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# Unpacking the Urban Infrastructure Nexus with Environment, Health, Livability, Well-Being, and Equity

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**Multi-objective sustainability planning in cities must address seven physical provisioning systems that are key to advancing local and planetary well-being. Recent progress in environmental and health footprinting, combined with new frontiers in unpacking infrastructure-well-being relationships, will advance urban nexus science to provide customizable information toward inclusive well-being on a finite planet, one city at a time, across the globe.**

## Provisioning Systems

Urban areas are home to more than 50% of the world's population and generate ~80% of the world's gross domestic product. Seven key physical provisioning systems—which provide water, energy, shelter (buildings), mobility and/or connectivity, food, sanitation and waste management, and green and public spaces—although essential for urban activities, are affecting human and planetary well-being at unprecedented levels.[1] Globally, these seven sectors are associated with >88% of greenhouse gas (GHG) emissions, >90% of water withdrawals, and ~20 million premature deaths worldwide and lie at the heart of advancing both human and planetary well-being.[1,2]

Cities and urban provisioning systems are therefore increasingly becoming a focal area in the quest for sustainability, which is often described as advancing human well-being on a finite planet. Over the past two decades, several action plans have emerged in city policy agendas to variously address global environmental priorities (e.g., global GHG mitigation through the low-carbon-city agenda), as well as local priorities related to resilience (e.g., Rockefeller's 100 Resilient Cities Program), health (e.g., the World Health Organization's Healthy Cities initiative), quality of life (the livable-cities concept), and equity (the inclusive-city concept). More recently, the nexus among these goals has been recognized, for example, with the sustainable- *and* livable-cities concept and the United Nation's Sustainable Development Goals (SDGs), which include SDG 11 (focus on sustainable cities), as well as other goals related to the environment (e.g., water, land, energy, and climate, related to SDGs 6, 15, 7, and 13, respectively), reducing inequality (SDG 10), zero hunger (SDG 2), zero poverty (SDG 1), and advancing human health and well-being (SDG 3).

Rather than address each goal one by one, cities are seeking an overarching framework (e.g., Figure 1) to track progress toward the multiple societal outcomes related to sustainability, broadly categorized as environment, health and well-being, security, and equity. As shown in Figure 1, the key physical provisioning systems often transcend urban administrative boundaries and interact with social provisioning systems to shape the sustainability outcomes. Nexus linkages occur not only among the outcomes but also through interdependencies among the key provisioning sectors. I also distinguish between final desired societal outcomes and features that are presumed to enable such outcomes. For example, livability, which is defined as the characteristics that make a location a desirable place to live,[2] is associated with advancing the final outcomes of health and well-being. Likewise, resource-efficient strategies are often presumed to lead to improved environmental outcomes. In both cases, tracking the final societal outcomes empirically is beneficial because they are often mediated by human behavior and other confounding variables. Social equity is even more complex because it addresses inequality *and* fairness in the distribution of burdens and benefits in society,[3] requiring analysis of relevant policies. Thus, there is an urgent need to unpack the complex infrastructure-sustainability nexus to help guide next-generation multi-objective city sustainability plans to reach their goals. I unpack the urban infrastructure-sustainability nexus in stepwise fashion below by highlighting recent advances and introducing emerging new methods.

## Infrastructure, Environment, and Planetary Boundaries

Over the past decade there have been significant advances in assessing how local urban infrastructure provisioning affects the broader regional and planetary environment. It is now well recognized that cities draw a majority of their resources through vast supply chains that extend well beyond urban administrative boundaries. For example, studies of numerous world cities have shown that a majority of the demand for electricity, water, petrofuels, construction materials, and food in cities is met through imports; electricity, food, and freight travel an average of ~200 miles, 1,200 miles, and 600 miles, respectively, in the US.[4] Consequently, the concept of transboundary environmental footprinting of community-wide infrastructure provisioning—which combines material and energy flows in cities associated with the key provisioning sectors with the life-cycle assessment of generating these flows—has been applied both in research studies[5] and in city protocols for GHG

 

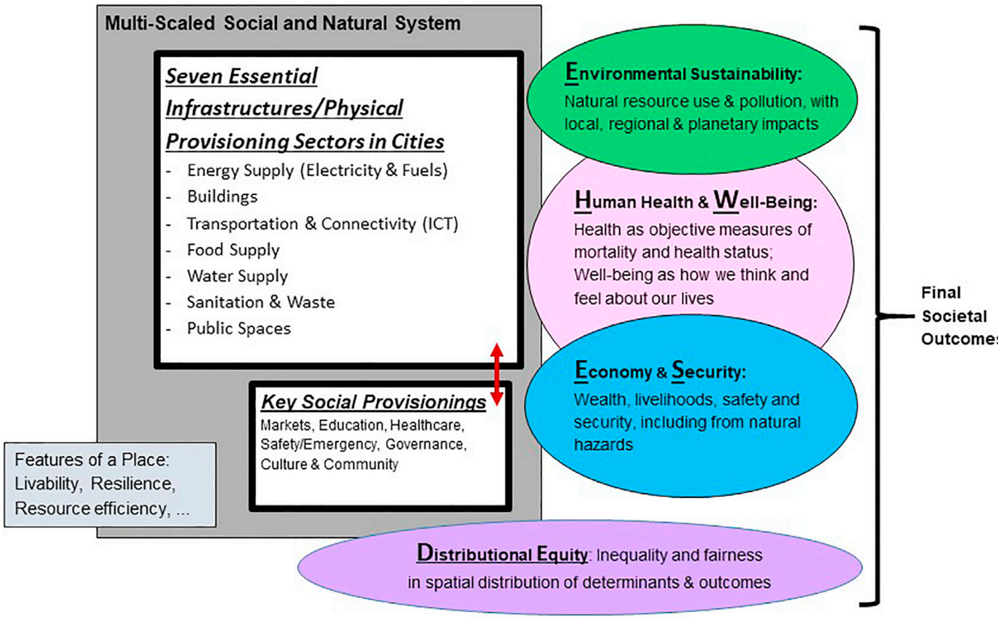


**Figure 1. The Infrastructure-Sustainability Outcomes Nexus**

Conceptual framework linking key physical infrastructure provisioning systems in urban areas to multiple final sustainability outcomes of environmental sustainability, health and well-being, security, resilience, and equity. Livability, resource efficiency, and resilience are represented as the characteristics of a place that supports achieving the final outcomes. We include information-communication technology (ICT) within the category of providing mobility and/or connectivity.

accounting.[6] Transboundary environmental footprinting has been extended to several resources, including water, energy, and land,[7] in addition to GHG emissions, thus enabling infrastructure linkages with multiple SDGs related to these aspects. Such coupled water-land-GHG footprints enable the identification of trade-offs and co-benefits across various dimensions of environmental sustainability both within and across city boundaries. Transboundary footprints go beyond the traditional in-boundary focus on local urban environmental concerns to address regional and planetary impacts.

### *Infrastructure, Inequality, Pollution, and Health*

The linkage between infrastructure provisioning, environment, and local-level inequality and deprivation has also been quantified—for example, census data from Indian cities have identified wards (precincts) that lack access to clean water, sanitation, energy, and adequate housing. Across ten Indian cities studied, the lack of access varies from <5% for electricity to >40% for access to a closed sewage system. Consumer surveys can further reveal inequalities in the consumption of electricity or floor area and the amount and types of cooking fuels.[8] These characteristics of urban infrastructure linked with models of associated air and water pollution can yield objective assessments of health risks with the use of models such as those from the Global Burden of Disease methodology[9] to provide estimates of years of life lost and premature mortality in cities as a result of infrastructure deficits or associated pollution emissions. Such methods have now also been applied in a spatially explicit manner in the US to inform how household consumption in various counties can cause transboundary inequalities in the distribution of air-pollution-related health risks by race and income across the nation.[10]

### *Infrastructure and Livability*

Although much progress has been made in characterizing the infrastructure-resource-pollution-health nexus (as described above), it has been more difficult to unpack the connection between physical provisioning and the broader concept of livability, i.e., a place's features that influence quality of life. A primary reason is that livability is a multi-faceted construct that has been described with the use of numerous conceptual frameworks, including Maslow's hierarchy of needs, the Place Pyramid, and other multi-level frameworks that incorporate social and built-environment determinants to health.[3] Correspondingly, operational metrics of livability are also normative and focus on what experts think should be important, resulting in widely varying livability indices based on the multiple underlying conceptual frameworks. Some livability metrics focus largely on the standard of living, and others address the more subjective aspect of quality of life. Thus, there is wide variation in the types of parameters measured across the more than 30 livability indices that are now in the market.[11] Furthermore, normative indices will not reveal complex infrastructure-related phenomena that affect quality of life, safety, and security at intra-urban scales, such as frequent street flooding from cloud-burst events or neighborhood-level power outages, data on which are largely unknown and unavailable in the public domain.

### *Infrastructure and Subjective Well-Being*

In contrast to the normative quest for a universally applicable livability index, new methods for directly surveying populations on their own assessment of their well-being (i.e., subjective well-being) represent a new frontier for directly assessing livability priorities in that they yield insights that are data driven and relevant to the social-ecological and infrastructural features of each locale. Early work, such as in the Better Life Index, combined such subjective well-being assessments with objective metrics in an attempt to represent aggregate livability scores at the national scale. Meanwhile, at the city level, studies sought to unpack the relationship between green infrastructures and various measures of personal well-being ranging from psychological measures[12] to more global measures of life satisfaction tracked across cities.[13]

In recent years, definitions and instruments for measuring individual well-being across the population have converged.[14] Subjective well-being, defined as judging life positively and frequently experiencing pleasant emotions,[15] fundamentally represents how we think and feel about our lives. It is understood to have both cognitive (how we think) and affective (how we feel) elements, as well as a sense of life purpose (meaningfulness or eudaimonia). Surveys capturing many of these elements have been administered, for example, across all households in the UK over several census cycles.[16] Results reveal that among the largest determinants of reported well-being are employment (including agency at work), income, physical health, social and family relationships, demographics (age and race), and intra-personal factors (e.g., personality). Unpacking the influence of the built environment among these other determinants can be quite complex and must consider all of these mediating and moderating variables.[14] Further, whereas comprehensive national surveys have been conducted in a few countries such as the UK, large-scale well-being assessments at the intra-urban scale are sparse in many countries, particularly in the Global South.

## Infrastructure, Well-Being, and Equity

Emerging methods that couple intra-urban-scale subjective well-being assessments with queries on urban residents' satisfaction with various household- and neighborhood-level infrastructures and services yield a powerful new way of unpacking infrastructure determinants of well-being to inform both livability and equity. In a recent workshop of the interdisciplinary Sustainable Healthy Cities network, aimed at co-producing metrics for livability and equity, a conceptual model employing a three-factor theory of satisfaction with services[17] gained traction among researchers, city planners, and policymakers. Highlighted in Figure 2, it suggests that infrastructures can be classified into three types according to their association with well-being outcomes and related threshold effects:

- Foundational: those attributes of the built environment, including household and community attributes of physical and social provisionings, wherein improved satisfaction with these attributes is positively correlated with increased well-being (after confounding effects of other variables are addressed) but only up to a threshold. After this threshold, improvements in these attributes no longer offer greater well-being. Examples might include basic infrastructure provisions such as access to clean water, sanitation, or electricity.
- Consistently important: those attributes where improved performance is correlated with greater well-being but with no threshold effect. Here, better infrastructure is consistently associated with improved well-being at both high and low performance and high and low levels of well-being. Examples might include education, healthcare, or transportation.
- Added bonus: those sectors or services wherein improved performance has a reverse threshold effect, i.e., these sectors contribute to well-being *after* higher levels of well-being have already been attained—hence the terminology of the added bonus. Ultra-high-speed internet and housing size could be examples of added-bonus attributes.

## Infrastructure, Basic Needs, and Sufficiency

The above conceptualization of subjective measures of well-being versus a subjective rating of infrastructure performance can help assess livability attributes most relevant to each city's context. This approach also has profound implications for equity and environmental sustainability by focusing both on the concept of basic needs (i.e., achieving minimum levels of electricity, water, or living space related to the foundational attributes) and on the concept of sufficiency (i.e., sufficiency in attaining high levels of well-being),[18] wherein potential excess consumption can be revealed in the "added-bonus" categories.

Thus, from an equity perspective, cities might want to first prioritize public investments in those foundational sectors and services wherein improvements in performance are associated with improvements in well-being, particularly for those residents experiencing low levels of well-being. In contrast, for those sectors or services that are in the category of "added bonus," cities might want to explore whether these services are having a large environmental impact by using the aforementioned environmental footprinting approaches and implementing awareness or behavioral-nudging campaigns that highlight the concept of sufficiency.

More importantly, the framework indicates that distributional equity can be assessed both in terms of inequality in determinants such as income or access to basic services (such as electricity, etc.) and in terms of the outcomes on the right side of Figure 1. With an outcomes focus, nuanced understanding of infrastructure linkages with inequality in well-being outcomes can inform strategic prioritization of public funds toward those sectors where well-being deficits are seen and highlight where sufficiency thresholds are exceeded. This motivates the framing of distributional equity in the context of both determinants and outcomes in Figure 1, and this framing could help design city-customized pathways to advance well-being for all within planetary boundaries.

## A Reason for Hope

Sustainability nexus science—i.e., the science of unpacking infrastructure relationships with multiple sustainability outcomes (of environment, health, livability, well-being, and equity)—has developed rapidly over the past 10–20 years. Cities have led the charge by taking the leap to declare ambitious policy agendas. Scientists are working hard to catch up with the policy process. Developing science to inform policies and action can be slow and challenging because it requires

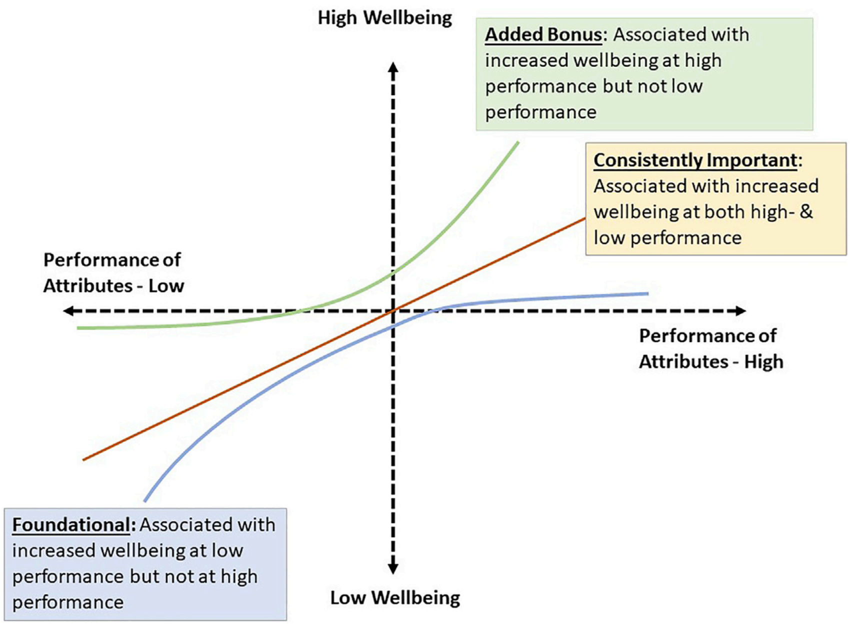


**Figure 2. Types of Infrastructure-Well-Being Relationships**
A three-way typology of different infrastructure provisioning systems based on their patterns of association with well-being outcomes, including consideration of thresholds. Adapted from a three-factor theory of services.[18]

interdisciplinary teams of scientists who can work with each other across disciplinary siloes to build a new urban-systems science that is closely engaged with the key questions that practitioners are grappling with. Yet, dramatic progress has already been made in both the science and the practice. For example, in terms of environmental sustainability, the science of urban environmental footprinting, which is relevant to planetary boundaries, has advanced rapidly to become institutionalized in city GHG-accounting protocols within a span of 5 years from research[5] to practice.[7] Models linking infrastructure deprivation, as well as pollution from infrastructure operations, to health are also emerging to address in-boundary and transboundary health effects on different populations within and outside cities.

Although much research has been done on livability, the quest for a single universal index for urban livability might not be realized, nor is it practical. Instead, increasingly robust instruments that directly measure individual subjective well-being and infrastructure performance assessments across large populations in different city neighborhoods can reveal customized information relevant to each city as to which attributes of household and neighborhood social and biophysical infrastructure might be prioritized to advance well-being. To ensure equitable allocation of public resources, we must consider inequality not only in terms of determinants (such as income and infrastructure access) but also in terms of outcomes (such as those related to health and well-being). Linking concepts of basic needs and sufficiency with empirical measures of infrastructure performance and equity and with environmental footprints will be a powerful instrument for cities to advance inclusive well-being for all within planetary boundaries.

Advancing this new frontier requires a foundational shift toward a highly interdisciplinary, action-focused research philosophy wherein teams of researchers—spanning infrastructure engineering, environmental science, industrial ecology, urban planning, public policy, and public health—work together with city practitioners in diverse cities worldwide to advance the science of the urban sustainability nexus.

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