Looking for Metropolitan ecological area

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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 how to look for metropolitan ecologacl areas and why so many of the acknowledged ecological housing complexes are located on the outskirts of cities or suburbs and . 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 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 showed 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][4][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][10][11][12][13][14][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][18][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][33][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. [36][37][38][39][40]

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	• Density • Topography • Location • Exposition	• Technological density • Sealing of soil • Open space design at specific locations • Residues	• Preliminary land uses	• Density of jobs • Building quality and form
TRANSPORT		• Means of transport • Distance covered • Travel time	• Combination of routes	• Nearness
RESOURCES, ENERGY	• Resource base	• 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	• Density of resources • Energy cascades • Space heating and hot water demand • Process energy demand • Light and power demand	• Environmental impacts • Used resources • Energy generation technologies • Formation of clusters
ECONOMY	• Mix of functions	• Facilities	• Mix of economic sectors	

Elements of integrated spatial and energy planning

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.

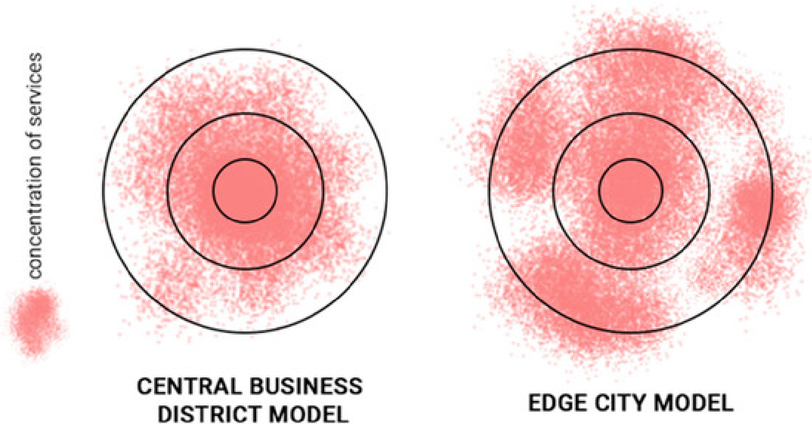

Figure 2. Authors' diagrammatic representation of service distribution within cities of different morphological models: in the American central business district model and in the Polish edge city model.

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).

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

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.

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 PM2.5 and PM10 dust concentration limits are regularly exceeded [53].

2. Method

In the research, the empirical method of conducting a series of computer simulations using the ELAS tool [39] was adopted (Fig. 4). Total energy consumption, ecological footprint and CO_2 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 (Fig. 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/m^2 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/m^2 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 CO_2 lifecycle emissions) (Tables 3, 4 and 5). 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.

3. Main conclusions and future remarks

- Suburban locations are not in general favouring urban energy efficiency, but with some improvements they can achieve similar or even better results than locations close to the functional centre of the TMA. The preconditions are; self-sufficiency, energy efficiency, renewable energy sources application, ecological sustainable mobility patterns and vicinity of services.
- Both the improved architectural and urban aspects; including the energy efficiency of buildings, sustainable mobility, municipal infrastructure and access to relevant services had the greatest impact on the remarkably good results of suburban housing complexes.
- Energy and environmental improvements concentrated only at architectural scale (building energy performance only) when combined with unecological lifestyle, non-renewable energy provision and unsustainable mobility patterns (trend scenario) proved to be even worse than standard energy-saving approach concentrated at architectural scale with ecological mode of development (standard scenario). This proves the importance of implementing energy-saving and environmentally friendly activities both on an architectural scale in the form of restrictive energy standards and at the interdisciplinary urban scale (green scenario).
- Obtaining particularly good results of urban energy efficiency in the suburban locations was possible thanks to a certain morphological model of Tricity Metropolitan Area (edge city model)
- Location of an eco-district within the city's administrative area is not the most important factor in shaping spatial energy efficiency (locations having best parameters: districts close to the services with good connection to municipal infrastructure), further important factors: mobility and access to municipal infrastructure
- Eco-districts with restrictive energetical and environmental parameters may become a remedy for chaotic suburbanization and provide an alternative approach, basing on comprehensive spatial planning, respecting sustainable mobility and a rational low emission
- A novelty was conducting innovative comprehensive research based on understanding the relations between central business district model with Polish edge city model with the analysis of urban energy.

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