Spatial Planning and Energy Efficiency in Urban Form

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As the urban population grows, so does their energy consumption, making efficiency critical to mitigate emissions and resource use. Thus, spatial and transport planning must include energy efficiency and their strategies, as these are vital to urban sustainability. In this sense, compactness has been shown to have many positive aspects that serendipitously go much in line with Jacobs' ideas. The urban environment is expected to host a growing number of dwellers in the coming decades, and compact urbanism is one possible solution to keep energy consumption under control while providing all the benefits of proximity.

Keywords: sustainable cities ; urban form ; urban planning ; transport planning

1. Eco-Districts: Harvesting Renewable Energy within the Built Environment

The development of more ecologically based and liveable cities has been advocated as a priority when aiming for sustainability [1] Integrating renewable energies into spatial planning, i.e., the creation of eco-districts, was suggested in [2][3] as a possible path to achieve this goal. Eco-districts should aim not only for their own energy independence but also to exchange surpluses with neighboring districts [4][5]. However, studies by Lombardi and Trossero [6] and by Bracco et al. [7] showed that self-sufficiency may be hard to achieve on a large scale, as it requires harnessing multiple renewable energy sources locally and the means to deal with their intermittencies.

Solar power is a renewable energy source that can be harvested in the urban environment and is a prime candidate for eco-district development. Integrating solar systems into the built environment can have several advantages, e.g., exploiting unused urban surfaces, limiting losses associated with long-distance transmission of electricity, and creating a more resilient electric network, capable of supporting extreme weather conditions [8][9]. Incentives for the installation of solar photovoltaic energy and solar energy solutions in cities are a possible policy to foster a transition to eco-districts [10][11]. Indeed, a study in the city of Daejeon, South Korea, found that the citywide deployment of solar energy via rooftop photovoltaic panels could fulfil over half of the city's energy needs [12]. A similar study in San Francisco, USA, found slightly lower but still significant savings, namely, 23–38% [13]. For an in-depth review on the deployment of renewable energy sources in urban areas, see [14].

2. Urban Sprawl

Urban sprawl is an extensive low-density, single-type land use that creates a lack of continuity and directedly impacts spatial, transport, and environmental planning [15][16]. Strong negative correlations exist between urban sprawl, energy consumption, and emissions [17][18]. Sprawled city development leads to large commuting distances, which in turn requires extensive roads that inevitably end up congested by excessive private car use. Other consequences are an increase in both air and noise pollution, a significant reduction in public transport ridership, and negative socio-economic consequences [17][19][20][21][22][23]. Studies [24][25] showed the clear effects of residential location on traveling distances, modal share, and transport energy consumption. Dwellers of sprawled suburbs have the worst accessibility and are restricted to motorized transport modes, as walking or cycling is not possible with homes being so distant from destinations. Consequently, transport energy consumption is high, as motorized private transport remains the best (most of the time the only) modal choice option for suburbs dwellers [26].

To avoid deepening the negative consequences of urban sprawl, cities must stop planning strategies that can result in sprawled neighborhoods and fight existing sprawl with policies that can infill central urban spaces [24][25]. The solution might lie in the past, within the utopian city plans developed by Howard or Le Corbusier [18][26][27][28]. A study by Monteiro et al. [29] compared a real city with sprawled districts with its redraft as a Garden City. Results showed that the Garden City layout improved accessibility to urban facilities and jobs by 41%, which can directly lead to a reduction in transport energy consumption and better public transport planning. This result provides a glimpse of what can be gained by planning cities and their expansions in a more thoughtful way.

An urban compact design is usually seen as a sustainable urban form [30]. Compact development leads to densification and mixed land use, which reduces distances and improves accessibility. These efficient land use policies reduce commuting time and private car use, directly impacting transport energy consumption [22][31][32][33]. A study by Zahabi et al. [34] found statistical significance between built environment variables and transport emissions in Montreal, Canada: A 10% increase in accessibility to public transport, density, and mixed land use results in a 3.5%, 5.8%, and 2.5% reduction in GHG, respectively. Likewise, a study on the Puget Sound region, Washington, USA, revealed that a 100% increase in mixed land use, residential, and intersection density in urban areas would reduce transport emissions by 31.2–34.4% [35]. Stone et al. (2007) [36] found similar results and highlighted the importance of compactness in reducing VMT. Wang and Zhou et al. (2017) [37] presented a literature review on the relationship between the built environment and travel behavior in urban China. The authors confirmed a strong connection between high density and mixed land use with shorter trips and larger active modal shares. In contrast, residents in the suburbs spend more time communing and have greater motorized transport dependency. Wu et al. [38] used survey data with over 22,000 traffic trip samples from nine streets in Ningbo, China, to analyze transport energy consumption with a regression analysis. With respect to built environment variables, they found that an increase of 1% in population density, mixed land use, and road intersection density lead, respectively, to decreases of 0.094%, 0.415%, and 0.079% in total transport energy consumption.

Although several studies show a positive impact of mixed land use and sprawl reduction on energy consumption, other aspects may arise. If, on the one hand, mixed land use can decrease transport energy consumption; on the other hand, it can increase overall building energy consumption, making it important to understand the relationship between the spatial arrangement of buildings in a high mixed land use zone and their electricity demands [39]. Similarly, densification and infill can compromise perceived neighborhood pleasantness [40]. It is thus important that urban planners and municipal authorities understand and analyze the positive and negative consequences of planning strategies and policies before fully committing to them.

3. Densification and Infill

Densification, i.e., the increase in population density, and infill, i.e., rededication and development of previously derelict or underused land to new land uses or construction, of urban conglomerations may come in many guises. It can lead to reductions in transport energy consumption and environmental impacts [24][41][42][43][44][45].

Transit-oriented development (TOD) is a medium to highly dense, mixed land use urban design concept in which public transport-based mobility defines the urban planning, with public transport catchment areas below 600 m [46][47][48][49][50]. A study by Nahlik and Chester [47] on the impact of TOD on VMT showed that residents of TOD areas tend to drive less compared to residents of non-TOD areas. The impact of a TOD solution in Las Vegas was analyzed by Nahlik and Chester [46]; the authors concluded that it could decrease GHG emissions by 470,000 t of CO_2 equivalent per year and reduce PM_{10}-equivalents and smog formation by 28–35%. Silva et al. [51][52] evaluated the energy implications of six urban development alternatives for the city of Porto, Portugal (infill, consolidated development, modern development, multi-family housing, TOD, and green infrastructure), having found that TOD comes on top, with a 15% reduction in transport travel, followed by consolidated development, with 9% reduction.

Concerning infill, Monteiro et al. [24] analyzed the infill potential in the city of Coimbra, Portugal, strictly following the Municipal Master Plan and national regulations for buildings. They found an increase of 36% in the potential per capita active modal share and a reduction of 76% in transport energy consumption in comparison to the real city, proving that the infill is a viable strategy to combat urban sprawl.

4. The D-Variables of Compact Planning

The D-variables were proposed to guide planners when considering a densification or infill strategy [31][32]. Their impact on transport energy is as follows [31][32]:

D-ensity measures: higher population and job density can reduce the number of trips and trip length, as origins and destinations are closer to one another.

D-iversity measures: high mixed land use can reduce motorized transport and encourage active transport.

D-esign measures: network design can reduce motorized traffic, e.g., street networks with a large number of intersections decrease motorized traffic and network distances and encourage active transport modes.

D-estination accessibility: higher number of urban facilities and employment opportunities reduce trip distances and trip numbers and increase the viability and convenience of active transport modes.

D-istance to transit: adequate coverage of catchment areas for public transport reduces private transport and incentivizes active mobility.

To measure the impact of these variables, statistical models are commonly used and results are typically presented in percentage changes between the scenarios being studied [32]. Although these studies provide important prediction data, their practical application is still limited [32]. Stevens [32] highlights that planners and researchers

> *"should probably not automatically assume that compact development will be very effective at achieving that goal. If anything, planners should probably assume for now that compact development will have a small influence on driving, until and unless they are given a compelling reason to believe otherwise. At a minimum, planners and municipal decision makers should not rely on compact development as their only strategy for reducing vehicles miles travelled unless their goals for reduced driving are very modest and can clearly be achieved at a low cost."*

The above is a warning that infill and densification are not universal solutions to reduce transport energy consumption, due to both local constraints and densification itself [53][54]. A study on perceived neighborhood physical pleasantness showed that, in general, people prefer detached and single-family housing [40]. Indeed, the authors of [55] found that, in response to this market demand, development trends on a dynamic tourist coastal privileged detached urbanism, rather than compact buildings.

As different strategies provide different results, so do different cities behave differently in response to those strategies, further emphasizing the importance of local context when considering an urban layout. As [56] highlights, distinctions should be made according to urbanization levels and dynamics, history, culture, and social and economic inequalities.

5. Urban Public Spaces

Urban public spaces, i.e., outdoor or indoor spaces with free public access where people can gather or pass through (e.g., parks, squares, streets, public shopping malls, streets, walkways), are an essential part of a city's built environment [57][58][59]. If urban public spaces offer some protection against motorized traffic, people tend to feel more secure, comfortable, and less annoyed [60]. Research suggests that policymakers and municipal authorities should focus on the creation of inclusive and safe urban public spaces [60]. Existing urban green infrastructure (such as parks and urban forests) should be protected and new ones should be promoted and built [61].

Additionally, retrofitting renewable energy sources in urban public spaces should become a common norm [62]. Passive strategies that use the intrinsic characteristics of the materials composing the built environment are being studied and implemented for higher energy efficiency and CO_2 emissions reduction [63][64]. The use of green areas and vegetation, as well as cool and reflective materials, is well documented [65][66]. A study by Rosso et. al. [67] tested the application of photoluminescent materials on the built environment, for example, on sidewalk pavements, and demonstrated that it can be used as a passive strategy to reduce energy consumption by contributing to public space lighting with no energy consumption. Similarly, Akbari and Matthews [66] evaluated the installation of cool pavements to mitigate summer urban heat islands and improve outdoor air quality and comfort. Nevertheless, although the energy efficiency and thermal comfort capabilities are clear, using cool coatings for buildings and city infrastructure may cause increased glare to pedestrians and increase walking discomfort [68]. Pavement energy harvesting is considered to be a sustainable energy source, with the potential to yield efficiencies of around 40–65% [69]. Heat-harvesting pavements and road pavements capable of converting vehicles' mechanical energy into electric energy [70][71] have also been proven as possible energy recovery solutions. However, energy-harvesting pavements require more examination to assess their power output, durability, and lifetime [72].

6. Urban Geometry and Buildings Energy Consumption

Buildings energy consumption can be evaluated based on four main factors: urban geometry, building design, system efficiency, and occupant behavior [73]. The focus is on the design and form of the cities, i.e., the urban geometry, the intersecting factor of urban planning, and building energy consumption. Urban geometry and morphology typically relate to the availability of daylight, outdoor temperature, wind speed, and air and noise pollution [74], all of which can create microclimates within a certain urban environment, such as urban heat islands (UHI) and street canyons (SC). It also influences building energy consumption patterns, heat losses, and solar exposure [75][76][77][78]. Thanks to computing advances, simulations of the built environment and urban form become possible, providing an important theoretical base for the relationship between urban geometry and building energy consumption [73][79].

A study by Silva et al. [80] used a spatially explicit methodological framework based on neural networks to assess the effect of urban form on energy demand. Results show that urban form can explain around 78% of the variation in energy use, with features such as number of floors and mix of uses as the most relevant. Studies using digital elevation models (DEMs) are also an important part of the research regarding the relationship between the urban environment and building energy consumption [73]. Shaping and grouping buildings are long known [81]; the novelty of recent research is that computer capabilities now enable quantitative analyses and comparisons between different urban forms. A study by Taleghani [82] analyzed the impact of thermal comfort on energy use in the Netherlands, based on different urban block types. The authors concluded that between single, linear, and courtyard urban blocks layout, the three-story courtyard presented the best results, with 22% less use of energy and 9% less thermal discomfort in comparison to the single urban blocks layout.

The impact of densification from high-rise construction can also be estimated. Densification has been associated with lower per capita energy use, unlike detached housing, whose heat-energy efficiency is low [83][84][85]. However, tall buildings that are too close mutually shade each other, reducing their access to natural light and negatively impacting energy efficiency [86][87], creating a push–pull effect. Building solutions, such as improved thermal insulation of the building envelope, can help mitigate these compactness issues [88]. Actual figures on building energy demands can be estimated from 3D geometric models and data on building construction, as demonstrated by Eicker et al. [89]. These authors found that separating buildings can increase energy demand for heating by 10–20% and reduce renewable energy integration by up to 50%, while mutual shading can increase heating energy demand by 10%. Because of the above findings, some authors proposed moderate compactness as a compromise solution between compact and detached development [88][89][90][91].

Harvesting wind within the urban environment has also been an active research topic recently [92][93]. Gil-García et al. [92] analyzed the potential for harvesting urban wind in the region of Cádiz, Spain, and found that over 68,000 kWh/year could be generated, for an investment return rate of just six years.

Passive solar design should also be incorporated into house plans at the design stage, as suggested in [94]. Cheng et al. [95] developed 18 models to assess the solar potential of urban geometric types, based on the built form, site coverage, and land plot ratio. Other estimations of solar potential based on the urban built environment include [96][97]. Urban geometry can also impact the energy collected from facades and roof tops, with the potential to improve the thermal comfort of buildings [82].

The attention that UHI and SC have received from researchers in the last decades justifies a more in-depth review of these topics, which is carried out in the next two subsections.

6.1. Urban Heat Islands

The development of urban areas usually leads to a reduction in green areas, an increase in waterproof surfaces, the use of high solar absorptance materials, and a reduction in natural ventilation. These are all factors that can lead to an urban heat island effect, as they change surface albedo, emissivity, and evapotranspiration [98][99]. The UHI effect can be defined as a thermal phenomenon in which temperatures in urban cores are higher than in their rural surroundings [98][100][101]. It has an impact on energy efficiency [102][103][104] because increased temperatures raise the energy needs for cooling [105]. An analysis of the UHI effect and microclimate variability in Hong Kong found clear connections between urban morphology and local meteorological factors and concluded that the degree of the UHI phenomenon is more severe in areas of high public activity and heavy transportation [106].

Strategies to reduce the UHI effect include the use of materials with high albedo ratings for surfaces such as pavements [101][107][108][109], the creation or regeneration of urban waterbodies [110][111][112], and the use of vegetation cover [113][114]. Urban green spaces can contribute to reducing UHI effects [65][115][116][117] and are one of the most effective solutions in comparison to other mitigation strategies [118]. A study by Das et al. [119] quantified the cooling effect of urban parks in a tropical mega metropolitan area in India. Findings revealed that urban parks help regulate outdoor temperature, an effect that is proportional to size and greenness. Correct conservation of urban parks is thus essential for climate mitigation in tropical cities [117][119]. Further evidence that urban greenery is important in regulating the UHI effect can be found in [120]

[121][122][123][124]. Vegetation solutions can come in many guises, such as green urban parks [125][126], urban forests [127], buildings roofs and facades [128][129][130], and street sidewalk vegetation [131][132][133]. Quantitative results include that of Klemm et al. [133], who found that a 10% tree cover in a street can lower average radiant temperature by about 1 °K, and [120], [102], in which the combination of different vegetation solutions is examined, having found such combinations can achieve reductions in temperature between 1.5 and 2.0 °C [14] or 2.0 °C [102], along with improving the outdoor environment and thermal comfort [86][131][134][135].

Regulating outdoor temperature can also reduce building energy consumption. In some studies [136][137], an up to 10% reduction was found. Urban parks can directly reduce building energy consumption, but only within a certain radius of around 300 m, according to Kim et al. (2019) [137]. Another study on the cooling effect of urban parks was carried out by Xu et al. [138], who evaluated the situation in Beijing. The best results were achieved by the combination of manmade shading devices, trees, grass, and waterbodies, which together can reduce heating up to 102,069 J.m^{-3} during the period between 10:00 h and 16:00 h. A study by Kaloustian and Dias [139] in Beirut, Lebanon, found that areas with larger garden fractions can have a difference of up to 6 °C cooler temperatures in comparison to surrounding denser areas. This can lead to lower cooling energy demands of 270 W/m^2 (80 W/m^2 vs. 350 W/m^2). Similar results were obtained by Brown et al. (2015) [140], who tested the Park Cool Islands (PCI) design of urban parks in five cities. Results show that reductions between 52 and 60 W/m^2 could be achieved in the cities of Alice Springs, Australia; Kyoto, Japan; and Toronto, Canada, demonstrating that decreasing air temperature through a PCI was a moderately effective strategy [140].

Urban greenery solutions can also make active mobility more attractive by providing more pleasant travel conditions [122][126][141][142][143].

Another strategy to mitigate UHI effects is to correctly execute high-rise [144]. Compact high-rise buildings can prevent cool winds from entering city centers and remove the accumulated heat [145]. A study by Wang et al. [141] concluded that high-rise building construction in adjacent areas of green spaces should be sparser, instead of more compact alternatives, and take advantage of existing water bodies, as they can also directly impact building energy consumption. Adjacent construction areas of urban parks should be planned in accordance with one another, as the impact that each has on the other should always be taken into consideration [141].

A study by Okeil [146] presents a holistic approach to buildings' energy efficiency based on their form. The author provides a systematic comparison and an evaluation between the urban built environment and energy efficiency by maximizing solar exposure in winter and reducing heat gains in summer to mitigate UHI effects. The result is an optimized urban form model based on square blocks, with buildings along the edges whose height varies continuously (see [146] for figures and details).

6.2. Street Canyons

Street canyon refers to a street flanked by tall buildings on both sides, giving it a canyon-like appearance [147][148]. SCs can cause changes in wind, air quality, and temperature [149][150][151], creating a microclimate within the SC and its surroundings. These effects depend on street orientation, aspect ratio, materials albedo, and obstruction angles [75][79][131][152][153] and typically aggravate climate comfort, both indoor and outdoor. SCs are a very complex phenomenon but essentially their main effect is to increase the heat island effect [131][154][155][156][157]. Albeit canyons can increase shading, the reflectivity of buildings traps heat outdoors due to parallel facades, increasing outdoor temperature [75][158]. E-W-oriented canyons are particularly stressful in this respect because they receive sunlight the whole day [159]. Concerning indoor comfort, canyons can increase building climatization energy spending by up to +30% for offices and +19% for housing [75], depending on canyon geometry.

Pollution is another concern, as buildings shield the outdoor space from all winds (except those flowing parallel to the street), causing vortices between buildings that stop the pollutants from naturally dispersing [149][160][161][162]. A study in Athens, Greece, showed that the potential for natural ventilation for both single-side and cross-ventilation is seriously reduced within canyons by 82% and 68%, respectively [162]. When wind flows parallel to the street, pollution escapes but the wind chill effect is exacerbated, causing outdoor discomfort and additional needs for heating in the buildings in winter [75]. The placement of deciduous trees and design features, such as high aspect ratios, larger street width, galleries, and overhanging facades, can mitigate the SC effect and improve outdoor thermal comfort [131][133][152][158]. Narrow streets can, however, limit overheating in the summer, and this knowledge should be considered in due context when planning new neighborhoods.

Urban development policies need to take UHI and SC effects into account and make proper use of effective ways to reduce excessive urban heat. Achieving this goal requires a comprehensive understanding of these effects in their local and regional context. Ideally, building density, urban surface fraction, building materials, and canyon structure should all be considered in urban design together with the characteristics of the city's climate [155].

7. Additional Challenges in Developing Countries

In developing countries, lack of infrastructure creates added difficulties, and some authors suggested that energy sustainability strategies must go hand-in-hand with sanitation, solid waste management, and food security strategies to eradicate poverty [163][164].

Rapid urbanization and climate change are worsening the vulnerability of undeveloped urban areas of the global south [165]. As societies evolve from the primary sector to the secondary and tertiary ones, more full-time, higher-income jobs are created. Given that economic growth is correlated with transport energy consumption and CO_2 emissions [166], urbanization and development are expected to increase emissions in developing countries [167]. Despite the wide promotion of built environment sustainability, these countries lack the means and opportunities to make an adequate energy transition, and thus, this transition remains far from implemented in most developing countries [168][169]. Indeed, and in practice, research in India has shown that the increase in private transport between 1981 and 2005 accentuated environmental degradation [170].

Two studies on African cities show that, even though globalization brought ideas and policies derived from developed countries, those cities still face additional challenges [168][171], making the transition to sustainable energy not as straightforward as research from the global north might suggest. Cities in Africa are very unique and diverse in culture and other contextual issues, requiring different perspectives on how to make that transition [172]. Challenges relate, among others, to insufficient and inconsistent data [173][174], as well as weak governance systems and high percentage of informal economic activities, which hinder the implementation of the necessary strategies [174][175], mostly due to the mismatch between the availability of resources and their fair distribution. The authors of [168] summarize the concerns that African countries are facing into two main groups: (a) general barriers in developing countries—basic needs, not fully implemented sustainability, and inequitable resources distribution; (b) barriers specific to African countries—developing economics, urban poverty, population and poor utilities, and the dichotomy between the different countries.

In general, the studies [168][171][176] suggest that the widespread use of renewable energy resources and a focus on developing a sustainable built environment would highly benefit developing countries, acting as a step to minimize poverty rates and to overcome current and future environmental problems.

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