Spatial Synergies Between Blue-Green Infrastructure and Urban Renewable Energy Systems

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Abstract. With rapid urbanization, cities are facing increasing challenges because of limited space, growing infrastructure loads, and rising requirement for renewable energy. In order to achieve ecological-energy synergies within limited urban space, more and more attention has been paid to the integration of blue-green infrastructure (BGI) with urban renewable energy system (RES) through intelligent design and spatial planning, and many explorations have been demonstrated. In this paper, the BGI-RES integrations have been classified into embedded, shared-space, ecologically coupled and network-based types based on the different synergic ways, and the recent advancements have been comprehensively summarized, respectively. Moreover, these approaches have been comparatively discussed from spatial suitability and trade-offs between ecologic, energy, and social performance. The main barriers have been pointed out, and the future directions for sustainable development have been proposed from the aspects of system planning-oriented integration, multi-dimensional evaluations and policy support for practice. This systematic review aims to provide a foundational framework and insightful guidance for researchers, planners, and policymakers engaged in creating more sustainable, resilient, and synergistically efficient urban environments for the future.

Keywords: Blue-Green Infrastructure, Urban Renewable Energy Systems, Spatial Synergy, System Planning-Oriented Integration, Multifunctional Infrastructure.

1. Introduction

As the primary centers of global energy consumption and greenhouse gas emissions, cities play a critical role in low-carbon transitions and sustainable development. With rapid urbanization, cities are facing increasing challenges because of limited space, growing infrastructure loads, and rising requirement for renewable energy. Traditionally, blue-green infrastructure (BGI) is associated with urban greening and landscape engineering, focusing on natural and semi-natural areas that provide ecological services, and renewable energy system (RES) is responsible for generating clean power as an alternative to fossil fuels which induce great environmental pollution during energy delivering. BGI and urban RES are often planned and governed by individual departments within different frameworks, resulting in limited coordination between their layouts and functional objectives, and also spatial competition.

In order to achieve ecological-energy synergies within limited urban space, more and more attention has been paid in recent years to the integration of BGI with urban RES through intelligent design and spatial planning, and many explorations have been demonstrated, even though there is still a large room for improvement. In this review paper, the advancement of integration between BGI and urban RES has been comprehensively summarized based on the different synergic ways, the advantages and disadvantages have been comparatively discussed, the main barriers and challenges have been pointed out and the future directions for sustainable development have been proposed.

2. Concepts

2.1. Blue-Green Infrastructure in Spatial Systems

In urban planning, BGI is a form of ecological infrastructure embedded in the spatial structure of cities, instead of a collection of isolated green spaces. It is a strategic system that supports ecological regulation, public services, and long-term urban sustainability. In this case, green and blue spaces of urban infrastructure are of great importance comparable to that of transportation or utility networks.

From spatial planning, the features of BGI lie in its continuity, multi-scale organization, and public orientation. In a citywide system, BGI typically functions as a network connecting parks, streetscapes, water bodies, and open spaces with different spatial scales. Its continuity enables ecological flows and human movement, while the multi-scale nature promotes the feasibility of diverse coordination and urban planning objectives. Moreover, BGI is generally designed as a long-term public asset which matches the regular frameworks and public governance, distinguishing it from temporary or private land uses. All these merits make BGI valuable and flexible in urban spatial system [1].

These spatial properties endow BGI a big platform for integrating distributed RES. With the characteristics of decentralization and space-dependance for urban RES, their integration requires continuous and adaptable space that is compatible with public use. The network of BGI meets all these requirements, and has the potential to host renewable energy technologies while maintaining its ecological functions and public accessibility. This understanding establishes a spatial and planning-oriented strategy for integrating BGI with urban RES [2].

2.2. Urban Renewable Energy Systems in Spatial systems

Different from the traditional centralized and engineering-oriented energy facilities, urban RES are distributed and could move closer to end users, rising a question of how to integrate it into the spatial systems with a wide range of carriers across multiple locations. This creates new challenges of accessibility, connectivity, and coordination with existing urban systems including BGI. On the other hand, the effectiveness of urban RES is greatly dependent on the surrounding environments, such as residential areas, public spaces, ecological networks, transportation corridors, land-use patterns, and social acceptance, and cannot be evaluated solely with the technical parameters of output efficiency or capacity. Therefore, the integration of urban RES into high-density and multifunctional urban spaces should be carefully designed to balance the energy production, ecological functions and social activities. Otherwise, conflicts of shading, visual impact, or reduced accessibility will be generated without spatial coordination, undermining both energy objectives and planning goals.

From a governance perspective, urban RES also have the features of public infrastructure, their spatial configuration is closely linked to land-use regulation and long-term urban sustainability. Therefore, provident planning plays a critical role, and incorporating urban RES considerations at early stages of spatial planning could relieve objective competition, reduce spatial conflicts, and enhance the overall performance and social acceptance [3, 4].

2.3. Spatial Integration of Blue-Green Infrastructure and Urban Renewable Energy Systems

To improve the overall performance of limited urban space, the integration of multiple functions within a single spatial framework rather than allocating land to isolated uses has been developed. This approach emphasizes functional complementarity and coordinated performance from ecological, social, and infrastructural dimensions, and it is regarded as an effective means to enhance land-use efficiency and promote system-level performance under spatial constraints [5]. In this case, considering BGI and urban RES as interdependent components within a shared spatial network could facilitate functional coupling between ecological and energy services under conditions of land scarcity and climate uncertainty [6], and the spatially integrated planning might enable reinforcement of both ecological environment and energy outcomes [7].

3. Advancements

3.1. Embedded Integration

Embedded integration means the direct incorporation of renewable energy technologies into BGI systems, such as green roofs, vegetated building envelopes, and landscape-based shading structures. This integration strategy relies on the multifunctional use of already constructed BGI spaces, allowing

RES to operate with minimal spatial change. From a planning perspective, this approach represents the lowest level of spatial integration between BGI and urban RES, as the energy function is directly embedded in an established land-use and landscape frameworks [8].

In practice, embedded integration is generally in the forms of photovoltaic systems combined with green roofs, building-integrated photovoltaics (BIPV) facing green spaces, or solar shading structures in park amenities and pedestrian corridors. These approaches share a common spatial way that energy technologies are introduced as additional spatial layers coexisting with the primary ecological or social functions, but not compete with them for land or visibility. Therefore, this type of integration aligns well with the existing planning and design, making it easy to implement within current urban development and the renewal [9].

From a spatial and ecological view, embedded integration generally retains the continuity and accessibility of BGI. The installations of RES are restricted in predefined spatial envelopes, their impacts on ecological and public service are generally controlled within existing planning and design regulations. Meanwhile, the distributed and small-scale natures of embedded RES mean that the energy output is typically not high and strongly dependent on local conditions, such as orientation, shading, and seasonal variations. Therefore, the evaluation of embedded integration should not focus on maximizing energy production, but in terms of compatibility and continuous contribution at urban scale [10].

Overall, embedded integration has features of low spatial conflict, high compatibility with existing BGI, and low governance. Its designing significance is not the individual energy performance, but the capability to achieve the coexistence of BGI and urban RES within everyday urban spaces is more important. This type of integration is the initial form of BGI-RES coordination.

3.2. Shared-Space Integration

Shared-space integration refers to co-existence of renewable energy facilities within urban public spaces, enabling energy production in parks, plazas, parking areas, as well as pedestrian corridors. This strategy incorporates RES into urban spaces primarily intended for public use, making spatial compatibility and social interaction main considerations during the planning. The important challenge is to achieve the multifunctional use of public areas without compromising the accessibility, ecological service, and social functions [11].

Typical applications of shared-space integration include solar canopies and small wind-driven power generators in urban parks and photovoltaic carports in parking centers. These practices demonstrate that public spaces can simultaneously provide support for urban RES in addition to the primary functions. However, the visibility and physical presence of renewable facilities within the shared spaces might affects the user's experience and landscape appearance. Therefore, shared-space integration inherently involves a higher potential for spatial and functional conflicts than embedded approaches [3]. Large or poorly integrated energy installations may alter the projected routes, reduce the flexibility of use, or disrupt the intended spatial and experiential functions of public environments. Moreover, social acceptance should be significantly considered in shared-space integration, incompatible energy installations within local spatial space may reduce user satisfaction and public support, even when ecological or energy benefits are evident. These challenges cannot be overcome by technical optimization, but require deliberate planning based on multi-scale considerations [12].

Overall, shared-space integration highlights the conflicts between multifunctional land use and public space quality. While it could expand renewable energy deployment within cities, the success is strongly dependent on proactive planning to manage spatial conflicts and align energy objectives with public space values. This type of integration necessitates planning-led approaches to coordinate competing demands within shared urban environments [13].

3.3. Ecologically Coupled Integration

Ecologically coupled integration is the most intensive form of BGI-RES integration. In this approach, RES is directly linked to ecological processes rather than only sharing space, it emphasizes functional interdependence between energy production and ecosystem, targeting to align energy generation with ecological regulation and long-term environmental sustainability [10].

Typical applications of ecologically coupled BGI-RES integration is employed when ecological functions and energy potential overlap, such as coupling wetlands and soils with RES. This approach requires RES to adapt to ecological conditions, making the performance closely aligning to ecosystem health and stability. When compared to the above-discussed strategies of embedded and shared-space integrations, the ecologically coupled system displays significantly higher system complexity. It involves interactions from multiple dimensions, including ecological process, energy performance, spatial configuration, and social service, each of which operates on different temporal scales. During practical applications, while energy systems may respond to operational demands, ecological processes such as vegetation recovery or soil regulation often exhibit mismatch, increasing uncertainty of the integrated system in terms of environmental performance or early failure. Therefore, careful coordination across planning, design, and management along with long-term monitoring and management is critically required [14], proposing huge demands on governance capacity, interdisciplinary expertise, and institutional coordination.

Overall, ecologically coupled BGI-RES integration provides high potential for synergistic ecological and energy outcomes, but also entails high requirements of precise planning, long-term commitment, and management capability. Rather than serving as a universal approach, this type of integration is specifically suited to urban conditions where ecological service, governance capability, and long-term planning horizons could adequately support its complexity.

3.4. Network-Based Integration

Network-based integration moves beyond individual projects or localized frames to citywide infrastructure networks with BGI and RES as interlinking components. This approach emphasizes the cooperation of multiple ecological spaces and distributed energy devices within a continuous spatial system, promoting the integration to operate at a level of urban structure [8]. In this strategy, BGI serves as a spatial network providing continuity for distributed RES deployment. When BGI and urban RES are planned together, their spatial complementarity could enable an efficient transfer from fragmented, site-specific solutions to system-level integration, reinforcing the ecological service, energy providing, and spatial functions to an elevated level [15]. Therefore, planning attention should especially be paid to spatial connectivity, alignment between ecological routes and energy systems, and the capability of networks to support variable energy distribution and ecological continuity simultaneously. When compared to the embedded or shared-space approaches discussed above, this types of integration places greater emphasis on network coordination, rather than localized design optimization.

From the view of urban planning, the main significance of network-based integration lies in its enhancing urban governance to a system scale. By incorporating RES considerations into the overall planning of BGI networks, cities can run in a more efficient way by reducing land-use conflicts, improving spatial utilization, and enhancing the resilience of both ecological and energy systems [8].

Overall, this approach represents a substantial transition from localized and project-based integration toward city-wide infrastructure cooperation, agreeing well with the modern planning principles which prioritize networked systems and spatial coherence.

4. Discussions

4.1. Spatial Suitability

For various BGI-RES integrations, there is not a universal model for the spatial compatibility, and the specific integration strategy is largely determined by the urban environments as well as the availability and configurations of spatial carriers, such as rooftops, open spaces, ecological corridors, and infrastructural interfaces. Even though the spatial continuity and multifunctionality of BGI create opportunities for integrating distributed RES, the effective outcomes are generally shaped by local urban features, land-use policy/planning, competing spatial demands, and BGI conditions. In practice, the integration approach that performs well in one local environment may lead to spatial conflicts or inefficiency when transferred directly to another urban condition, disclosing that environment-sensitive planning is necessary for coordinating BGI with urban RES.

During an integration planning, the primary challenge is not technical feasibility, but lies in spatial coordination of renewable energy facilities with existing land functions, ecological processes, and public uses. Limitations such as competing land uses and requirements to maintain landscape continuity or appearance will impose a significant influence on the feasibility and performance of integrated systems. Therefore, spatial planning plays dominant role in designing a synergic integration of BGI with RES [16].

4.2. Trade-offs

In the integration of BGI and urban RES, ecologic, energy, and social performance can not achieve the best simultaneously. Generally, an integrating strategy prioritizing ecological performance can not match the requirements for optimal energy outcomes, and the approach emphasizing vegetation continuity, microclimate regulation, or hydrological services don't meet the spatial or operational conditions of RES facilities, while energy-oriented configurations will sacrifice the ecological performance of public space. In addition, RES installation in urban space may induce obvious change in landscape appearance and convenience of everyday life even the ecologic impacts are well controlled, leading to poor acceptance or resistance of public users. So, a scientific and precise balance should be conducted to achieve a trade-off after comprehensive and multi-dimensional considerations of all ecologic effects, energy output and public attitudes [17, 18]. This is the core for assessing the overall performance of a synergic integration of BGI with urban RES.

In recent years, more and more works are advocating to evaluate BGI-RES integrations in terms of multi-objective balance, emphasizing the microenvironment-sensitive and spatial coordination between ecological benefits, energy output, and social acceptance.

4.3. Key Barriers

Along with the growing interest in integrating BGI with urban RES and the increasing demonstrations, there are still some barriers and challenges hindering the actual implementation at urban scale. The first one is that there is no unified approach to design, manage and evaluate the integration projects [14], because the ecology, energy and urban space are generally planed and managed separately in different departments based on their distinct disciplines to pursue parallel objectives without comparability, and no single department is responsible for overseeing everything in the integration at once, leading to misalignment between BGI and RES in spatial strategy and poor performance of the integrated system. The second obstacle is the inconsistency in data scale and the lack of top-level comprehensive data analysis. Ecological evaluations often operated at a selected spatial region, while energy assessments are always relying on aggregated or regionally scaled datasets [11], and the collected data are analyzed separately in ecologic or energy agency without interdepartmental analysis. The third challenge is about the financial evaluation. The benefits such as improved mental health and ecosystem services, and heat reduction of BGI-RES integration is diffuse and long-term, while the costs and investment are immediate, making it difficult to to see a return on the investment in short time [19]. Finally, public acceptance and policy support are also barriers currently for spatial synergy between urban BGI and RES [20].

5. Toward the future

5.1. System Planning-Oriented Integration

The integration of RES into urban BGI involves multiple spatial interconnections between land-use structures, ecological networks, and public space systems. The location, formation and scale of RES may lead to spatial competitions and ecology/energy conflicts, and greatly influence the landscape appearance, ecosystem service, and everyday social practices. These problems cannot be well resolved with conventional engineering-oriented approaches for single-objective project, even though technical optimization is essential for performance improvement. They are calling for a system planning-oriented integration through interdepartmental cooperation.

A system planning-oriented integration prioritizes spatial coordination and multi-dimensional organization beyond isolated technical maximization. It considers BGI not only as green space, but also as a continuous spatial platform for distributed RES, thereby reducing land-use conflicts and improving system compatibility. More importantly, it changes the integration to a system-level governance by combining energy considerations within spatial strategies and long-term sustainability. In this case, a system planning-oriented integration also establishes a possible way for evaluating BGI-RES integration from various dimensions including spatial, ecological, energy, and social performance.

5.2. Multi-Dimensional Evaluations

Based on the system planning-oriented integration through interdepartmental cooperation proposed in Section 5.1, the rational evaluation of urban BGI-RES integration could be accessed smoothly. It is a multi-dimensional work based on the system performance instead of that on individual techniques, all the outcomes across diverse levels should be comprehensively considered [21].

At the physical level, the integration of renewable energy should match or reinforce the primary spatial-ecological system through high compatibility with land-use, good connectivity within BGI networks, and positive impacts on ecosystem continuity [8]. In the dimension of public use, RES integration can not destroy the landscape, and should receive social acceptance. At the performance level, the ecological process can not be obviously disturbed by RES integration. Upon satisfying all these prerequisites, the energy output of integrated RES should be optimized to the highest level.

5.3. Policy support for practice

Practicing the system planning-oriented integration necessitates the requirement that the urban planners can work not only as spatial coordinators, but also as system integrators with knowledges on ecology and energy [21]. Thus, they can integrate the considerations on distributed RES within land-use planning and spatial guidance as well as BGI design, while ensuring compatibility with ecological continuity and public space functions [22]. A feasible way is to create interdepartmental cooperation involving experts from science, technology, and policy from the beginning of the project [23]. This needs a strong policy support from different related agencies to establish a regular platform combining urban planning, energy, ecology and environment authorities to align the integration optimization, decision-making process, multi-dimensional evaluation criterions, and the invest return budget [24].

In a word, an effective system planning-oriented BGI-RES integration needs strong policy support from administrators to create interdepartmental cooperation.

6. Conclusion

In conclusion, integrating BGI and RES within a shared spatial network could facilitate functional coupling between ecological and energy services under the condition of limited urban space. After a brief conceptual introduction of BGI and RES as well as their integration, this paper has summarized the recent advancements of embedded, shared-space, ecologically coupled and network-based BGI-RES integrations. The comparative discussions revealed that BGI-RES integration is multi-dimensional work, and its overall performance relies mainly on the spatial suitability and trade-offs between ecologic, energy, and social performance, instead of the individual ecologic effects and energy yields or efficiency.

Although many advancements along with demonstrations of BGI-RES integration have been achieved, there are still some barriers and challenges, such as separate planning of ecology and energy from different departments pursuing parallel objectives, inconsistency in data scale and the lack of top-level comprehensive data analysis, financial investment return evaluation, wide scale social acceptance and strong policy support. All these obstacles hinder the actual spatial synergy between urban BGI and RES at urban scale.

Therefore, a system planning-oriented integration based on interdepartmental cooperation should be established in the future. It will change the integration from single-objective or project based level to a system-level governance by combining energy considerations within spatial strategies and long-term sustainability. At the same time, the interdepartmental cooperated system planning-oriented integration also paves a way for multi-dimensional evaluations of BGI-RES integration from physical, public use, and performance levels. At last, but most importantly, policy support from administrators is strongly needed for facilitating the future development of BGI-RES integration.

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