%, and CO₂ lifecycle emissions, respectively 137%, 128% and 114% when compared to the reference location.

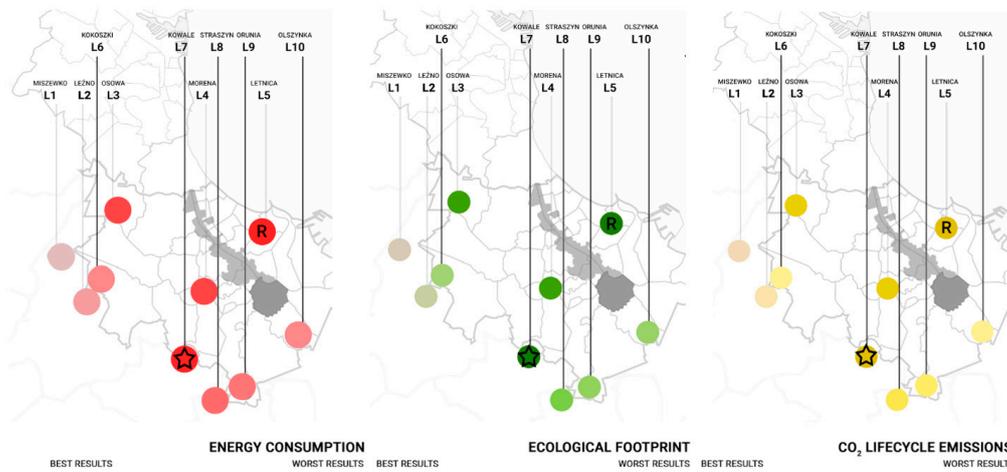


Figure 8. Present state, low energy scenario results. Graphical representation of ELAS simulation results according to total housing complex energy consumption, ecological footprint and CO₂ lifecycle emissions. Markings: R—reference location; star—results better than or equal to the reference location results.

This indicates the conclusion that when we holistically assess urban and architectural factors, increased energy demand is also associated with greater ecological footprint and CO₂ lifecycle emissions. It may be caused by a significant distance from the functional center of the city—about 14 km, in a straight line, from the functional center of the city. Locations situated less than 10 km in a straight line from the functional center of the city of Gdansk had the most favorable results in terms of energy consumption, ecological footprint and CO₂ lifecycle emissions.

Energy consumption, ecological footprint and CO₂ lifecycle emission results for almost all locations exceeded the reference Letnica (L5) location results. Kowale (L7) was the exception, probably due to the special local conditions and the presence of primary and mid-range services in the area. The result for this location, despite the distance from the center of 8 km and the location outside the administrative borders of the city, was even better than at the reference location.

The results for the locations of Morena (L4) and Olszynka (L8) were also noteworthy, both at a distance, in a straight line, of only 3 km from the functional center of the city. However, their results differ significantly and exceed the data obtained for the reference location Letnica (L5) that is 5 km away from the functional center of the city, and significantly differ from each other (within all three parameters tested).

These results indicate that the distance in a straight line from the functional center of the city is not the only reliable way to assess environmental aspects and potential energy demand; therefore, further urban parameters need to be considered. Moreover, the presence of a variety of relevant services of different ranges may play a significant role in assessment of the results of urban energy efficiency.

3.2. Present State Simulation: Passive House Standard Scenario

Under the passive house scenario, all final results were reduced in terms of energy consumption, ecological footprint and CO₂ lifecycle emissions (Table 4, Figure 9). Percentage differences between individual locations also decreased.

Interestingly, the most favorable results, better than in the reference location Letnica (L5), as before, were from Kowale (L7), but also another district, Morena (L4). Slightly worse results, higher by only 1 percentage point compared to the reference location, were obtained on the outskirts of the city, in Osowa (L3).

Table 3. Result data of simulations: low energy standard (building energy standard of 40 kWh/(m²·Year)).

Output Data	Locations Tested: Low Energy Standard									
	Miszewko (L1)	Leżno (L2)	Osowa (L3)	Morena (L4)	Letnica (L5)	Kokoszki (L6)	Kowale (L7)	Straszyn (L8)	Orunia (L9)	Olszynka (L10)
Energy consumption (kWh)	54,267,936	50,762,872	38,932,856	38,900,023	37,047,656	44,071,322	36,199,281	41,016,579	41,551,361	42,932,507
	146%	137%	105%	105%	100%	119%	98%	111%	112%	116%
Ecological footprint (SPI) m ²	6,024,085,939	5,759,029,148	4,916,787,686	4,934,771,756	4,789,809,352	5,277,107,694	4,727,598,080	5,064,534,320	5,103,508,131	5,201,765,190
	126%	120%	103%	103%	100%	110%	99%	106%	107%	109%
CO ₂ life cycle emissions	21,650,524	20,331,041	16,371,591	16,415,068	15,850,677	18,139,226	15,558,251	17,140,597	17,323,736	17,785,305
	137%	128%	103%	104%	100%	114%	98%	108%	109%	112%

Numbers in bold show the results closest to the results of reference location.

Table 4. Result data of simulations: passive house standard (building energy standard: 15 kWh/(m²·Year)).

Output Data	Locations Tested: Low Energy Standard									
	Miszewko (L1)	Leżno (L2)	Osowa (L3)	Morena (L4)	Letnica (L5)	Kokoszki (L6)	Kowale (L7)	Straszyn (L8)	Orunia (L9)	Olszynka (L10)
Energy consumption (kWh)	49,972,236	44,617,172	32,787,156	32,080,923	32,751,956	39,775,622	31,903,581	36,720,879	37,255,661	38,636,807
	153%	136%	101%	98%	100%	121%	97%	112%	114%	118%
Ecological footprint (SPI) m ²	5,800,720,882	5,427,878,913	4,585,637,451	4,535,172,508	4,566,444,295	5,053,742,638	4,504,233,024	4,841,169,264	4,880,143,075	4,978,400,134
	127%	119%	101%	99%	100%	111%	99%	106%	107%	109%
CO ₂ life cycle emissions	20,617,370	18,818,211	14,858,761	14,621,833	14,817,523	17,106,073	14,525,097	16,107,444	16,290,582	16,752,152
	139%	127%	101%	99%	100%	115%	98%	109%	110%	113%

Numbers in bold show the results closest to the results of reference location.



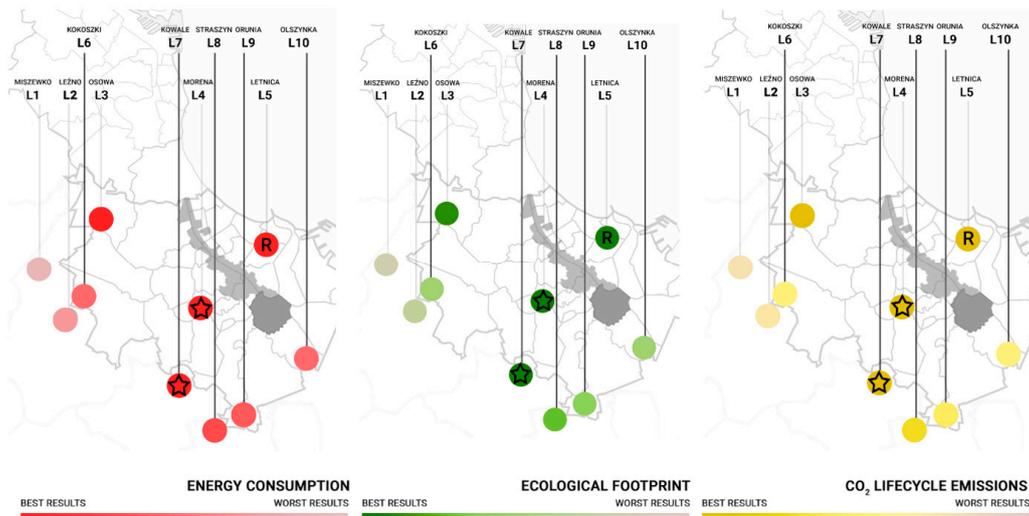


Figure 9. Present state, passive house standard scenario results. Graphical representation of ELAS simulation results according to total housing complex energy consumption, ecological footprint and CO₂ lifecycle emissions. Markings: R—reference location; star—results better than or equal to the reference location results.

3.3. Potential Future Simulation: Trend Scenario and Passive House Standard

In the combination of trend scenario with passive house energy rating, the least favorable results were from locations furthest from the center and lacking in basic services (Table 5, Figure 10). This scenario showed that even with the application of restrictive passive house standards, the final results may be worse than with the application of usual energy-saving model (scenario 1) as in (L2), (L5) and (L7). The reasons for this may be the non-ecological lifestyle of residents, the use of non-renewable energy sources as the main energy source (for powering buildings and vehicles) or the increased individual mobility of residents.

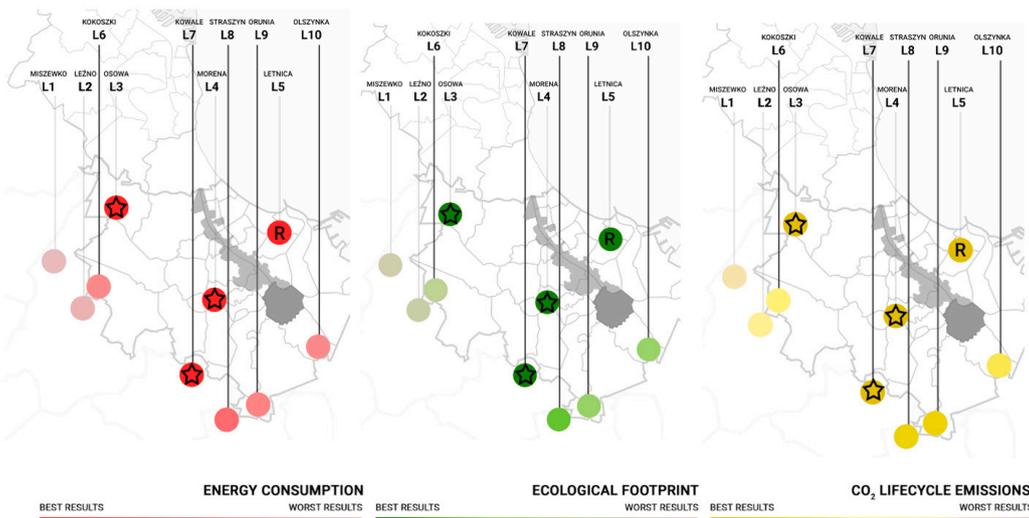


Figure 10. Potential future trend scenario with passive house results. Graphical representation of ELAS simulation results according to total housing complex energy consumption, ecological footprint and CO₂ lifecycle emissions. Markings: R—reference location; star—results better than or equal to the reference location results.

3.4. Potential Future Simulation: Green Scenario with Passive House Standard

The most favorable option in terms of energy consumption, ecological footprint and CO₂ lifecycle emissions for all locations, considering activities at an architectural scale (improvement of energy efficiency) and urban scale (mobility, renewable energy sources), was a combination of the green scenario with the passive house standard (Tables 6 and 7 and Figure 11).

Significant improvement in results is visible in all locations. The most favorable results were at the locations of Kowale (L7), Morena (L4) and Osowa (L3), which were more favorable than at the reference location of Letnica (L5).

Significant energy and environmental optimizations at an architectural and urban scale can result in development complexes situated on the outskirts of cities having similar or even better results than locations close to the center. Such results would not have been achieved without optimization at different scales. This confirms the thesis that if a green scenario and restrictive energy efficiency standards are used, it is possible for suburban locations to favor urban energy efficiency. The key in this is also the lifestyle of inhabitants, sustainable mobility patterns, optimized municipal infrastructure and access to services.

In terms of energy demand, the greatest improvement in results took place in Osowa (L3), Morena (L4) and Kowale (L5). Interestingly, the results here were more favorable than in the reference location Letnica (L5). Possible reasons for these results are first- and second-degree services achievable in the immediate vicinity. In the case of Kowale (L5), although it is not located within the administrative borders of Gdańsk, services of a degree of centrality of four are available within a range of maximum one kilometer (such as specialized shops, high schools or vocational schools (1.00 km), bank branches, medical specialists, secondary schools (1.00 km), grocery stores and primary schools) and proximity to waste collection points and public solid waste collection (until 3 km), a degree of centrality from 5 km to 9 km.

For Morena (L4), services to a degree of centrality of four are available within a maximum of one kilometer. Specialized shops, high schools or vocational schools are distanced at 1.00 km, bank branches, medical specialists, secondary schools are also at a 1.00 km distance, as well as grocery stores and primary schools. At a 4.3 km length is the sewer line between the settlement and the sewage treatment plant at a distance of 6.80 km, with public solid waste collection at a distance of 6.10 km.

Olszynka (L10) turned out to be the biggest surprise regarding the results. Despite the location within the administrative boundaries of Gdańsk and the close proximity to the functional center, this location obtained poor results. This was most likely caused by lack of first-order services (grocery stores, kindergartens, elementary schools, etc.) in close proximity to the newly designed building complex, and, in addition, the lack of remote facilities, such as garbage dumps.

This simulation showed that the close location of certain services (their reachability on foot within about 1 km from the planned building complex) may be more important for urban energy efficiency than location within the administrative borders of the city.

Comparison of Energy Results within Given Categories in Relation to Reference Location: Letnica (L5)

Everyday mobility is highest in the locations most distant from the centers: L1, L2, L6, L9, L8. The only exception is Olszynka (L10), located near the center, whose everyday mobility result is more than twice as high as in the reference location. Most likely, such results are determined not only by the distance from the city center, but also by service facilities at the appropriate degree of centrality.

This can be proved by the results in the category everyday mobility for Osowa (L3), Morena (L4) and Kowale (L7), which, despite their visible distance from the functional center of Gdańsk, have access to key service elements in the immediate or close vicinity. In terms of everyday mobility by individual car, the difference in kilometers traveled per year per entire building complex is nearly 1,000,000 km more for the Olszynka location (L10) compared to the location of Orunia (L9).

Interestingly, the results of vacation mobility are similar in all locations—this demonstrates the relatively similar mobility of residents regardless of where they live.

The percentages of space heating and hot water supply are also the same in all locations, because the same data for the building complex and their energy standard were adopted as fixed.

Electricity demand was also a constant value and these results are similar in all locations

Visible differences in results can be seen at municipal services. Based on the results of the analysis, the energy consumption associated with municipal services is the highest in the locations furthest from the functional center and facilities due to the remoteness of facilities, such as garbage dumps, water intake points and waste collection points.

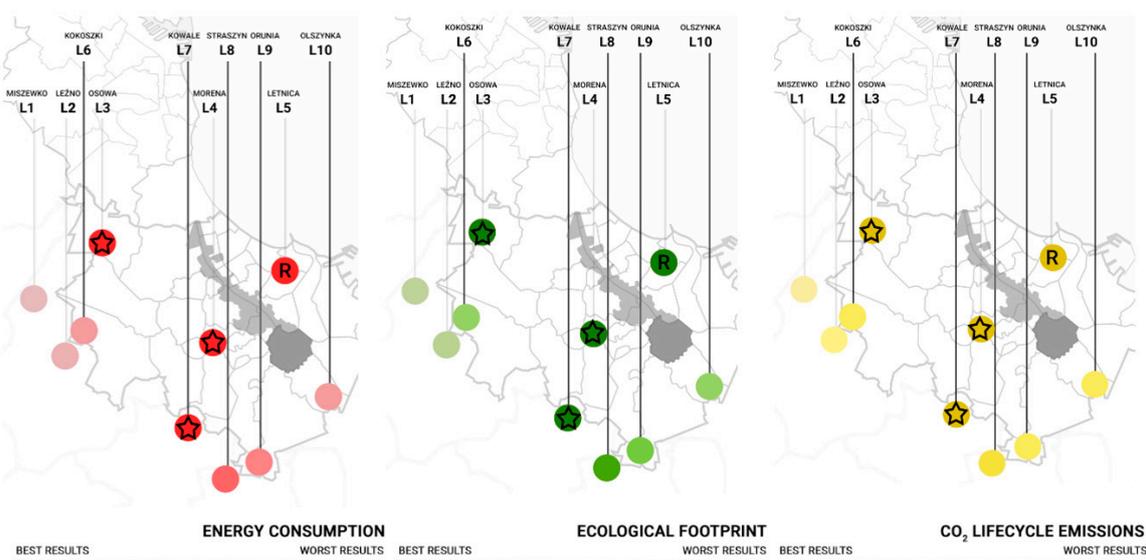


Figure 11. Potential future green scenario with passive house results. Graphical representation of ELAS simulation results according to total housing complex energy consumption, ecological footprint and CO₂ lifecycle emissions. Markings: R—reference location; star—results better than or equal to the reference location results.

Table 5. Result data of simulations: trend scenario and Passive House standard (building energy standard: 15 kWh/(m²·Year)).

Output Data	Locations Tested: Low Energy Standard									
	Miszewko (L1)	Leżno (L2)	Osowa (L3)	Morena (L4)	Letnica (L5)	Kokoszki (L6)	Kowale (L7)	Straszyn (L8)	Orunia (L9)	Olszynka (L10)
Energy consumption (kWh)	59,342,700	52,929,545	38,764,469	37,896,135	38,709,938	47,083,968	37,645,777	43,430,764	44,103,942	45,730,380
	153%	137%	100%	98%	100%	122%	97%	112%	114%	118%
Ecological footprint (SPI) m ²	7,136,200,490	6,746,831,773	5,865,891,843	5,809,289,644	5,841,834,312	6,346,613,716	5,768,570,272	6,124,566,619	6,170,830,264	6,269,818,619
	122%	115%	100%	99%	100%	109%	99%	105%	106%	107%
CO ₂ life cycle Emissions	24,216,167	22,354,485	18,300,446	18,034,562	18,253,399	20,561,818	17,903,304	19,543,039	19,764,347	20,214,782
	133%	122%	100%	99%	100%	113%	98%	107%	108%	111%

Numbers in bold show the results closest to the results of reference location.

Table 6. Result data of simulations: green scenario and passive house standard (building energy standard: 15 kWh/(m²·year)).

Output Data	Locations Tested: Low Energy Standard									
	Miszewko (L1)	Leżno (L2)	Osowa (L3)	Morena (L4)	Letnica (L5)	Kokoszki (L6)	Kowale (L7)	Straszyn (L8)	Orunia (L9)	Olszynka (L10)
Energy consumption (kWh)	45,056,643	40,308,565	30,203,982	29,444,156	30,270,629	36,229,117	29,226,473	33,570,636	34,243,815	35,288,151
	149%	133%	99%	97%	100%	120%	97%	111%	113%	117%
Ecological footprint (SPI) m ²	2,289,807,602	2,056,150,315	1,653,062,687	1,599,948,288	1,672,806,160	1,877,966,775	1,581,881,362	1,775,467,982	1,834,976,404	1,857,967,307
	137%	123%	99%	96%	100%	112%	95%	106%	110%	111%
CO ₂ life cycle emissions	8,630,809	7,846,437	6,636,217	6,428,498	6,728,780	7,287,172	6,352,932	6,982,459	7,229,713	7,257,662
	128%	117%	99%	96%	100%	108%	94%	104%	107%	108%

Numbers in bold show the results closest to the results of reference location.



Table 7. Potential future. Comparison of energy results within given categories in relation to reference location: Letnica [L5].

Category of Results	Locations Tested: Green Scenario and Passive House Standard									
	Miszewko (L1)	Leżno (L2)	Kokoszki (L6)	Olszyna (L10)	Orunia (L9)	Straszyn (L8)	Letnica (L5)	Osowa (L3)	Morena (L4)	Kowale (L7)
Everyday mobility in number (total per Year (kWh/Year))	17,887,487	13,180,900	9,310,883	8,186,851	7,122,713	6,479,132	3,148,145	3,050,602	2,296,644	2,104,306
Everyday mobility in comparison to reference location	568%	419%	296%	260%	226%	206%	100%	97%	73%	67%
Vacation mobility in number (total per Year (kWh/Year))	9,056,385	9,029,119	9,057,279	9,033,767	9,040,367	9,030,501	9,050,918	9,061,195	9,039,356	9,060,207
Vacation mobility in comparison to reference location	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Space heating hot water supply (total per Year (kWh/Year))	8,470,648	8,464,798	8,441,384	8,469,156	8,458,222	8,459,800	8,445,505	8,457,114	8,450,472	8,446,450
Space heating and hot water in comparison to reference location	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Electricity in number (total per Year (kWh/Year))	6,307,930	6,328,444	6,303,866	6,316,579	6,300,861	6,311,279	6,296,290	6,342,836	6,330,493	6,312,918
Electricity in comparison to reference location	100%	101%	100%	100%	100%	100%	100%	101%	101%	100%
Municipal services (total per Year (kWh/Year))	1,261,586	1,209,256	1,195,560	1,199,797	1,198,533	1,174,972	1,180,554	1,177,955	1,177,766	1,198,285
Municipal services in comparison to reference location	107%	102%	101%	102%	102%	100%	100%	100%	100%	102%



4. Discussion and Conclusions

A novelty was conducting innovative comprehensive research based on the combination of a Polish edge city model analysis with analysis of urban energy efficiency. Such research is original in social sciences and it responds to the most urgent social, energetical and environmental problems.

According to the initial research hypothesis, the most advantageous scenario for each location is the combination of interdisciplinary urban solutions with adaptations at an architectural scale (green scenario combined with the passive house standard).

Improving the energy efficiency of building blocks alone resulted in a significant reduction in energy demand; however, the largest saving occurred when investing in energy efficiency at both an architectural and urban scale, including ecological lifestyle, mobility and the use of renewable energy sources.

With the development of decentralized energy systems [27] and growing environmental awareness of inhabitants [28], there is a great potential to strengthen the sustainable energy transition and almost equalize the energy parameters of suburban dwelling complexes with those located closer to the city center. Lower carbon technologies, such as smart grids and microgeneration equipment, can provide support to make energy consumption and energy costs more transparent to individual users [28]. However, they also require a greater change in users' behavior [30]. Respecting this, they may constitute a solution for energy acquisition in peripheral areas where building new infrastructure is not always profitable.

Community engagement [57] of individual suburban householders should be strongly emphasized in a transition to the decentralized smart grid projects and local forms of energy generation linked to a more sustainable lifestyle. These actions can be developed as a part of the 'Transition Towns' movement [28,58], underlining the need to use local energy and local basic good supplies and production in post-oil cities.

Suburban locations are not, in general, favoring urban energy efficiency, but with some improvements, they can achieve similar or even better results than locations close to the functional center of the TMA. The preconditions are: self-sufficiency, energy efficiency, renewable energy source application, ecological and sustainable mobility patterns and vicinity of services.

The study showed that, with appropriate architectural and urban parameters, suburban housing complexes can have the same or better results of urban energy efficiency than those situated closer to the functional center of the TMA. Hence, it was possible to compensate for the results of urban energy efficiency in the case of districts located far from the functional center of the city and its infrastructure.

Location of an eco-district within a city's administrative area is not the most important factor in shaping spatial energy efficiency. Locations having the best parameters were districts close to services with good connections to municipal infrastructures. Further important factors were mobility and access to municipal infrastructures.

The most favorable locations turned out to be those that were not necessarily the closest to the functional center of the city but had services of possibly all centrality degree. Both architectural and urban aspects had the greatest impact on the remarkably good results of suburban housing complexes in relation to energy efficiency of buildings, sustainable mobility, municipal infrastructure and access to relevant services.

The application of only a restrictive energy-saving standard in the entire district (passive house) with the absence of urban optimization and the lack of social commitment to the ecological lifestyle (trend scenario) resulted in the final results of energy demand, CO₂ lifecycle emissions and ecological footprint being similar or worse than in the basic version (low energy scenario).

This proves the importance of implementing energy-saving and environmentally friendly activities both at an architectural scale (in the form of restrictive energy standards) and urban (green scenario).

Eco-districts with restrictive energetical and environmental parameters may become a remedy for chaotic suburbanization and provide an alternative approach, based on comprehensive spatial planning, respecting sustainable mobility and a rational low emission approach.

The reason for such favorable results in the suburbs of the Tricity metropolitan area was probably their specific morphology—the Polish edge city model.

Furthermore, the Vauban eco-district, due to the typology of its buildings and its dimensions, was possible to use at the TMA scale and created the potential to use it for testing in other edge city locations.

The study showed the potential for favorable parameters of urban energy efficiency in suburbs that can be correlated with intensified services. Therefore, the schematic distribution pattern of best urban energy efficiency in individual parts of the edge city may differ significantly from a city model with the occurrence of a central business district.

In future studies, it would be interesting to extend the research to other cities with this type of suburb (e.g., European and American cities) and compare the results. Officially classified edge cities are large metropolises that comprise of at least five million square feet (465,000 m²) of leasable office space (e.g., the Paris and New York models also have an active center and active suburbs). However, Tricity metropolitan area has all the features of an edge city concentrated in a smaller area that allowed for successful empirical research and can be developed further.

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