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Review

Challenges Ahead for Sustainable Cities: An Urban Form and Transport System Review

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Abstract: This article reviews the critical issues surrounding the development of sustainable urban environments, focusing on the impact of transport and urban form on energy consumption and greenhouse gas emissions. The aim is to provide an overview of the state-of-the-art on the subject and to unravel what directions the literature suggests for sustainable urban planning. Current research and practices are synthesized, highlighting the interdependence of urban design and transportation systems in achieving sustainability goals. Important dimensions and practices of city planning and transport policies are explored, including urban form, urban sprawl, mixed land use, densification and infill, and urban public spaces, and how these directly influence transport dynamics, including modal choices and energy consumption. Innovative approaches in urban planning, such as transit-oriented development, and technological advancements, such as electric mobility, are also examined and their potential roles in sustainable urban transport. The conclusion underscores the urgency of adopting holistic and adaptable strategies to foster sustainable urban environments, calling for concerted efforts from policymakers, urban planners, and communities. Awareness of the conclusions can help municipal decision-makers in planning their cities for a sustainable future. Finally, the authors analyze important directions for future research and practical applications towards developing cities that are environmentally sound, socially equitable, and economically viable.

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

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1. Introduction

Urban population has been rising for the past decades, with currently more than half (55%) of the world's population living in cities, a number expected to increase to 68% by 2050 [1–3]. Cities are the main engines of global economic growth, and despite occupying just 3% of the earth's surface [3], they are responsible for more than 75% of a country's gross domestic product [4,5]. Cities consume large quantities of energy and require an uninterrupted supply, totaling 78% of global primary energy, leading to 70% of annual global carbon emissions [2–4,6]. Urban transport and buildings encompass most of this energy consumption and carbon emissions [2,7]. In fact, urban transport accounts for 4 billion tons of CO_2-eq/year, making up more than 40% of the transport sector's total emissions, while buildings consume more than one-third of the final energy consumption globally, and this value is even higher in developed countries [8]. It has become essential to optimize resource consumption in cities [9], as cities are often associated with energy inefficiency, misuse of land and non-renewable resources, and air, sound, and water pollution [10]. There is a growing mismatch between energy supply and demand in developing countries, as supply remains stable while demand grows 7% annually due to increased population growth, rapid urbanization, and expanding economies [4], leading to frequent blackouts [11–13]. The relationship between cities and climate is reciprocal [14], and it is of extreme importance to create, develop, and aim for a more sustainable built environment. Planning to improve city sustainability is crucial for city dwellers' quality of life and our planet's overall sustainability.

Because energy consumption in urban areas is very high and on the rise, it got under the spotlight of local and worldwide research and decision-makers [15,16], and the choices made by municipal authorities and urban planners can significantly impact a city energy efficiency and emissions [17], as well as the thermal comfort of city dwellers [18]. Those choices inevitably act on the built environment, which is linked to urban form, transport systems, and human behavior. A simple form to define the built environment, and the one used for the purpose of this review, is a multidimensional concept that "comprises urban design, land use, and the transport system, and encompasses patterns of human activity within the physical environment" [19]. Handy et al. [19] identified six dimensions of the urban built environment: density and intensity, mixed land use, street connectivity, street scale, aesthetic qualities, and regional structure. A desirable and pleasant urban built environment has to be able to improve energy efficiency, environmental quality, accessibility, comfort, feel-at-ease sensation, and overall quality of life of urban residents [19–21]. This focus on the built environment positions it as an instrumental piece for paving the development of cities and has been an important avenue of research in both spatial and transport planning fields [19].

As the form and function of the built environment impact energy consumption, urban design strategies are crucial to reach energy efficiency and climate targets [22–24]. City-level energy planning presents itself as a strenuous task, typically referred to as "wicked problems", implying ill-defined, multi-faceted, and dynamic problems that require carefully curated strategies and policies, facing many obstacles and additional challenges [25]. One of the biggest challenges is the consolidated urban built environment, i.e., existing urban areas, where changes, regeneration, or renovation is demanding and also requires altering people's behavior in order to reduce energy consumption [26].

City resiliency, i.e., its ability to withstand a wide array of shocks and stresses [27–29], is another central component of sustainable development and has been an active avenue of research in urban planning [27,30–36]. Technical and economically viable solutions are needed to reduce the cost of urban energy transition towards sustainable and resilient cities. Otherwise, the transition could be too expensive to undertake [22,35–38].

Given the number of publications on energy efficiency and consumption of the built environment, this literature review focuses only on transport and spatial planning dimensions. It aims to be a review of recent research, highlighting the most important results and discoveries of the past decade, and provides insights on what could be the focus of future research in the spatial and transport planning energy dimensions of the urban built environment. The conclusions of this review can help municipal decision-makers to plan their cities for a sustainable future, in addition to suggesting research directions to other academics working in the field. For more reviews regarding the different topics presented in this article, please see [39–46]. The term built environment can also refer to buildings, but these are not the focus of this review. The authors suggest the MDPI Energies Special Issue "Thermal Behaviour, Energy Efficiency in Buildings and Sustainable Construction" [47] and the review from Quan et al. (2021) [48] for a deep dive into buildings energy consumption and efficiency.

Figure 1 provides an overall view of the topics focused on this review. An extensive list of all the references cited herein can be found on the Supplemental Materials.

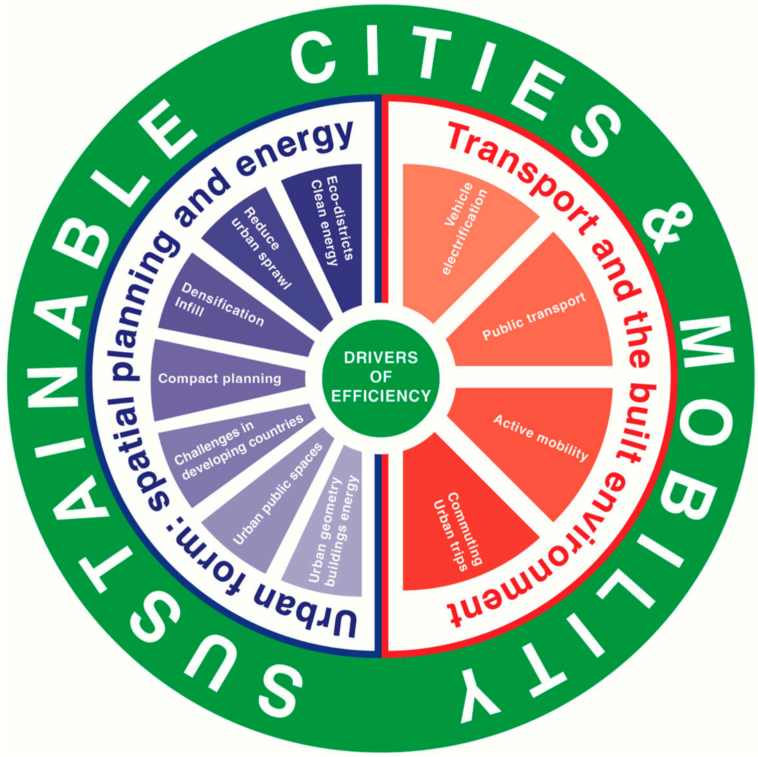

Figure 1. Summary of topics addressed in this review.

Section 2 reviews the relations between transport and the built environment. This is followed by a discussion on developments concerning urban form and energy efficiency in Section 3. Finally, in Section 4, the findings are put together and summarized, and a direction for sustainable urban development is proposed. Section 4 ends with suggestions for new research avenues.

2. Transport and the Built Environment

Transport has a crucial role in the development and daily life of our societies [49]. However, it remains an essential source of harmful air pollutants [50,51], surpassing one-fifth of global CO_2 emissions in 2021 [52–54] (21–23%, depending on the source). The urban form and built environment directly influence the travel mode choice of dwellers, with consequences on transport energy consumption [26,55–58]. Numerous studies over the past decades looked at the relationship between the urban form and CO_2 emissions and transport energy consumption [59–74]. Reducing fuel consumption and associated emissions is possible by focusing on three main areas: fuel type, fuel efficiency, and vehicle miles traveled [75–77]. While the first two areas are not directly related to the built environment, the latter is, as research shows that land use and urban design policies can help reduce motorized modal share and transport energy consumption in the urban environment [78–81]. The high modal share of private motorized transport is one of the main causes of high transport energy consumption in cities [82]. Urban regeneration policies must be part of the solution by creating new infrastructure and fostering a jumpstart of active mobility (walking, cycling), mobility as a service, and zero-emission vehicles [83]. City size and spatial clustering also have a significant impact, as high-density development can help reduce commuting distance and time, as well as fight back against urban sprawl and its long-term negative consequences [55].

Understanding which factors can improve travel patterns, reduce energy consumption, and promote an urban environment with low-carbon and sustainable development has been, and remains, an active research topic for urban planners [63].

2.1. Commuting and Urban Trips

The relationship between the built environment and commuting trips has received continuous interest, as shown by the research [59,84–86]. Recently, the work [87] demonstrated the potential for commuting trips to significantly increase CO_2 emissions in two major cities in China and India. Economic growth and motorization in those cities are inducing fast urbanization and urban sprawl, leading to an expected increase in the annual average CO_2 emissions per person from 0.22 t in 2012 up to 1.6 t in 2030, a 727% rise if "business as usual" conditions are maintained.

A study on vehicle miles traveled (VMT) in the Baltimore area (USA) confirmed that the built environment affects commuting trips, but also that its influence extends to non-commuting trips [88]. For commuting trips, employment density, street connectivity, and accessibility are statistically significant regressors for reduced VMT, as closer jobs and more job opportunities, smaller blocks, and denser intersections provide shorter paths and alternative travel modes. For non-commuting trips, mixed land use and street connectivity were found to be positively significant, as higher street connectivity provides closer opportunities, as does a higher mixed land use [88,89]. When comparing residents' density at neighborhood locations with employment density in business areas, [85] the latter has more impact on vehicle miles traveled. This dependence on trip purpose (commuting or non-commuting) was also studied by Yang et al. [90], who examined the effects of the built environment on CO_2 emissions for different trip purposes in Guangzhou, China. An important conclusion was that urban planning should consider both types of trips, as some built environment elements may be specific to a particular purpose (e.g., bus stop density, distance to city public centers). The authors also state that urban growth should avoid the expansion of the urban periphery and a polycentric development should be advocated for. Higher mixed land use is desirable, as it enables shorter trips, a reduction in the number of trips, and higher active mobility levels.

Other studies confirm that polycentric urban conglomeration policies, which aim for a higher road density, even if narrow, are more effective in reducing travel time than wide arterial roads that can encourage urban sprawl [64]. Likewise, population densification was also proven to be an effective strategy to reduce VMT [91]. According to a study made in California, a 10% increase in residential density may be able to reduce VMT by 1.9% [92]. Densification also leads to more social opportunities nearby, which is usually also sought-after by inhabitants.

2.2. Active Mobility

The built environment can impact active mobility in many ways [93–95]. Often praised by policymakers and a prominent research topic, active modes are nevertheless still underused while motorized private transport is overused [78,96–98]. In the study on how the built environment can affect physical activity, Handy et al. [19] highlight the importance of the former in increasing the number of pedestrians and cyclists on urban trips, with physical exercise as a by-product. Mixed land use, street connectivity, and an overall thoughtful design were proven to enhance the attractiveness and feasibility of both active transport modes [19].

Other built environment characteristics can influence active mobility ridership as well [93–95,99,100]. Street aspect ratio and direction [101–105], street vegetation, and shade availability [106–108] were found to play a role in pedestrian thermal comfort and overall city walkability. Christiansen et al. [99] confirmed positive associations of active modes of transport with four characteristics: mixed land use, residential density, intersection density, and number of parks. However, not all were linear, suggesting that optimum values may exist for each component and that going beyond them will not bring benefits. In particular, residential densities over 12,000 dwellings/km^2 do not seem to improve walking for transport. Also, the physical aspect of the built environment influences citizen perception of neighborhood pleasantness, which in turn affects the propensity to use active modes, as pleasant environments are more likely to be threaded [100,109–112].

Fostering active mobility is one way to reduce transport energy consumption and CO_2 emissions [59,78]. A study by Monteiro et al. [78] analyzed the cycling full potential of Coimbra (Portugal) based purely on trip distances and frequencies; results showed that if the full cycling potential were to be achieved, active mobility (walking plus cycling) would increase by 154%, directly leading to a reduction of 22% in transport energy consumption. A study for the same city showed, by evaluating the exposure to pollutants while commuting, that a reduction of approximately one-third in the inhalation of traffic pollutants could be achieved by using a route that is on average only 6% longer in comparison with the shortest route [113].

These studies highlight the importance that the built environment can have in encouraging active mobility. Municipal authorities should provide the necessary walking and cycling infrastructure, with safe and comfortable bike lanes and street furniture (bicycle parking, rest places, etc.), and adopt policies that reward active mobility, such as the coordination with public transport and discouragement of motorized transport.

2.3. Public Transport

Public transport is an intrinsic part of urban mobility whose impact on transport energy efficiency and greenhouse gas (GHG) emissions is widely recognized [15,114–117]. Increased public transport rideability is necessary to ensure a good public transport service by decreasing waiting time and increasing lines. Built environment characteristics, such as high population density in residential neighborhoods and high job density in business districts, can lead to high rates of traffic congestion and parking difficulties, inducing a widespread use of public transport in lieu of private motorized transport [118], resulting in lower transport energy consumption and emissions. Nevertheless, a study by Li and Zhao [89] that explored car ownership and car use near metro stations in Beijing concluded that proximity to metro stations was not that impactful in reducing car ownership and use. This finding is a reminder that stand-alone policies and strategies to improve transit ridership might not be as impactful as could be expected. Additionally, the effects of the built environment on the reduction in private motorized transport usage can also be limited if, e.g., free parking is provided at destinations [118].

2.4. Vehicle Electrification

At the time of writing, almost every major car brand offers electric vehicles (EVs) in their model range and has committed to an entire model range of just EVs in the foreseeable future [119,120]. International and national authorities are showing signs of commitment to ensuring zero-emission new car sales in the next decade [121]. EV market share is also steadily increasing and it is expected that GHG emissions, air pollution, and the depletion of natural resources for the production of fossil fuels will slowly decline [49,122].

The growth of EV driving around requires creating adequate charging infrastructure in the built environment [123]. EVs are also being considered for mobility as a service solution and the built environment may need to be optimized for parking and charging stations for this mobility solution, as Gonçalves et al. [124] highlighted. A study by Fernández-Rodríguez et al. [51], based on two case studies from Italy and Spain, analyzed the potential use of railway and metro power supply facilities to charge EVs, as that would simplify the deployment of charging infrastructure in cities and allow for harvesting a significant amount of braking energy from trains. Karan et al. [125] analyzed an integrated building and transportation energy use to design a comprehensive GHG mitigation strategy in Pennsylvania, USA. Initial results showed that, on average, each individual produced around 20 lbs (9.1 kg) of CO_2 per day, of which 62% was from transport. Changing fossil fuel motorized transport for EVs powered by solar electricity, a 12.2% CO_2 reduction per day could be achieved.

Electrification of public transport vehicles can also play an important role [126] and has proven to have economic benefits [127]. Replacing internal combustion engine (ICE) public transport fleets with electric trains and hybrid buses could decrease their share in

GHG emissions by 32% [128]. Also, new methodologies to analyze the efficient energy consumption of electric public transport based on the route topology, traffic schedule, and vehicle specifications are being developed [129]. Electric buses can additionally provide other environmental and financial advantages, in terms of improved air quality, noise levels, and reduced cost of ownership and maintenance. However, their acquisition cost is a significant disadvantage, with a premium of over $100,000/vehicle compared to ICE buses [130].

The future of urban mobility might evolve into the massification of EVs, electrification of public transport, and micromobility, e.g., bicycles, scooters, in a mobility as a service or increased ownership basis. It is nowadays becoming clear that vehicle electrification is part of the solution, and many researchers and municipal authorities are actively working on promoting a zero-emission urban transport system.

3. Urban Form: Spatial Planning and Energy Efficiency

This section discusses the relationship between spatial planning and energy efficiency, highlighting the most relevant research and research avenues.

The challenges that the urban built environment faces in the transition to sustainable, low-carbon energy systems are massive [131], and urban design and planning play an undeniable role in addressing them, by means of implementing policies that privilege energy efficiency [132,133]. However, in the past, energy efficiency and sustainability have not been on the radar of urban planners very often. Considering land use as an example: Although it is considered a planning tool for energy efficiency, in many cities, the lack of coordination between urban planning and city-wide energy planning led to large patches of single land use, an inefficient solution [25,133–135]. Nowadays the relationship between urban and energy planning is largely present in current energy-optimized city planning [133,136–139]. For a detailed critical literature review on the importance of coordinating urban and energy planning, see [44]. At a larger scale, initiatives such as the European Commission initiative Covenant of Mayors, Local Governments for Sustainability, and C40 Cities Network (ICLEI) [6,140–142], can bring together municipal authorities to collaborate towards more efficient and sustainable cities.

It is important to note that advances in computer-based technologies provided spatial planners with new resources and tools that can yield quantitative and expedited analyses of energy consumption and sustainability measures [143–146]. A study by Ferrari et al. [147] evaluated the practical usage of these tools by urban planners.

3.1. 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 [148] Integrating renewable energies into spatial planning, i.e., the creation of eco-districts, was suggested in [149,150] 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 [151,152]. However, studies by Lombardi and Trossero [153] and by Bracco et al. [154] 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 [155,156]. 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 [157,158]. 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 [159]. A similar study in San Francisco, USA, found slightly lower but still significant savings, namely, 23–38% [160]. For an in-depth review on the deployment of renewable energy sources in urban areas, see [45].

3.2. 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 [161,162]. Strong negative correlations exist between urban sprawl, energy consumption, and emissions [163,164]. 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 [163,165–169]. Studies [79,170] 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 [78].

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 [79,170]. The solution might lie in the past, within the utopian city plans developed by Howard or Le Corbusier [78,164,171,172]. A study by Monteiro et al. [143] 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 [173]. 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 [168,174–176]. A study by Zahabi et al. [128] 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% [177]. Stone et al. (2007) [178] found similar results and highlighted the importance of compactness in reducing VMT. Wang and Zhou et al. (2017) [179] 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. [26] 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 [180]. Similarly, densification and infill (see Section 3.3. for definitions) can compromise perceived neighborhood pleasantness [21]. 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.

3.3. 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 [79,181–185].

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 [80,81,186–188]. A study by Nahlik and Chester [81] 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 [80]; 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. [189,190] 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. [79] 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.

Densification also relates to building energy consumption. This subject is addressed in Section 3.7.

Different strategies provide different results, and local context should always be considered when aiming to densify a city.

3.4. The D-Variables of Compact Planning

The D-variables were proposed to guide planners when considering a densification or infill strategy [174,175]. Their impact on transport energy is as follows [174,175]:

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 [175]. Although these studies provide important prediction data, their practical application is still limited [175]. Stevens [175] 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 [69,191]. A study on perceived neighborhood physical pleasantness showed that, in general, people prefer detached and single-family housing [21]. Indeed, the authors of [192] 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 [193] highlights, distinctions should be made according to urbanization levels and dynamics, history, culture, and social and economic inequalities.

3.5. 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 [194–196]. If urban public spaces offer some protection against motorized traffic, people tend to feel more secure, comfortable, and less annoyed [197]. Research suggests that policymakers and municipal authorities should focus on the creation of inclusive and safe urban public spaces [197]. Existing urban green infrastructure (such as parks and urban forests) should be protected and new ones should be promoted and built [198].

Additionally, retrofitting renewable energy sources in urban public spaces should become a common norm [199]. 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 [200,201]. The use of green areas and vegetation, as well as cool and reflective materials, is well documented [202,203]. A study by Rosso et. al. [204] 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 [203] 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 [205]. Pavement energy harvesting is considered to be a sustainable energy source, with the potential to yield efficiencies of around 40–65% [206]. Heat-harvesting pavements and road pavements capable of converting vehicles' mechanical energy into electric energy [207,208] have also been proven as possible energy recovery solutions. However, energy-harvesting pavements require more examination to assess their power output, durability, and lifetime [209].

3.6. 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 [210]. For this review, 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 [211], 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 [212–215]. 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 [210,216].

A study by Silva et al. [217] 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 [210]. Shaping and grouping buildings are long known [218]; the novelty of recent research is that computer capabilities now enable quantitative analyses and comparisons between different urban forms. A study by Taleghani [219] 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 [220–222]. However, tall buildings that are too close mutually shade each other, reducing their access to natural light and negatively impacting energy efficiency [223,224], creating a push–pull effect. Building solutions, such as improved thermal insulation of the building envelope, can help mitigate these compactness issues [225]. Actual figures on building energy demands can be estimated from 3D geometric models and data on building construction, as demonstrated by Eicker et al. [226]. 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 [225–228].

Harvesting wind within the urban environment has also been an active research topic recently [229,230]. Gil-García et al. [229] 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 [231]. Cheng et al. [232] 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 [233,234]. Urban geometry can also impact the energy collected from facades and roof tops, with the potential to improve the thermal comfort of buildings [219].

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.

3.6.1. 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 [235,236]. The UHI effect can be defined as a thermal phenomenon in which temperatures in urban cores are higher than in their rural surroundings [235,237,238]. It has an impact on energy efficiency [239–241] because increased temperatures raise the energy needs for cooling [242]. 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 [243].

Strategies to reduce the UHI effect include the use of materials with high albedo ratings for surfaces such as pavements [238,244–246], the creation or regeneration of urban waterbodies [247–249], and the use of vegetation cover [5,250]. Urban green spaces can contribute to reducing UHI effects [202,251–253] and are one of the most effective solutions in comparison to other mitigation strategies [254]. A study by Das et al. [255] 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 [253,255]. Further evidence that urban greenery is important in regulating the UHI effect can be found in [42,256–259]. Vegetation solutions can come in many guises, such as green urban parks [260,261], urban forests [262], buildings roofs and facades [263–265], and street sidewalk vegetation [266–268]. Quantitative results include that of Klemm et al. [268], who found that a 10% tree cover in a street can lower average radiant temperature by about 1 °K, and [42], [239], 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 [45] or 2.0 °C [239], along with improving the outdoor environment and thermal comfort [223,266,269,270].

Regulating outdoor temperature can also reduce building energy consumption. In some studies [271,272], 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) [272]. Another study on the cooling effect of urban parks was carried out by Xu et al. [273], 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 [274] 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) [275], 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 [275].

Urban greenery solutions can also make active mobility more attractive by providing more pleasant travel conditions [257,261,276–278].

Another strategy to mitigate UHI effects is to correctly execute high-rise [279]. Compact high-rise buildings can prevent cool winds from entering city centers and remove the accumulated heat [280]. A study by Wang et al. [276] 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 [276].

A study by Okeil [281] 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 [281] for figures and details).

3.6.2. Street Canyons

Street canyon refers to a street flanked by tall buildings on both sides, giving it a canyon-like appearance [282,283]. SCs can cause changes in wind, air quality, and temperature [284–286], creating a microclimate within the SC and its surroundings. These effects depend on street orientation, aspect ratio, materials albedo, and obstruction angles [212,216,266,287,288] 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 [266,289–292]. Albeit canyons can increase shading, the reflectivity of buildings traps heat outdoors due to parallel facades, increasing outdoor temperature [14,212]. E-W-oriented canyons are particularly stressful in this respect because they receive sunlight the whole day [104]. Concerning indoor comfort, canyons can increase building climatization energy spending by up to +30% for offices and +19% for housing [212], 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 [284,293–295]. 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 [295]. 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 [212]. 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 [14,266,268,287]. 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 [290].

3.7. 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 [296,297].

Rapid urbanization and climate change are worsening the vulnerability of undeveloped urban areas of the global south [298]. 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 [299], urbanization and development are expected to increase emissions in developing countries [300]. 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 [301,302]. Indeed, and in practice, research in India has shown that the increase in private transport between 1981 and 2005 accentuated environmental degradation [303].

Two studies on African cities show that, even though globalization brought ideas and policies derived from developed countries, those cities still face additional challenges [301,304], 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 [305]. Challenges relate, among others, to insufficient and inconsistent data [306,307], as well as weak governance systems and high percentage of informal economic activities, which hinder the implementation of the necessary strategies [307,308], mostly due to the mismatch between the availability of resources and their fair distribution. The authors of [301] 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 [301,304,309] 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.

4. Conclusions

Jane Jacobs in "The Death and Life of Great American Cities" [310] stressed the importance of the built environment and presented criteria that planners should have in mind: a high concentration of population, buildings of mixed use, shorter city blocks, and an attention to the wide-range age gap. These strategies, Jacobs argues, would help retain diversity, create better living conditions, and improve quality of life [310].

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. Lower VMT, higher active modal share, and better public transport service all contribute to lower energy consumption and emissions, in contrast with urban sprawl, which increases motorized transport dependency and inefficiencies due to traffic congestion near, and at, arrival at the destination. However, to capitalize on proximity benefits policies must also include better accessibility (e.g., higher mixed land use), adequate active transport provisions (e.g., infrastructure investments, rights-of-way privileges), improvement of public transport (more/faster lines, stops density, electrification), and discouragement of private car use.

Nevertheless, there are many factors that come into play to make a liveable and vibrant urban environment. For example, the perceived physical pleasantness of the urban environment, which can attract or repulse people from cities, seems to decrease with excessively concentrated environments and tall buildings [21,311]. Excessive concentration also creates heat island and canyon effects, inefficiencies from shading, and makes it easier for pandemics, such as COVID-19, to spread [312]. Polycentric development and moderate concentration development can be good compromise solutions in this respect. In any case, energy efficiency integration within municipal plans and strategies is key for the future development of cities [313]. Land use policies can be more effective if supportive transportation policies are developed [118].

The above development guidelines can lead to new proposals for urban layouts or forms. Nowadays these layouts are put to test, owing to advances in computational power and tools. Research on benchmarking of city layouts has already started [21,78,79,143,311,314] and can provide quantitative predictive data for public discussion, prior to decision-making.

The diagram of Figure 2 clarifies how the concepts and topics of Figure 1 interconnect and summarizes the relationships between the reviewed materials. It is a proposal for path towards sustainable urban planning.

Briefly, the diagram shows that urban form planning should aim at some densification while retaining provisions for public and active transport, which in turn should form the core of a properly integrated urban transport system. Interconnecting urban form and transport will lead to new city concepts, which can be benchmarked before being put into public discussion. Ultimately, this discussion will lead to political decisions when opportunities arise to expand city limits or intervene in the existing urban space.

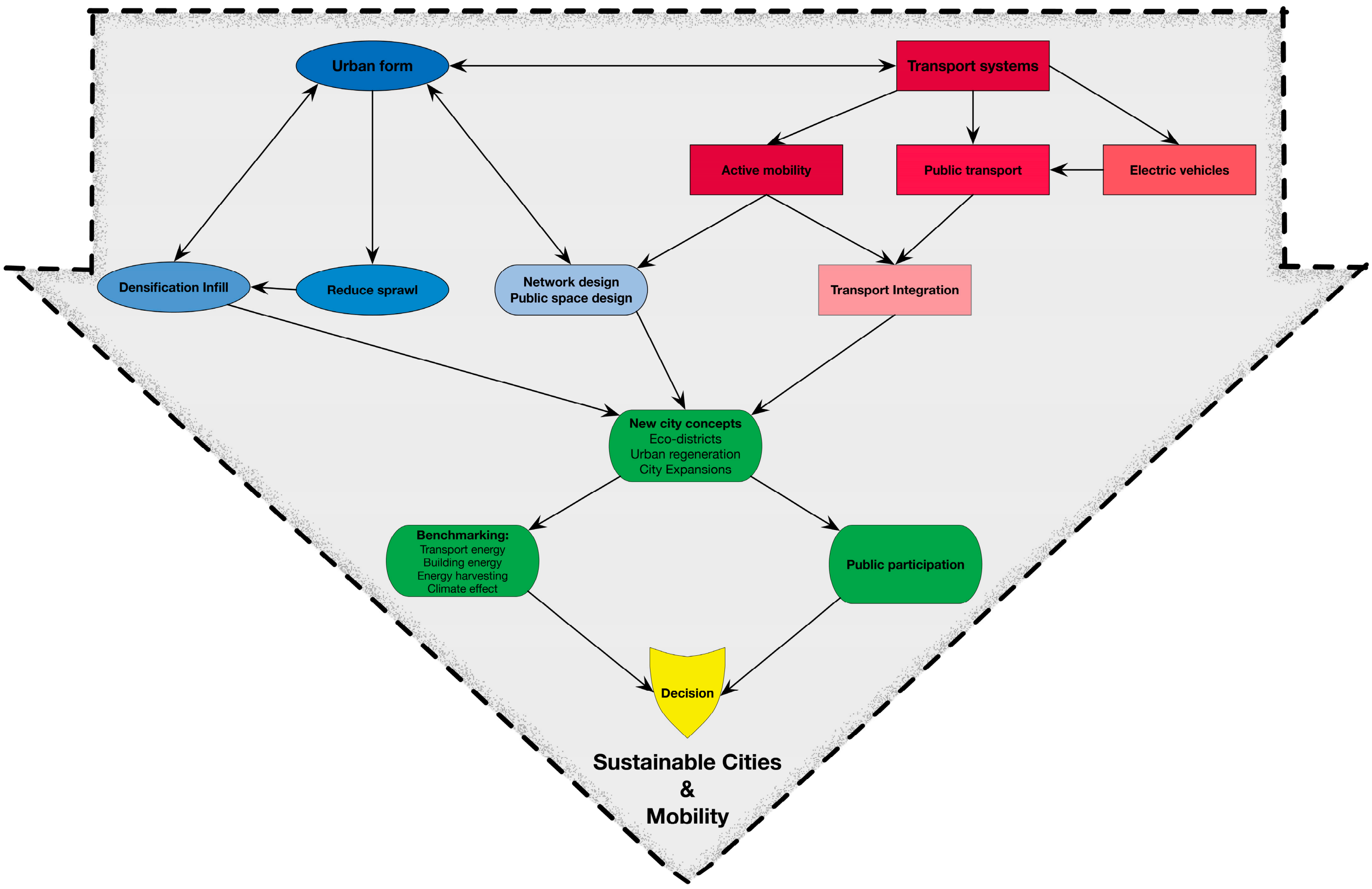

Figure 2. Towards sustainable urban planning: relations between urban form, transport systems, and decision-making for new city concepts.

Directions for Future Research

There are many challenges ahead to achieve truly sustainable cities, and opportunities are plenty for future research and practical applications in the spatial and transport planning fields towards efficient and sustainable cities. Some major directions include the following:

1. Find and benchmark urban forms that compromise between efficiency and pleasantness. Densification provides efficiency but can feel unappealing to inhabitants. Designing and experimenting with new urban forms can lead to new solutions, in which people enjoy living while maintaining efficient and sustainable energy consumption. Classic urban form concepts can also be looked at as development solutions. The Garden City and neighborhood unit development, revamped as the 15-Min City [315], are just two concepts that are now being reconsidered.
2. City expansions. As cities grow, new neighborhoods frequently need to be added. Research should be carried out on how to improve urban expansions based on quantitative indicators and scenario simulations. Expansions can also be a testbed for new urban forms that later provide valuable field data.
3. City infill and sprawl-combating measures. Decision-makers deal with problems of real and sprawled cities. Reducing its impact and filling in cities requires developing infill planning methods and policies to bring people closer to the center.
4. Smart cities and energy efficiency. Big data can provide information on the built environment [316], and evidence mounts that the Internet of Things (IoT) can be used in smart cities to reduce energy consumption. Research and development are necessary to fulfil this potential.
5. There is a growing research avenue on green energy harvesting in cities. The transition to the practical application should be more supported and stimulated.

6. Research and practical solutions for developing countries. Global North solutions may not fit developing countries. Alternative, tailormade solutions need to be researched.
7. Integration of spatial planning with building planning to reduce the impact of heat islands and streets canyons. It is especially important that municipal master plans predict the UHI and SC effects and take adequate mitigating actions.
8. Energy planning integration with both spatial and transport planning. Nowadays urban planning implies cooperation between spatial and transport planning, although in practice, they are still commonly treated separately. A truly integrated urban planning based on spatial, transport, and energy dimensions can provide clear strategies and policies towards more sustainable cities.

"City growth has caused climate change, but that growth is also what's going to get us out of it" [317]. The challenges ahead for sustainable cities are numerous and worrying, but research over the past decade has shown that spatial, transport, and energy planning fields are aware of and facing the problems. It will be up to the politicians to implement the solutions. Many already exist.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/en17020409/s1, Table S1: List of references with authors, publication date, location of research and topic of research.

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