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How Can Sustainable Infrastructure Help to Mitigate Climate Change Challenges?

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Abstract. More than half of the world's population now lives in cities, and cities produce a large share of global greenhouse gas emissions; urban infrastructure is therefore central to climate change mitigation. This paper explores how sustainable urban infrastructure, that is, public transportation, renewable energy systems, green buildings, water management and urban planning, can reduce emissions and also improve living conditions, and why some cities have built it better than others. Four cities enter the study: Copenhagen and Curitiba as relatively successful cases, and Los Angeles and Jakarta as cases with more complicated results. Cycling networks, bus transit joined to land-use planning, urban parks and their funding, and mass rapid transit are all included in the comparison. Four conditions emerge from these four cases. First, infrastructure works better if planners treat it together with land use and pedestrian access instead of constructing it as a separate project. Second, investment and government support are necessary, but a large budget does not guarantee a good result; the low-cost bus system of Curitiba shows this. Third, the benefits do not spread equally on their own; in Los Angeles the competitive park funding process repeated the inequality that it was set up to correct. Fourth, sustainable infrastructure needs continuous monitoring, maintenance and adjustment, and no city should treat it as finished once construction ends. Therefore, sustainable infrastructure should be judged by whether residents can reach it and use it, and not by its physical presence alone.

Keywords: sustainable urban infrastructure, climate change mitigation, environmental equity, comparative case study, public transportation

1. Introduction

Urban areas are now home to over 50% of the world's population [1]. They also generate a large proportion of global greenhouse gas emissions (GHG) [1]. GHG emissions have many different sources, from the transportation sector to the buildings themselves [1]. Thus, cities occupy an advantageous position for the reduction of GHG emissions [2, 3]. Large metropolitan areas such as New York and London have already tried different ways of lowering GHG emissions and improving the quality of life of their residents. Their solutions run from better waste disposal systems to more streamlined transportation modes.

Most of these solutions are grouped under the heading of "sustainable urban infrastructure." In this paper the term is used for infrastructure systems that support sustainability, such as public

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transportation, renewable energy infrastructure, green buildings, water management and urban planning strategies. This paper puts forward the view that sustainable urban infrastructure forms an important part of the reduction of global greenhouse gas emissions, and that it can improve the quality of life of urban residents. The different ways in which cities have tried to build such infrastructure will also be explored, together with the problems they have met. Sustainability here is not purely environmental, for example lower energy use; it also covers whether the solutions are socially just, for example whether the policies put an unfair burden on residents with fewer resources. Trade-offs between environmental and social goals are common; the benefits of green infrastructure do not reach everyone equally. In South Africa, for example, "wealthier census tracts contain residential areas in closer proximity to parks" [4], and this shows that environmental improvements may bring different benefits to residents according to where they live.

Green urban design can lower emissions and improve the quality of life, but difficulties still exist. Cities may set strong sustainability goals and make ambitious plans, but the necessary funding is often difficult to obtain; public or private support is considered "a key barrier for reaching urban sustainability goals" [5]. Also, successful implementation rests on good coordination among the participating agencies. Because of these problems, a sustainable design proposal does not by itself guarantee long-term change. Some cities have completed their plans, and others have put forward ambitious plans but have had trouble with the implementation [2, 6]. This raises the question of why some cities are more successful than others. Wealth may be one factor, since sustainable infrastructure needs considerable funding. However, money alone may not be enough. Government support, long-term planning and public participation may all affect whether sustainable infrastructure succeeds.

This paper will investigate how sustainable infrastructure can reduce GHG emissions, and why some cities have been more successful in making changes than others. Cities that are regarded as successful will be compared with cities that still have difficulties, so as to identify what makes sustainable infrastructure effective.

2. Literature review

The term "sustainable infrastructure" looks broad, since infrastructure may cover transportation, buildings, systems or public space. In this paper sustainable urban infrastructure means city systems that are planned and managed to reduce environmental harm and to support social and economic needs. The Inter-American Development Bank defines it as infrastructure that is planned, designed, constructed, operated and finally decommissioned in ways that support economic and financial, social, environmental and institutional sustainability throughout the whole project life cycle [7]. This definition is useful because it shows that sustainable infrastructure is not about one particular object. The success of a project is related to its financing, its maintenance, whether the people it should serve can actually reach it, as well as whether it has achieved its final function.

Such a wide definition matters most in the study of cities, since urban infrastructure is closely tied to energy use and gas emissions. In the view of the IPCC, cities are major sites for climate mitigation, because urban form, transportation systems, buildings and energy infrastructure all shape how people move, how they consume energy and how they use resources [3]. At the same time, urban planning may lock a city into high-emission patterns, or it may help the city move towards lower-emission development. Compact urban form, transit-oriented development, walking and cycling infrastructure, building efficiency, electrification, and green and blue infrastructure can all help to lower emissions [3]. Therefore, sustainable infrastructure should not be taken as a single

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object; it works more as a system in which transportation, energy, land use and buildings all affect one another.

Sustainable infrastructure is also not confined to environmental questions. It carries social justice implications as well, as different groups may not benefit equally from sustainable design. Urban green space, for example, purifies air, reduces the urban heat island effect, supports biodiversity and provides space for rest, exercise and social interaction [8]. However, these benefits are only real if people can actually reach the green space. In addition, their study of 254 Chinese cities revealed large inequalities in access to urban green space. Higher housing prices were associated with better access to green space, and this shows that environmental benefits are often tied to social and economic status [8]. This is important, since a city may look green from outside and still share the actual environmental benefit unequally.

For this reason, the success of sustainable infrastructure cannot be judged by the number of new systems a city builds. It also has to do with whether residents find those systems accessible and affordable. Public transportation, for instance, reduces car dependence only if it is reliable and reaches the places where people live. Green space has to be close enough for residents to use before it can improve public health. Energy-efficient buildings produce wider effects only when they are not confined to wealthy districts. Thus, social accessibility is also part of the success of sustainable infrastructure.

Implementation is another major problem. Many cities have sustainability goals, resources and ambitious plans, and they still have trouble putting those plans into practice. The report by Bonilla-Roth and Zapparoli on the financing of urban infrastructure for sustainable cities shows that the infrastructure demands of growing cities often go beyond the financial capacities of local governments [9]. Their study of medium-sized cities in Latin America and the Caribbean estimated large infrastructure investment needs, and it stressed that financing, creditworthiness, planning capacity and governance all affect whether a city can carry out sustainable projects [9]. Therefore, wealth may help cities to build sustainable infrastructure, but money by itself is not enough. Successful implementation also rests on strong institutions, long-term planning and other factors that support both the construction and the maintenance of projects.

In general, the existing literature shows that sustainable urban infrastructure can support climate change mitigation, and that its success involves several connected factors. First, infrastructure has to be understood broadly, so that social and financial dimensions are covered along with the environmental ones. Second, cities hold a central place in climate mitigation; their design shapes the transportation system, the buildings and the land use patterns. Third, social equity is necessary if sustainable results are to be achieved. Whether residents can actually reach these systems and gain from them should not be ignored. The above themes form the basis for the comparison between cities that are considered successful and cities that still have trouble building sustainable infrastructure.

3. Methods

Copenhagen, Curitiba, Los Angeles and Jakarta will be compared here, in order to find out why some cities build sustainable urban infrastructure more successfully than others. The four cities were not chosen for using the same type of infrastructure; they were chosen because they show different ways in which sustainable urban infrastructure may succeed or run into trouble in practice. Taken together, they make it possible to compare transportation systems, green space, funding, accessibility and long-term implementation in different urban settings. Copenhagen and Curitiba

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serve as relatively successful cases, and Los Angeles and Jakarta show more complicated results. These cases therefore help to show which factors affect success and which of them matter more.

4. Case studies

4.1. Copenhagen, Denmark

Copenhagen serves as a successful case because it shows how sustainable transportation infrastructure can become part of everyday urban life. The city is widely known for its bicycle infrastructure, where cycling is treated as a practical transportation mode and not just as recreation. As Lonardi, Szell, and De Bacco [10] put it, "Bicycle infrastructure networks must meet the needs of cyclists to position cycling as a viable transportation choice in cities". Sustainable transportation therefore has to do with the quality of the infrastructure and not with individual willingness alone. The Copenhagen case supports the view that sustainable behavior becomes more realistic once a city provides convenient systems.

The Copenhagen case suggests that sustainable infrastructure succeeds more often when city planners design it as part of a whole urban system instead of a set of isolated projects. However, a few bicycle lanes alone would not change people's transportation choices at the city level. Cycling is made safe and convenient by a connected bicycle network that gives residents protected routes in different parts of the city. Sustainable behavior becomes easier once the infrastructure of a city makes sustainable choices practical.

4.2. Curitiba, Brazil

Curitiba is another successful case, and it differs from Copenhagen in that it challenges the idea that only wealthy cities can create sustainable infrastructure. The city reflects the view that a sustainable city must combine social, economic and environmental goals "in an integrated process" [11]. Its planning strategy therefore linked transportation, land use, waste management, public welfare and environmental goals together, instead of treating each urban problem on its own.

Curitiba's planning connected transportation with land use in a more specific way. In the 1960s, the planning team of Jaime Lerner concentrated on controlling urban sprawl, reducing downtown traffic, preserving the historic center and building "a convenient and affordable public transport system based on express buses" [11]. In addition, the city was encouraged to grow along five major transport axes that radiate from the city center. Commercial activities and higher-density housing were put near these transit corridors, so that people could live closer to public transportation. Part of the city center was also closed to cars and redesigned with pedestrian streets. Curitiba's planning thus did more than add public transportation; it reshaped the way people move through the city.

4.3. Los Angeles, USA

Los Angeles is useful as a contrasting case, because it is a well-resourced city in a high-income country and still has trouble with unequal access to sustainable infrastructure. The sustainable infrastructure examined here is urban parks and green space. Parks matter because they can improve social interaction, reduce heat and raise the general quality of life in dense urban neighborhoods. However, Los Angeles shows that the presence of green space does not guarantee that all residents benefit from it equally. Despite the wealth and public resources of the city, only 29 percent of Los

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Angeles residents lived within one-quarter mile of a park facility [12]. Park access is therefore still a major problem in the city.

Los Angeles tried to answer this problem through Proposition K, a park bond measure passed in 1996. The funding was meant to increase access by paying for park land acquisition, improvements to existing parks, construction and maintenance. In theory it should have given neighborhoods easier access to parks of better quality. However, the funding process itself created another barrier. Most of the money was allocated through a competitive grant system, and community-based organizations in poorer neighborhoods therefore had to compete for funding instead of receiving support automatically on the basis of need. Wolch, Wilson, and Fehrenbach [12] explain that "a CBO must compete directly with the Los Angeles Recreation and Parks Department and other public agencies with extensive experience in applying for public funds". The process for solving the problem of unequal park access is thus itself unequal. Communities with fewer resources were put at a disadvantage, as they had less experience in competing for public funding. As a result, the areas that needed parks most did not always receive the strongest support, and residents in park-poor neighborhoods were still left without nearby, usable green space.

4.4. Jakarta, Indonesia

Jakarta is a good example of a city that is still trying to build sustainable infrastructure under difficult conditions. It stands for a rapidly growing city in which traffic congestion and private vehicles create problems. The sustainable infrastructure examined here is MRT Jakarta Phase 1, and it was built to move people from private transportation to mass rapid transit. MRT Jakarta Phase 1 was built to reduce traffic congestion and carbon dioxide emissions at the same time, so it worked both as a transportation project and as a climate-mitigation strategy [13].

The problem of Jakarta comes from its heavy reliance on private vehicles. Nurdjanah et al. [13] explain that the number of motorcycles and private cars in Jakarta was very high, and the rate of public transportation use stayed relatively low. Their analysis of MRT Jakarta Phase 1 found that 53.75% of MRT users had shifted from private transportation. Against the emissions that these users would have produced if they had kept their previous transportation modes, the shift reduced CO_2 emissions by 2,732.7 tons in 2019 and 6,043.9 tons in 2023.

However, the construction of transportation infrastructure is only the first step. The MRT can reduce emissions only if enough people really use it in place of private vehicles. The analysis by Nurdjanah et al. [13] shows that many MRT users did shift from cars or motorcycles, and it also notes that some of them shifted from other forms of public transportation. This is important, as replacing another form of public transportation does not cut emissions in the way that replacing a private car does. Therefore, the mitigation potential of the Jakarta MRT is stronger when access is expanded and more private-vehicle users are encouraged to change their daily transportation habits.

A further limitation is that the Jakarta MRT was not yet fully connected to the rest of the transportation system of the city. During the study period the MRT was "not integrated with the feeder transportation network" [13], and this limited its usefulness for residents who could not easily reach a station. The point matters, as the MRT is of little use to residents who cannot get to a station from where they live. The success of the MRT thus depends on other connections such as sidewalks or feeder routes as well as on the train itself, because these are what make the MRT part of daily travel.

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5. Results and discussion

The comparison of Copenhagen, Curitiba, Los Angeles and Jakarta shows that sustainable urban infrastructure reduces greenhouse gas emissions and improves the quality of life only when it is planned well and fitted into a large urban system. The case studies also suggest that wealth alone cannot explain success. Sustainable infrastructure is shaped by the relationship between planning, accessibility, public use and equity.

5.1. Complementary measures and integrated planning

The first major finding is that sustainable infrastructure works best when city planning includes complementary measures. The bicycle infrastructure of Copenhagen is successful because the transportation network lets cycling become part of daily life. Curitiba shows a similar pattern, but the strategy it adopted was different. Its bus system was designed to make destinations easy to reach, and this encouraged people to use it. In both cases the infrastructure shaped people's behavior by making sustainable transportation more practical. These examples show that individual action becomes more likely when the physical structure of the city supports it. Research also links shorter travel distances and well-developed transportation networks to greater use of alternatives to private cars [14, 15]. People use public transportation more readily when the options are safe and convenient.

This finding agrees with wider research on the influence of urban design on transportation behavior. A city's infrastructure affects the choices its residents make. Creutzig et al. [2] observe that the "built environment shapes and structures everyday life of its citizens". Transportation systems show this clearly, because their design affects whether people take public transit.

Research on travel patterns also shows that the organization of a city affects the way residents move [14]. The public often believes that only people with fewer financial resources take public transportation; the data show instead that trip length is the main determinant of that choice [14]. Also, Curitiba illustrates this, because denser housing and commercial activities along the bus corridors reduced the distance between residents and public transportation. The review by Buehler and Dill [15] gives further support to the importance of networks. Their conclusion is that "Most studies suggest a positive relationship between bikeway networks or aspects of the network and cycling levels" [15]. This helps to explain the success of Copenhagen, where the bicycle infrastructure is not limited to individual paths. The network gives cyclists connected routes and protected space, so that cycling can become part of daily transportation.

5.2. Investment and government support

A second finding is that investment is necessary for building sustainable infrastructure, and that wealth still does not guarantee success. Communities usually cannot organize and finance large infrastructure projects on their own, so support has to come from city governments or from smaller grants to nonprofit organizations. Thus, funding matters for more than construction alone. Copenhagen has the resources for a highly developed cycling network, and Curitiba shows that successful sustainability planning can also take place under lower-cost strategies. The bus system of Curitiba illustrates this point, as it was selected for its "extremely low costs of installation and operation" and its fast construction process [11]. Cities that meet the needs of their citizens therefore reach a higher level of success. Careful planning, together with the choice of infrastructure that fits local resources, is what makes sustainability possible.

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Government support is also necessary, as individual willingness alone cannot build or coordinate infrastructure. According to earlier studies, "Local authorities are key actors in the urban arena in terms of co-ordinating action between different partners and facilitating community involvement with policy programmes" [6]. Governments decide where the funding goes and how the different agencies work together.

The cases therefore suggest that the amount of money available is not the only factor that matters. In addition, cities need political commitment and a clear plan for the use of their resources. Also, the lower-cost system of Curitiba became successful because it formed part of a long-term planning strategy.

5.3. Equitable access is not guaranteed

A third finding is that sustainable infrastructure is not always equitable, so cities should pay closer attention to accessibility and to the question of who benefits from these projects. The clearest example is Los Angeles. Proposition K created funding for parks, and the competitive application process still made it harder for less-resourced communities to obtain support. Many residents in lower-income neighborhoods therefore continued to live without easily accessible green space. Jakarta also shows that equity is not guaranteed, as residents who cannot easily reach a station gain little from the system. These examples show that a project may look sustainable on the surface and still fail the people it is meant to serve. In Los Angeles wealth did not turn into equitable access, because inequality remains inside the city even where public resources are available. Money can certainly assist the implementation of sustainable projects, but it does not make those projects effective by itself.

Research beyond Los Angeles reveals the same pattern, as urban green spaces are "not always equitably distributed" [16], and Rao et al. [8] found that higher housing prices went together with greater access to urban green space in Chinese cities. Venter et al. [4] also found that "wealthier census tracts contain residential areas in closer proximity to parks". Unequal access to sustainable infrastructure is therefore not a problem of Los Angeles alone. A city may run all the environmental programs and still concentrate their benefits in wealthier areas.

Similar inequalities can appear in transportation infrastructure. Some neighborhoods always have better accessibility than others. People who live far from the stations cannot use these systems as easily. Sustainable projects should therefore not be judged only by whether they exist.

5.4. Continuous adaptation and long-term implementation

A fourth finding is that sustainable infrastructure needs continuous adaptation. Cities and transportation patterns change over time, and a project that worked well at first may later meet problems that call for maintenance.

Copenhagen shows this problem through bicycle congestion and uneven network accessibility. Its bicycle network is highly developed, and the city still meets problems such as congestion and uneven accessibility between neighborhoods. Even the highly developed network of Copenhagen contains bottlenecks and neighborhood-level disparities in accessibility [10]. Sustainable infrastructure is therefore not something a city finishes at one time. Instead, it calls for steady improvement and maintenance.

Jakarta also needs to go on expanding MRT connections, raising the number of private-vehicle users who shift to public transportation, and improving the energy sources of the system. Nurdjanah et al. [13] state that "implementing strategies to increase MRT passengers, and using renewable

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energy electricity sources would increase CO2 emission reductions". Jakarta should therefore go on expanding the MRT routes to reach more destinations, and this will make the system more useful and encourage more residents to choose public transportation.

The completion of construction should therefore not be treated as the end of implementation. Cities need to watch how the infrastructure is used, and then maintain it and adjust it where necessary. Toxopeus and Polzin [5] also support this point, and they explain that urban nature-based solutions often require "long-term strategies and dedicated maintenance budgets". The problems of Copenhagen do not mean that its system failed; they mark the areas that still need improvement and give useful lessons for future planning.

In general, the results suggest that sustainable urban infrastructure can help to mitigate greenhouse gas emissions, and that its effectiveness is tied to how well cities connect environmental goals to real urban conditions. A successful city does not simply build one green project. Careful consideration is needed to create systems that make sustainable behavior easy for residents. Long-term planning, public accessibility and social justice are all necessary for sustainable infrastructure.

6. Conclusion

This paper has investigated how sustainable urban infrastructure can mitigate greenhouse gas emissions, and why some cities carry it out more successfully than others. The four case studies show that infrastructure can encourage lower-emission behavior by making cycling, public transportation and access to green space more practical. They also show that different problems may appear in unexpected places and hold back the progress of sustainable planning. First, infrastructure works better when transportation planning is coordinated with land use and pedestrian access. Second, financial investment is necessary, and large budgets and expensive technologies still do not guarantee better results. Curitiba shows that a lower-cost strategy can work if it suits local conditions and is supported by long-term planning. Third, the benefits of infrastructure are distributed on the basis of equity. The unequal accessibility of parks in Los Angeles shows how important equity is. Lastly, infrastructure needs continuous adaptation as its surroundings change over time.

These results suggest that cities should measure sustainable infrastructure by more than its physical presence. A transportation line cannot be counted as fully successful if residents cannot reach it, and a green-space program cannot be counted as equitable if its benefits stay concentrated in wealthier neighborhoods. Therefore, successful implementation asks cities to consider all the factors together. Sustainable infrastructure can help cities to respond to climate change, but only if implementation and maintenance are treated as central parts of sustainability.

Sustainable urban infrastructure is still a major part of climate change mitigation, because the design of a city shapes the choices open to its residents. Individual willingness matters only where the surrounding system makes sustainable actions possible. Future urban development should therefore combine investment, policy, integrated planning, equitable distribution and continuous evaluation. Instead of copying a single model, each city should develop systems that fit its own conditions, and at the same time keep the benefits accessible to the people they are meant to serve.

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