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Passive and Active Solar Systems in Eco-Architecture and Eco-Urban Planning

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Abstract: The subject of this article is a presentation of multi-scale passive and active solar and shading systems in urban areas. This research assumes the hypothesis that insolation systems are interdependent and that their integration in urbanized space affects the city biome. Attention has been paid to the role of innovative solutions used in the field of ur ban insolation, such as heliostats in the development of future eco-architecture and eco-urban planning. This research has been based on the assumption that only by taking into account the close symbiosis between an energy-efficient building and its appropriate insolation, in combination with properly planned surroundings, it is possible to actually achieve the principles of sustainable development in the urban fabric. The analytical part concerns detailed investigation into solutions in the field of passive and active solar architecture and urban planning, regarding both insolation and shading. The article analyzes source materials, includes descriptions of case studies, and presents a comparative analysis of passive and active solar and shading systems. The research method, both empirically and theoretically, is closely related to case study analysis and has involved collecting and systematizing data on micro and macro "solar" design systems.

Keywords: passive and active solar systems; solar architecture; heliostats; multi-scale systems of insolation; future cities

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1. Introduction

The sun has always played an important role in architecture, and this is reflected in the planning of the urban fabric due to its importance for human health as well as for the quality of the natural environment. From ancient times until now, appropriate sun exposure for buildings has helped to create friendly, natural spaces for inhabitants and for wildlife, and thus has indirectly influenced the quality of life in urban areas. It was important enough for the inhabitants that provisions concerning it as a right appeared in different ages and in different cultures, for example, *Leges Duodecim Tabularum* in the Codex of Justinian and *De architectura libri decem* representing the Roman "right to the sun", the Doctrine of Ancient Light and Law of Ancient Lights in England, and the Doctrine of Prior Appropriation in the United States of America [1]. Despite the presence of the sun, which is the basis of all life on Earth, ensuring appropriate exposure to sunlight and the right amount of solar radiation in a densely built-up city is not an easy task, and it requires the implementation of regulations. Therefore, in many cities, legal provisions that take into account the requirement to maintain open spaces and pedestrian routes to ensure such sunlight (e.g., in New York City, San Francisco, Toronto, etc.) have been defined. These provisions relate to many elements, including the geometry of buildings, regulating their height, etc. In New York, access to sunlight in the urban fabric was historically covered by the Zoning Act (1916) [2,3]. Currently, the principles for designing energy-efficient buildings are largely based on creating optimal relationships between a building and its surroundings. The sun plays a fundamental role in modern design. Energy-efficient buildings are shaped in such a way that they have the largest possible surface open to the sun, to optimally use light and thermal energy, while maintaining compactness and at the same time avoiding heat loss. Such solutions introduce a spatial order, assume a reduction of pollutant emissions and support the protection of the natural environment. The introduction of various insolation systems into the urban fabric can significantly lead to the construction of an energy-sustainable city.

The academic literature abounds in information about active and passive solar systems, the history of their creation and development, as well as their use in architecture among many others [4–10]. However, in the changing economic conditions associated with the struggle against climate change, it seems more important to find links between the use of these systems at different scales and to ask whether such solutions can be safely used in urban systems in a model for a sustainable, zero-emission city. In their work, the authors have analyzed not only commonly known examples of solar architecture and solar urban planning against their historical backgrounds, but have also presented the latest patented, innovative solutions in this respect. The most important part is an analysis of the possibility of applying zero-emission solutions into the urban fabric at micro- and macroscales, thus supporting the Green Deal and the protection of the natural environment [11–18]. Attention has been drawn to the opportunity to chain solar systems into a synergistic system, allowing for an emission-free energy supply to houses, housing estates, districts and the entire city, while supporting its natural system by the lighting of areas where there are high buildings [19–22]. The authors argue that the integrated and chain-synergistic use of active solar systems should be a new trend in the design of ecological cities and districts, and that this can significantly contribute to improving the quality of the environment within an urban area.

2. Materials and Methods

Searching for an answer to the question of the direction to which eco-architecture and eco-urban planning will take in terms of the sun and its pro-health role, the article analyzes historical and contemporary solutions related to insolation. Concerning constantly progressing urbanization, which has problems with sunlight in modern, densely built-up cities, special emphasis has been placed on urban planning solutions. The research has taken into account such methods as heliostats, as these are slowly being introduced in urban areas both at the scale of a building and the city as a whole. The paper is divided into three fields of research: (1) a review of passive and active systems, (2) a historical review of solar systems used from ancient times to the present, (3) an analysis of the relationship between the use of solar energy at different settlement scales. The analytical part concerns detailed investigation into solutions in passive and active solar architecture and in urban planning regarding both insolation and shading. The authors' research hypothesis is the assumption that micro (on a building scale) and macro (on a city scale) solar radiation systems are mutually dependent and may interact synergistically. Their integration into the space of the urban fabric influences a city's biome and should set directions for the development of future eco-architecture and eco-urban planning. The results are presented in diagrams that combine multi-scale solutions for active and passive solar and shading systems. In these diagrams, active solutions for insolation are supported by passive solutions, with the macroscale (the scale of the residential complex) being the framework for the urban design of energy-sustainable cities and setting the stage for other energy-saving investments on an architectural scale. The article analyzes source materials, includes descriptions of case studies, and presents a comparative analysis of passive and active solar and shading systems. The research method, both empirical and theoretical, is closely related to case study analysis and has involved collecting and systematizing data on micro- and macrosolar design systems.

2.1. Solar Architecture and Solar Urban Planning: The State of the Art

2.1.1. The Health-Promoting Role of the Sun

The influence of the sun on human health has been known since antiquity. In the Egyptian city of Helum near Cairo, there was a sanatorium in which patients were treated with sunbaths. Another solar sanatorium, with a medical school founded by Hippocrates, was located on the island of Kos. Roman baths, in accordance with the principles of Pliny the Elder, "Sol es remediorum maximum", were also equipped with solariums. The sun sends an enormous amount of energy to the Earth. Light deficiency however causes a biochemical imbalance in the hypothalamus, which is believed to be the cause of winter depression, especially in northern countries. The sun's rays increase the amount of iodine in the thyroid gland, increase the number of red and white blood cells, produce vitamin D, which has an anti-inflammation effect in children, supports the treatment of inflammation, and has a bactericidal, virucidal and prophylactic effect on bone inflammation [23]. In 1903, the Danish physician Niels Rybug Finsen received the Nobel Prize for research into the healing effects of sunlight [24]. At the beginning of the 20th century, Auguste Rollier, author of the book "Heliotherapy", opened the first "Sun Clinic" in Europe in Leysin, Switzerland, designed by the Austrian architect Otto Wagner [25,26]. The sanatorium had a spacious roof terrace where patients could sunbathe. By 1933, a list of 165 diseases successfully treated with the sun's rays had been made. Conversely, a daily excess of artificial light (known as "light pollution") affects the secretion of melatonin, a hormone responsible for healthy sleep, and especially important for mental and physical well-being. Hence, it is important to properly illuminate buildings and the surface of the urban area.

2.1.2. Solar Architecture from Antiquity to Modernism

"Passive" houses, in terms of insolation, had already appeared in ancient cultures in South America, as well as in Egypt, Mesopotamia, Persia and China. In Greece, the way both houses and cities were built was an excellent example of solar construction, the aim of which was to provide each home with sufficient light and heat, especially in winter. Socrates' house, as described in ancient literature, looked toward the sun. The largest windows were located on the south side while the "pantry" on the north side served as a buffer space protecting against the cold [4]. Olynthus, one of the most important Greek cities, used southern solar exposure in its urban complex. Each of the houses had all its rooms used for living, opening onto the south side of a portico. In Delos, the walls on the north side were lower than on the south side, and this allowed for additional insolation of the rooms in winter and for limiting the inflow of sunlight during hot summer days. The Romans used glazing widely in winter gardens and glass houses, thus accumulating solar heat by creating a greenhouse effect in the interiors [27,28]. From the 1st century AD, Roman houses used flat and convex glass combined with metal. Marcus Vitruvius Pollio, a Roman architect living in the 1st century BC recommended that the appropriate location of a residential building should take into account its relation to the sun [29]. In Laurentum in the house of Pliny the Younger in the Apennines, solar heating was used by locating the so-called solar furnace room (a concentric room, with windows to the south, south-east and south-west, from where heat was distributed through a system of pipes to the rest of the house) [28]. Starting from the 1st century AD until the fall of the Roman Empire, solar energy was used to heat houses, conservatories and Roman baths, and an element of Roman law was the so-called "Solar Law". With the fall of the Roman Empire, the tradition of constructing conservatories and of using the sun in architecture disappeared for many centuries [27,30].

From the 16th century, domestic glasshouses added onto the southern side of buildings were commonly found in the Netherlands, France and England. In Renaissance Italy, Palladio used Vitruvius' advice on buffer spaces in his projects to place rooms more frequently used in winter on the south side with summer rooms on the north side. In the 17th century, in France and England, "fruit walls" were used—solar walls of various structures and a southern exposure [28]. In the 18th century, greenhouses and conservatories located against residential houses became common. In the 19th century, such elements were gradually transformed into larger buildings that housed exotic plants. Having a greenhouse at that time became synonymous with higher status, and this was one factor resulting in their development. An excellent example of such a building serving as a public space was the Crystal Palace of Joseph Paxton, built of glass and prefabricated elements for the Great International Exhibition in London in 1852. In the 19th century, Polish manors were in principle energy-efficient with a front facade, tilted axially toward the south, due to which the sun in the period from April to September could reach all walls of the house during the day [4].

Since the mid-19th century, there has been a growing interest in the active use of the sun in architecture. On a wave of interest in innovative solutions, solar collectors that use the energy of the sun to heat water, houses and support the functioning of various devices have appeared. In 1885, the French engineer Tellier introduced low-emission solar collectors to drive a solar pump used in agriculture [27]. In 1889, the industrial production of water tanks heated with the energy of the sun, patented by C.M. Kemp, was launched. Built in 1902, the Larkin Office Building, designed by Frank Lloyd Wright, was the first to be air-conditioned. At the same time, projects using photovoltaics were being developed [28].

At the beginning of the 20th century, the expression "light, air, sun" became one of the crucial postulates of modernist architecture. In 1943, in the Athens Charter, Le Corbusier called for the introduction of the sun into architecture as "a new and necessary task for architects". In his designs, the sun not only fulfills a hygienic, pro-health function, but remains an important means of architectural expression [12,30]. There are not only excellent examples of residential architecture open to the sun, but also modern factories using sunlight to illuminate working spaces. One typical example of solar architecture is the van Nelle coffee and tobacco factory in Rotterdam, which was built in 1930 by the architects Brinkman & Van der Vlugt. Another example are the buildings of the Bauhaus in Dessau designed by Gropius from 1926. Unfortunately, the enormous area of glazing and the absence of air conditioning in the summer did not meet the microclimatic requirements for the building. The construction of a Salvation Army shelter for the homeless in Paris, designed by Le Corbusier, has also become a negative example. However, the value of the sun "woven" into architecture was recognized, and in 1996, an international group of architects signed the "European Charter for Solar Energy in Architecture and Urban Planning". This charter was planned to set new directions and trends in the development of solar architecture focused mainly on obtaining and storing solar energy [30].

2.1.3. The Use of the Sun in Urban Planning

The use of the sun to create better architectural solutions has been echoed in urban design. The emergence of urban concepts in ancient Greece, aimed at making optimal use of the sun, was in part due to the need to protect the forests needed to supply wood for heating homes, building houses and ships. The location of a city and the way it was built were to ensure optimal benefits from solar energy. This was favored by the grid nature of city layout known from the classical period, making use of the sunny southern orientation of buildings and natural ventilation. An example is ancient Priene, where the topography supported "solar" solutions, due to which each of the houses in a row were fully open to the sun. Pre-Columbian settlements in southwestern North America are an interesting example of deliberate urban design using optimal sunlight conditions. Housing by the Anasazi was built into the southern walls of cliffs or in open terrain, and a characteristic feature was their compact, terraced buildings open to the south [31]. Acoma, inhabited by the Pueblo since the 12th century, consists of row buildings in the form of two or three-level houses. Massive external walls acted as accumulation walls, storing heat. The northern walls had only small window openings, serving as a buffer for the residential part, while the protruding horizontal walls covered with boards and branches created a shading zone. Based on the idea of a pre-Columbian "passive" house, the town of Taos among others in the Sangre de Cristo Mountains in the north-central region of New Mexico was founded in 1615.

In the era of intense industrialization, interest in health-promoting conditions increased in the then polluted, wet and shady cities. An example of a model housing estate that used orientation toward the sun to obtain optimal sunlight is the industrial town of Port Sunlight in England. The French architect Augustin Rey proposed two-, four- and six-story buildings for modern working-class housing and at the same time determined the minimum distances between buildings such that they would not shade one another during the winter. Augustin Rey also conducted studies on the size of window openings and their influence on interior lighting, as well as the geometry of the ceiling, which would allow better illumination of a room through reflected natural light. In designing *Cité Industrielle*, Tony Garnier used the ideal sunny city of Olynthus as a model. The buildings in the modern city faced south, and houses occupied only half of their plots, so as not to shade neighboring buildings during the winter. In the era of modernism, under the influence of the Athens Charter, there was a growing interest in green, sun-oriented city design. After the First World War, solar architecture was used in the design of housing complexes for the working class in the Netherlands, Sweden and Switzerland. Multi-family residential complexes designed in rows were being built, such as Tussendijken and Kifhoek in Rotterdam, or the Heuberg estate in Vienna. As part of the Bauhaus trend in architecture and urban planning, Walter Gropius created a large urban complex in 1928, while Dammerstock, May and Boehm in 1929 designed the Goldstein estate in Frankfurt am Main, and in 1925 Taut and Wagner, the Britz estate in Berlin. The construction of cheap, new, modernist housing, optimally oriented toward the sun, quickly turned out to be a success. A series of row-type houses, based on the north–south axis of the Siemensstadt housing estate in Berlin, were being planned. With time, however, it was noted that such an orientation of buildings resulted in an insufficient supply of sunlight for most of the day during the winter, a major obstacle to functionality. In the modernist postulates of Le Corbusier, there were ideas to create horizontal windows running from support to support, due to which interiors were to be evenly illuminated [13]. Horizontal windows illuminate an interior much better than vertical ones. In the late 19th and early 20th centuries, William Atkinson drew attention to the influence of tall buildings in Boston that limited the access of light to low-rise buildings, and thus the height of newly designed buildings was reduced [32]. Appropriate use of sunlight in urban areas is an important and at the same time difficult element of conscious and responsible city design. Such activities are part of a new trend for the pro-ecological use of natural resources by supplying energy to the lowest levels of the urban fabric (including urban greenery) through an appropriate amount of light.

3. Research: Passive and Active Solar Systems in Eco-Architecture and Eco-Cities

3.1. Passive and Active Systems in Solar Architecture

At Central European latitudes, the sun rises exactly in the east and sets exactly in the west only on March 21 and September 21; in summer, it lasts for as much as 16 h but in winter only 8 h [4]. In order to "keep" the sun inside the house for as long as possible, and at the same time store solar thermal radiation within rooms to give off heat after sunset, glazing of southern facades is needed using windows with high insulation and low heat transfer coefficients, along with accumulation walls made of appropriate materials that store heat such as stone, concrete or brick [5–7,20]. One of the most important issues affecting the microclimate of the interior of a house is its orientation. This allows for the use of sunlight during the day, zoning rooms in terms of thermal requirements and creating buffer zones e.g., a garage and utility rooms to the north, or a "winter garden" to the south [9]. Indoor solar light can also be actively "caught" through light chimneys—tubular skylights deflecting the sun's rays, solar lamps, and heliostats transmitting the reflected sunlight in any direction (Figure 1).

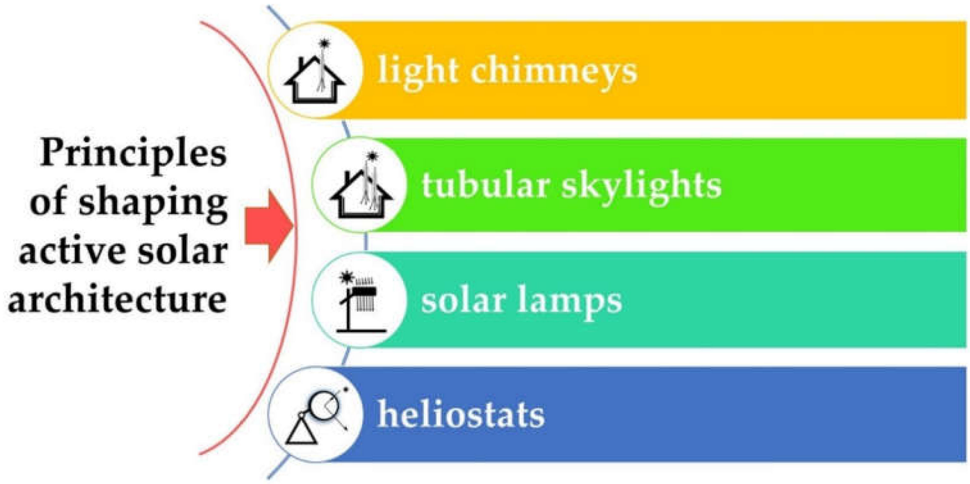

Figure 1. Principles for active solar architecture (authors, based on Baker and Steemes, 2000).

Currently, intelligent glass that can regulate transparency and screens reflecting the sun's rays are also used. Intelligent windowpanes often consist of thermal and optical properties that can automatically change their parameters depending on environmental conditions such as temperature or lighting and that can be controlled. Additionally, tinted, heat-absorbing glass is used, as well as selective panes covered with multi-layer coatings applied to both outer and inner surfaces.

The principles for passive solar architecture include (Figure 2):

- orientation;
- passive heating;
- creating buffer zones in buildings (a heat buffer using the greenhouse effect and a cold buffer using non-residential premises located on the north side) [9];
- use of an energy-saving form of building.

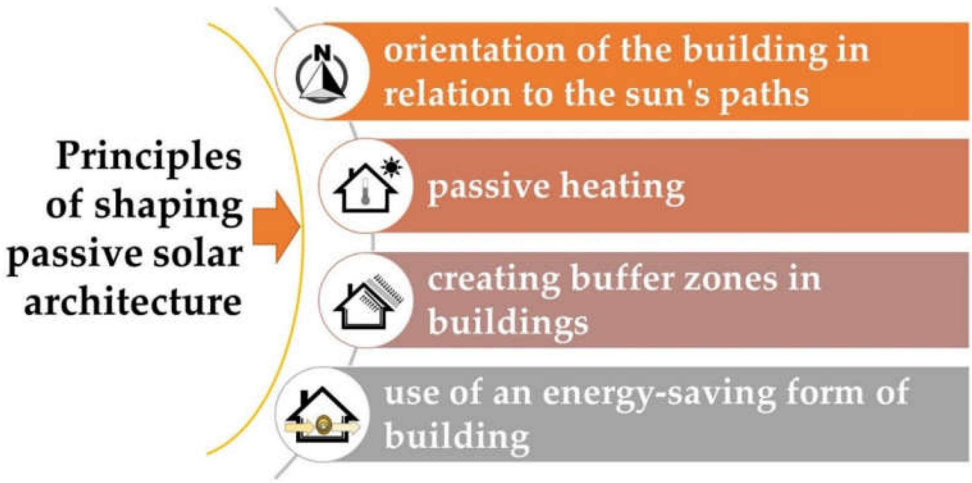

Figure 2. Principles for passive solar architecture (authors, based on Baker and Steemes, 2000).

The location of buildings using solar architecture should provide good insolation conditions (in this case, insolation means the average solar radiation per unit area) as well as the maximum number of sunshine hours per year. This situation is favorable for bioclimatic reasons, limits the use of artificial light and allows for the use of solar radiation energy in active and passive solar systems. The intensity of sunlight is significantly influenced by the orientation of the windows: most light penetrates through the windows in the facade of the building facing south-west, and through roof windows with an orientation from south-east to south-west at a slope of 30–45°, [10]. The inflow of solar radiation may be limited by shading from neighboring buildings or by trees; in this case, planting in the form of deciduous trees in summer protects against excessive sunlight but in winter enables maximum insolation.

When discussing solar architecture, the role of shading in energy-efficient and sustainable buildings cannot be overlooked. This function is fulfilled by active systems: intelligent glass panes allowing for automatic regulation of the light supply, shutters, awnings, curtains and blinds mounted outside the windows, between glass panes or inside the building, and passive shading systems such as absorption panes, selective panes, elements of garden architecture or natural shading in the form of trees, shrubs or climbers.

3.2. Passive and Active Systems in Solar Urban Planning

Contemporary cities are characterized by their large and constant development. The density of buildings seemed to be an ideal solution to the problem of urban sprawl over surrounding areas and has been identified as one of the priorities of sustainable urban planning. At the same time, the real need for modern cities is to improve the quality of the environment, eliminate pollution, minimize the urban heat island, and protect energy, raw materials and the natural systems of cities against the influence of human pressure. Compact and high-rise buildings in city centers not only seem to fail to solve these problems, but exacerbate them. In city centers, there is limited access to solar radiation, low air quality, often much higher temperatures and a lack of open spaces and greenery, which indirectly affect these phenomena [14,15].

Currently, architectural standards force an appropriate design on new buildings, and above all, these should meet energy-saving criteria. The relationship between urban and architectural design, intertwined into a single whole, is also important in contemporary energy-saving urban planning. High efficiencies in this area can be achieved through the appropriate design of residential and service complexes consisting of buildings designed to consume as little energy as possible, properly located, whose roofs and facades are available for renewable energy sources, and designed for an environmentally educated society that wants to save energy and monitor its consumption [16,17,33]. In a compact development, it seems almost impossible to maintain appropriate urban standards related to the orientation of the building, its location in relation to the surroundings and architectural standards concerning the form of the building, internal spaces, functional layout, etc. [18,19]. For difficulties illuminating rooms with daylight, collector-reflector systems integrated with the facade are used, allowing for a deeper penetration of daylight and its even distribution in the interior, such as light shelves, reflective windowsills or a system of curved mirrors. Heliostats that reflect the sun's rays inside are also used.

3.3. Heliostats and Their Application

One form of the active use of technology in insulating a building are the heliostats, which follow the apparent movement of the sun. They are equipped with flat or low curvature mirrors, and their goal is to reflect sunlight and direct it to a specific point. Heliostats are a basic element in tower-type heliopower plants; radiation is directed to the top of the tower, where a special receiver is placed whose task is to convert solar radiation from the many heliostats into heat, which is then converted into electricity. Despite the relatively simple operation, their construction raises many doubts and problems such as folding, assembly and, above all, synchronization of the work of sometimes hundreds of thousands of mirrors [20,34]. Heliostats are independent devices, each equipped with its own drive and position control system, and the construction of a heliopower plant has enormous costs, 40% of which are the building and commissioning of a heliostat field [35]. In addition, heliopower plants give rise to the high costs of servicing the heliostat field, e.g., cleaning the mirrors [36]. However, these devices can be selectively used in the urban fabric to illuminate a densely built-up area. Many solutions of this type already exist in cities.

3.3.1. Heliostats: Technological Aspects

Basically, heliostats consist of the following parts: base and foundations, drives for changing the elevation angle and azimuth, and mirrors with their supporting structure. The foundations and base of the heliostat should be solid enough to withstand the effects of changing weather and to ensure the functioning of the heliostat throughout its life cycle (20–30 years) [34,37]. The most important atmospheric factor influencing the high construction costs is wind pressure on the large plane that the mirror occupies. Different types of anchoring are used depending on the size of the heliostats. A concrete foundation is used for large heliostats (over 50 m^2 aperture), while piles driven into the ground can be used for heliostats in the 5–50 m^2 aperture range. For small heliostats ($\leq$5 m^2), anchors are used [35]. The task of the supporting structure and drives is to maintain a stable and precise positioning of the mirror, such that the reflected light falls on the receiver, often located several kilometers away. Depending on the power source, electromagnetic motors and hydraulic actuators are used, as well as various solutions such as worm, toothed, chain and wave gears, a capstan, planetary gears, linear actuators and others. On mirrors with surfaces in the range of 1–10 m^2 standard glass, thin-film glass with a thickness of <1 mm is used. In the future, glass will probably be replaced with polymers with appropriate parameters [35]. In Poland, at the Faculty of Energy and Fuels, a part of the AGH University of Science and Technology in Kraków, work is currently underway on the construction of a spherical heliostat, to protect the mirror against the adverse effects of external conditions while limiting wind pressure. According to the authors, the spherical shape of the heliostat will help to favorably distribute and protect its components from wind pressure, facilitate cleaning, and minimize dirt by easy drainage of rainwater from the protective dome. This will simplify the mechanical structure of the elements by replacing the actuators, contributing to better use and environmental protection. This technology is protected by patent no. PL.220774 [21].

3.3.2. Heliostats: Selected Case Studies of Urban Design

The sun plays a key role in urban space, has aesthetic and health-promoting functions, and affects the quality of life and comfort of residents. Sunlight allows well-known places to be looked at from a different perspective, bringing out their potential which is often extraordinary. One example of the use of heliostats on an urban scale is the Norwegian town of Rjukan, located in the Vestfjord valley adjacent to the Norsk Hydro hydroelectric power plant. Rjukan is surrounded by the Gaustatoppen Mountains where there is little sun from October to March. This location influences the inhabitants, their health and the economy. Indirectly, access to the sun or lack of it led to a situation in which the material and social status of the inhabitants were reflected in the insolation of their houses, depending on their height on the mountain slope [38]. For this reason, a group of architects proposed futuristic solutions based on an idea from over half a century ago to place heliostats on the slopes of the mountains, which would reflect and direct the sun's rays to the shaded town center. The scale and importance of the problem of insolation were proven by the fact that in 1928 a cable car route was opened, which allowed residents, for a small fee, to travel from the valley to the summit at a height of 886 m above sea level, from where they could rest in the sun's rays for at least a few hours during the day. In 2013, as part of the Rjukan Solar Mirror project, the Solspeil heliostat system was installed on the hillside to reflect and direct the sun's rays to the main square of Rjukan. Installed 450 m above the market square, three huge mirrors, with a total area of 51 m^2, move approx. every 10 s such that the market square remains illuminated for most of the day. The entire system is computer controlled and powered by solar batteries. This old idea and the innovative technical solution of the present time have had a real impact on the quality of life of the inhabitants in terms of physical and mental health as well as social contacts.

Another place that actively uses heliostats is the Austrian town of Rattenberg in the Tyrol. Here, a nearby hill to its south completely blocks sunlight from November to mid-February. Heliostats can solve this problem, and at Rattenberg, they are to be located approximately 400 m north of the town where their task will be to redirect sunlight to auxiliary floodlights located at the top of Castle Hill. Heliostats can move to different angles as they rest on a ball-joint, and their movement is controlled by a computer that automatically follows the movement of the sun.

Currently, the use of heliostats in the urban fabric is associated primarily with the problem of lighting in areas characterized by dense and high buildings. One such installation is the heliostat in Teardrop Park, a small city park located in downtown Manhattan near the site of the World Trade Center. Teardrop Park is surrounded by tall buildings that shade its space. Currently, the park is illuminated by three 240 m diameter mirrors placed on top of a residential building in Battery Park City overlooking the park [39]. Another park illuminated with a mirror system is One Central Park in Sydney where the Architectural Heliostat and Lighting System was conceptualized by architect Jean Nouvel and designed by Kennovations. The One Central Park lighting system is made up of 40 motorized heliostats located on the West Tower roof and 320 reflective mirror panels located on the East Tower cantilever. The light is redirected onto retail and landscape terraces [40].

A further interesting example of the use of heliostats to illuminate public spaces in Sydney is a 39-story tower at 14–22 Walker Street in Inner West Sydney. Heliostats placed on the roof of the building are 20 m high and reflect sunlight, directing it to the previously shaded Union Square [41].

3.4. Multi-Scale Model of Passive and Active Solar Systems

Contemporary ideas for ecological solutions in cities and housing complexes allow for a combination of various passive solar urban-planning solutions with active methods of using renewable energy in connection with municipal energy networks (Figures 3 and 4). This is favored by those with an interest in energy-saving solutions and the development of sustainable architecture and urban planning [16]. The diagrams below present solutions concerning active and passive solar and shading systems at two scales: the building scale (micro) and the residential complex scale (macro). In the diagrams, active solutions for insolation are supported by passive solutions; the macroscale (that of the residential complex) is the framework for the urban design of energy-sustainable cities and sets the stage for other energy-saving investments on an architectural building scale.

Historical analyses carried out for the purposes of this article show that passive solutions on a macroscale, including the optimal location of buildings, regulating the intensity of development, and modeling building height, dimensions and shape, have proven themselves in many cities, right back to antiquity. They have also turned out to be energy-efficient enough that they have found their continuation in modern eco-cities, such as Masdar in the UAE.

Using modern construction materials and research on energy-saving design methods, we can model the degree of permeability of buildings in relation to the sun's rays (e.g., using glass) or determine the optimal energy-saving type of urban development (e.g., quarter, linear or quarter-linear systems of buildings, etc.). Modern technological achievements allow us to supplement passive macroscale energy systems with active solutions, such as heliostats transmitting reflected sun rays, or intelligent mobile architecture using optimal sunlight conditions. These solutions are supported by the modern way of designing buildings, taking into account the use of active microsystems (such as light chimneys and solar towers) and passive microsystems (such as the glazing of southern facades, regulating the size and number of windows or the use of accumulation walls).

Figure 3. Multi-scale systems of passive and active insolation on micro- and macroscales (authors).

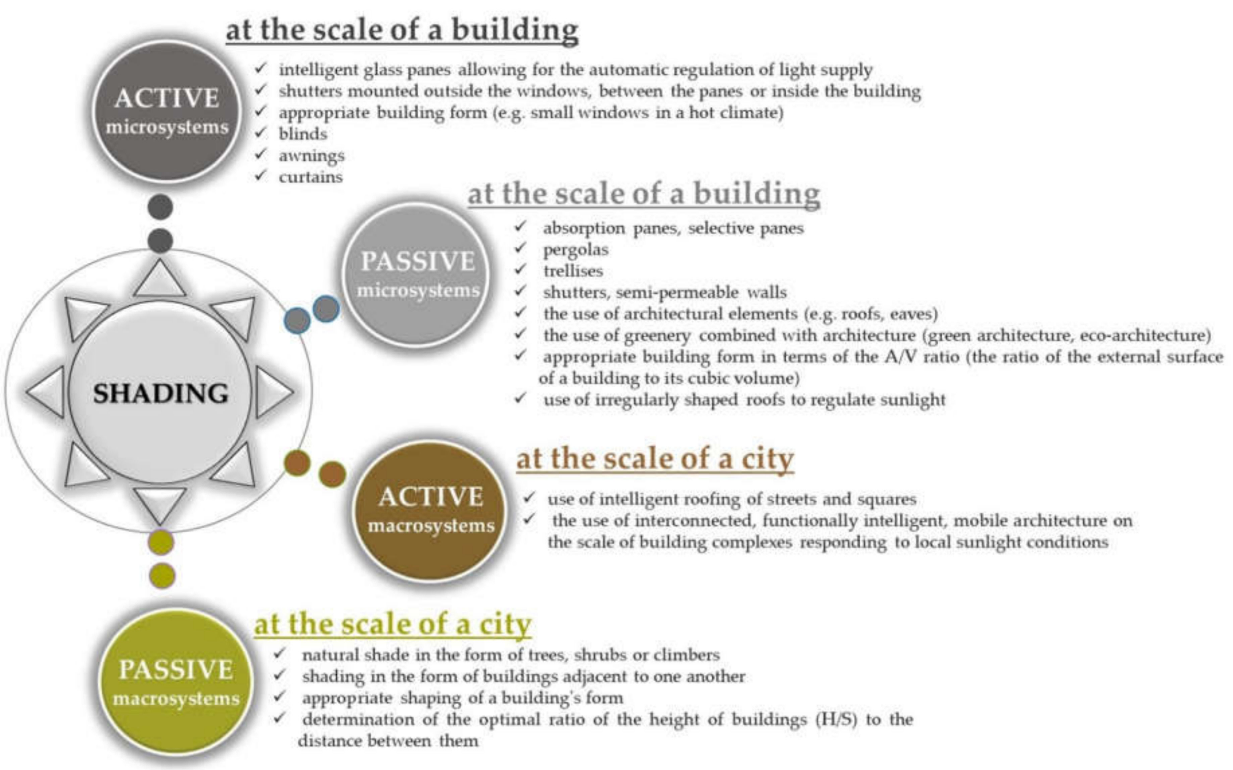

Figure 4. Multi-scale systems of passive and active shading on micro- and macroscales (authors).

In view of the constant warming of the climate, an important problem is how we can protect cities against excessive overheating, evaporation and the effect of the urban heat island. This is where multiscale passive and active shading solutions can help. Applications depend on the scale of a residential complex, e.g., intelligent roofing systems for streets and squares, the use of irregularly shaped roofs regulating sunlight, the use of functionally intelligent mobile architecture working together on the scale of the building, and the use of greenery combined with architecture, shutters, semi-permeable walls and other features.

4. Discussion

Interest in eco-urbanism itself, and its close connection with the use of renewable energy sources, should also affect the adoption of municipal and regional energy plans that will help in the assessment of solar potential, allowing for the identification of the most appropriate locations for passive and active uses of solar energy. This is one of the most important trends in the development of ecological cities, resulting in real energy savings with mutual benefits for man and nature. Due to innovative technological solutions, in the future, it will be possible to reflect, absorb, filter, store or even transport the sun's rays [14,17].

The intensive raising of awareness of the importance of sunlight and its beneficial effects in the urban fabric, on both humans by changing mentalities and responsible actions in urban space in the future, and on natural ecosystems, may have a significant impact on the development of preferred technologies related to illumination, and thus will contribute to reducing the negative impact of the city on the natural environment.

5. Conclusions

The geographical location of cities, their local physiographic conditions, insolation and level of pollution influence the diversity of climatic conditions in the urban fabric. In the city, there are microclimates (at the scale of buildings) and mesoclimates at the scale of districts and housing estates [42]. Both of these scales can be supplemented by the so-called neighborhood scale [43]. A phenomenon that significantly affects both the climate in the city and living conditions is the urban heat island, and this is related not only to the building system but also to traffic and the lack of ventilation. Due to the existing diversity of buildings, city space is characterized by uneven insolation where some of the radiation is dispersed and accumulated on the surfaces of buildings. The uneven distribution of solar radiation makes it much more difficult than in open areas to design sustainable architecture that makes use of the possibilities of insolation most efficiently. Urban areas, in comparison to areas surrounding a city, are characterized by 10% lower insolation in summer and up to 50% in winter [40]. Conversely, the value of absorbed energy is 15–30% higher than in surrounding areas [18,44]. The type, density and height of urban buildings are of great importance, while a quarter or linear layout is different than for dispersed buildings. It is important to remember other parameters influencing the local climatic conditions such as air circulation and humidity, which result in part from the location of housing complexes in relation to the system of main corridors ventilating a city [45]. When considering the energy-saving type of building complexes, it can be assumed that the optimal layout is a configuration of quarter and linear building, allowing for maximum insolation and heat accumulation, and at the same time ventilation. Among the parameters that have a direct impact on insolation, there is the density of buildings, the ratio of their height (H/S) to their distance from each other and the A/V ratio (the external building surface to its cubic volume) [18,44,46]. Among the problems of modern cities are the lack of space to allow for the optimal orientation of new buildings in terms of sunlight and ventilation, the obscuring of existing buildings that results in shading, and the limit to the supply of clean air.

When trying to find a solution for contemporary sustainable design on micro- and macroscales, new models for creating and redesigning existing buildings should be looked for. It seems important here to combine architecture and eco-urban planning in order to ensure the most efficient, energy-saving, and large-scale system for the urban fabric. In modern solar architecture, passive and active systems are combined, due to which a building functions similar to a living organism, optimally adapting to local climatic conditions.

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