THE ROLE OF FUNDING, FINANCING AND EMERGING TECHNOLOGIES IN DELIVERING AND MANAGING INFRASTRUCTURE FOR THE 21ST CENTURY

Report from the EPSRC-NSF Infrastructure Workshop

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UNIVERSITY OF CAMBRIDGE

CSIC Cambridge Centre for Smart Infrastructure & Construction

Cornell University Founded A.D. 1865

CPIP Cornell Program in Infrastructure Policy

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1.0 EXECUTIVE SUMMARY

Infrastructure provides the basic building blocks – in the form of critical public services – necessary for the functioning of any modern society. Services provided by infrastructure include safe and reliable transportation, widely available communications, low-cost clean water, dependable heating and cooling, affordable electric power, education and criminal justice, among others within the many definitions of infrastructure. Such services should be universally accessible. Their construction and operation should be administered with sustainable practices and carbon-emission reductions in mind. A vast array of infrastructure facilities, including roads, bridges, tunnels, dams, levies, cell towers, airports, seaports, schools and courthouses ensure that critical services are available, and help define a modern society.

Despite its paramount importance, many countries find it increasingly difficult to provide these services in an efficient and cost-effective way. Common challenges and exigencies include inadequate funding from traditional sources, equitable funding, large backlogs of deferred maintenance, slow adoption of proven technologies, large amounts of carbon emissions, infrastructure modernization to increase climate resilience, adaptation of infrastructure to meet societal needs and demographic change, and projects that are often over cost and over budget during the delivery phase. One overarching infrastructure challenge is the funding gap. The global infrastructure funding gap is estimated to be about USD $15 trillion, and USD $18 trillion if we also include investments needed to achieve UN Sustainable Development Goals.

Additionally, the increasingly complex interdependencies of our infrastructure systems means that we need to move away from traditional siloed approaches to infrastructure management, delivery and regulation to a system-of-systems approach. Challenges like reducing carbon emissions to net zero and making society resilient to the physical effects of climate change are systemic and require systems-based solutions to ensure that we are able to continue to deliver the services that society relies on.

To help address those challenges, the UK Engineering and Physical Science Research Council (EPSRC) and the US National Science Foundation (NSF) supported a Workshop entitled, *The Role of Funding, Financing and Emerging Technologies in Delivering and Managing Infrastructure for the 21st Century*. The Workshop was held in New York City from the 11th to the 15th of July 2022. It included 30 participants invited by US members of the organizing committee, and 25 invited by UK members as well as online participants.

The Workshop assembled a multidisciplinary group of international experts from academia, policy, and practice to explore how to improve infrastructure delivery through innovative funding and financing as well as emerging technologies. This Report captures the discussion and narratives arising from the Workshop and presents recommendations for policy, industry and future research. The Workshop focused on the interconnections between resilience, net-zero carbon and social equity within the context of infrastructure funding and financing. However, each challenge is examined separately in this Report for clarity. The complex interconnections across those issues are acknowledged throughout, with emphasis on the systems and systems-of-systems nature of those challenges.

Although this Report addresses challenges related to infrastructure delivery and resilience, and to historical inequities of infrastructure provision and services, challenges related to climate change are considered the most urgent and affect all of the others. Time is running out to address carbon emissions. The window of opportunity to keep an increase in global temperature to 1.5C in reach and to avoid the worst impacts of global warming is closing fast – at best we have less than seven years to halve current global emissions[1]. The built environment is estimated to contribute from 39% (UN, 2017) to 70% (WRI, 2021) of carbon emissions depending on how emissions are allocated by sector.

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[1] https://climateclock.world/

Infrastructure clearly has a significant role in reducing carbon emissions to acceptable levels.

New technologies related to materials, sensing, communication and computing are emerging at an accelerated pace compared to prior decades. Emerging technologies are being increasingly applied in infrastructure systems; they increase the timeliness and reliability of information about the current state of infrastructure. They support decision making and increase long-term infrastructure performance and return on investment. The data and insights generated from these technologies can empower decision-makers to improve design approaches and system resilience, decarbonize existing infrastructure networks and achieve more equitable service outcomes.

This Report contains a set of specific and actionable recommendations for policy makers, industry practitioners, and researchers. There are six recommendations for improving infrastructure funding and financing, seven related to emerging technology, ten for improving resilience, fifteen for achieving net-zero infrastructure, and ten for improving equity in infrastructure delivery.

Resilience, net-zero carbon, and equity are only achievable if adequate funding and financing mechanisms are in place to support and incentivize critical investments in infrastructure. Key recommendations include: (*i*) considering the adoption of funding mechanisms that correlate closely with infrastructure use and that vary with the value of the facility at that time; (*ii*) bundling together facility design, construction and operation into one long-term contract to reduce incentives to defer maintenance while enhancing incentives to adopt new technologies and improve life-cycle asset maintenance; (*iii*) adopting measures that support resilience by recognizing the need to plan for plausible events, not just the most likely ones; and (*iv*) incorporating stakeholders into decision-making about design and funding.

Adopting frameworks, such as the UK Task-force on Climate-related Financial Disclosures (TCFD), can drive thinking about possible future scenarios across a number of different variables, and improve and increase reporting of climate-related financial information. The use of scenario planning and modelling is a powerful means of exploring a range of possible futures and designing resilience solutions that can be adapted as the future plays out.

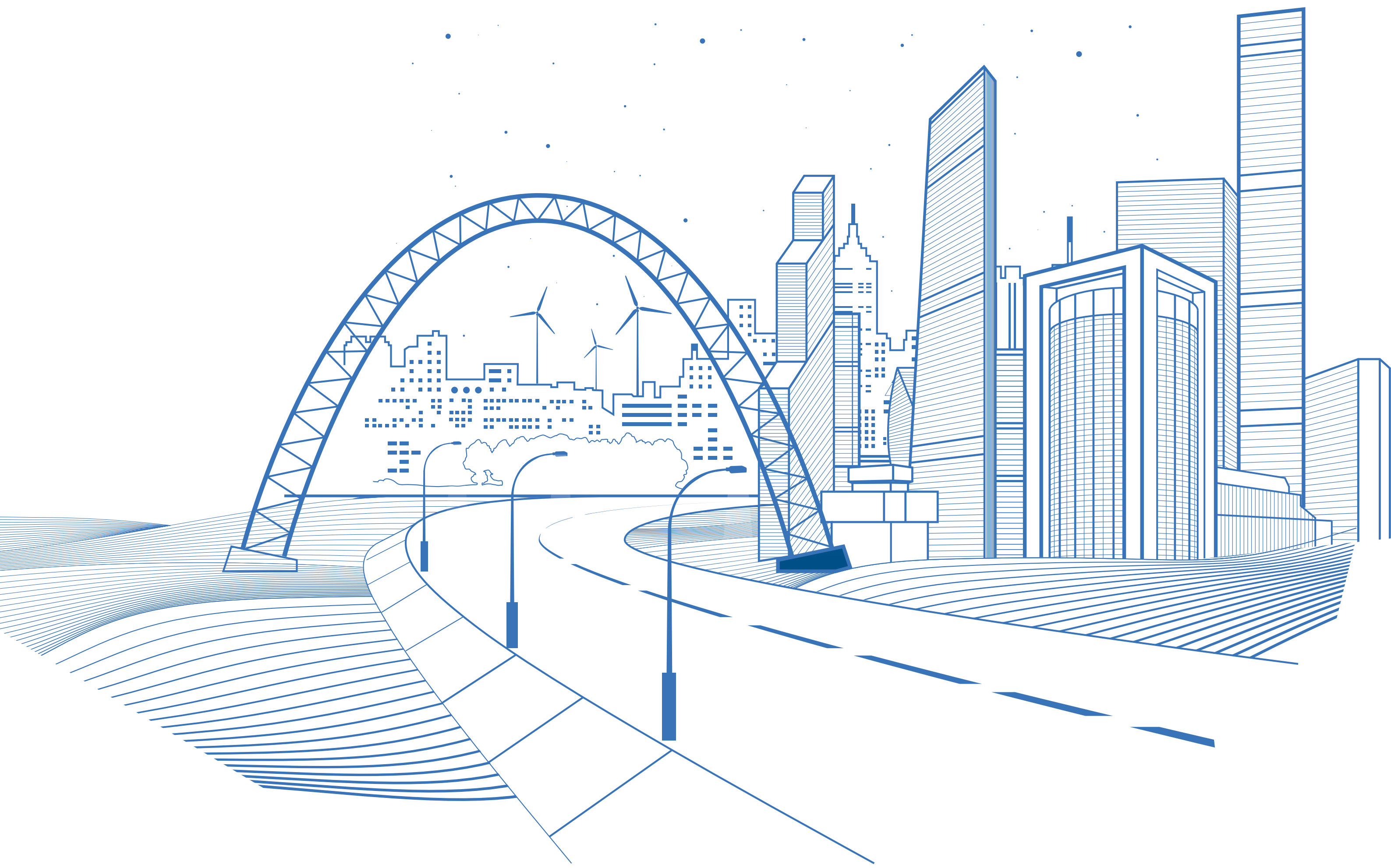
Key recommendations regarding infrastructure and the reduction of carbon emissions are:

- Every capital project proposal should be reviewed to ascertain whether reducing demand for infrastructure services or refurbishing existing infrastructure are viable and have carbon reduction as a key outcome within the options identified and proposed for implementation.
- Processes should be developed for capturing and analyzing carbon data and integrating with existing digital technologies and processes (e.g., BIM models, digital twins) to facilitate the advancement of accurate carbon measurement.
- All actions made or controlled by government at every level should be required to demonstrate how they support local communities and are consistent with UN Sustainable Development Goals while improving the performance and resilience of infrastructure assets and systems.
- Design codes should be reviewed and revised to reduce conservatism and the resultant over-use of material.
- Industry benchmarks and best practice to measure whole-life carbon need to be developed, refined and adopted in order to provide evidence to set targets and establish financial incentives for carbon reduction.
- Incentives for whole-life, risk-based management approaches need to be identified, with risks allocated to those best able to manage them. These should be embedded in contracts to drive adoption of monitoring approaches and motivate better-informed asset management decisions to reduce carbon emissions from operation and maintenance.

There is a need to regularly reassess the value of critical infrastructure because the value and highest/best use of infrastructure evolves over time. High-quality, system-level targets and metrics (and data) are needed to better understand the true impact of these systems and to benchmark existing performance. A whole-system approach should be taken at all stages of the project lifecycle, with a focus not only on the four traditional priorities (scope, cost, risk and time) but equally on the four new priorities (biodiversity, social value, resilience and carbon & environment). These eight whole-system priorities should be considered when capturing requirements, setting the desired outcomes and benefits, and developing, designing and delivering projects through operation, maintenance and end of life. They should be included (on a comply or explain basis) in business cases, strategies and procurement documents. Balanced scorecard reporting throughout the asset lifecycle should reflect all eight priorities equally, with front page space given to each. To underpin this whole-system approach, good-quality data is needed across all eight priorities. These data will enable a better understanding of the true impact of these systems and benchmarking of existing performance.

Guidance, tools and incentives are needed to enable engineers and planners to link desired outcomes and project appraisal processes with locally relevant solutions. Decision makers should account for the importance of equity in relation to economic viability – ensuring all communities have infrastructure that enables people to be productive and contribute to the future. One overarching Workshop focus was on distinguishing between the funding of infrastructure and its financing. Although adequate financing is an important issue, many critical infrastructure issues stem from inadequate funding, or the absence of underlying resources available for operation and maintenance as well as design and construction.

Overall, this Workshop Report reflects the urgency of addressing key infrastructure industry, policy and research challenges. The analysis and recommendations contained in this Report should be of interest to scholars, practitioners and policy makers with different backgrounds and perspectives. It should serve as a framework for prioritization of efforts in infrastructure studies and policies over the next five years, setting up a foundation for a new normal for infrastructure sustainability and resilience.



2.0 INTRODUCTION

2.1 Background

The United Kingdom and the United States are facing an array of similar and pressing infrastructure challenges. They include prioritising and creating new infrastructure, ensuring the performance and resilience of aging infrastructure systems, planning for an uncertain climate future while responding to ongoing extreme weather events, redressing historical inequity in infrastructure provision and operation, and reducing infrastructure-generated carbon emissions to net zero. These challenges must all be addressed in the context of limited public funding from increasingly constrained revenue sources.

Infrastructure provides the basic public services on which modern society depends and which all citizens have come to expect. Civil infrastructure includes a vast range of facilities, such as roads, railways, bridges, tunnels, seaports, airports, water networks, wastewater treatment systems, desalination facilities, energy production, transmission and distribution, and communication systems, among many others. Social infrastructure includes stand-alone facilities such as schools, hospitals, prisons and courthouses. All these facilities are part of broader networks as are the people that operate them and the people who use them, which complicates their design, operation, and maintenance.

Unfortunately, the United Kingdom, the United States, and many other countries in both the developed and developing world are served by ageing, underfunded, and often technologically outdated infrastructure. Climate change and resource scarcity as well as energy and cost-of-living crises complicate the task of ensuring that infrastructure delivers those critical public services.

New approaches to creating infrastructure, and maintaining and optimising the performance of infrastructure systems, are needed to rise to these challenges. Fresh delivery approaches and promising innovations allow for new commercial and financial models. Improvements in delivery and operating of infrastructure have the potential to boost its productivity and efficiency while reducing environmental impacts. Increasingly, new technologies are enabling more efficient and effective delivery, monitoring and maintenance of the built and natural environment. However, climate change and the ageing of our assets speaks to the urgency and scale necessary for adoption of these technologies.

Infrastructure policy recommendations typically focus on creating new and innovative financing tools. However, the key constraint or gap globally in infrastructure development is often a lack of underlying funding for critical projects. Constructing new infrastructure and rehabilitating old at the pace required by modern urban and rural communities requires substantial funding, often with assistance from privately provided finance. Private investment will flow naturally once adequate, reliable funding sources are in place to support Project Preparation Facilities (PPFs) and develop a pipeline of investable projects, and risks are suitably identified and shared. We need alternative approaches to facilitate private involvement while being mindful of the realities of a post-COVID world that has strongly affected the physical, social and economic fabric of society.

There is a mature market for private sector investment in infrastructure, with a global pool of sophisticated investors. However, the current model of asset-based financing for infrastructure should evolve to fit into a systems-based approach to managing infrastructure, and alternative approaches will need to be embedded in public policy and funding to facilitate private-sector investment.

A better understanding is needed of how the large financial risks associated with infrastructure delivery and operation are shared and managed across public and private partners. Those partners have various infrastructure funding and financing mechanisms at their disposal. Emerging technologies are essential for efficient and effective project delivery as well as for better management of infrastructure. They will increasingly be seen as critical requirements for the financing and funding of infrastructure, including private investment in project equity via project finance.

In the context of major public investment in infrastructure programs, this Report explores how a multi-disciplinary systems approach can improve infrastructure delivery by using innovative funding and financing alongside deployment of emerging technologies. It addresses numerous pressing policy challenges, including infrastructure resilience, net-zero carbon, and social equity, to identify potential policy implications and research needs.

2.2 Context and urgency

Although this Report addresses challenges related to infrastructure delivery and resilience, and to historical inequities of infrastructure provision and services, challenges related to climate change are considered the most urgent. Time is running out to address carbon emissions. The window of opportunity to keep an increase in global temperature to 1.5C in reach and to avoid the worst impacts of global warming is closing fast – at best we have less than seven years[2] to halve current global emissions (IPCC, 2021). The built environment is estimated to contribute 39% of energy-related carbon dioxide (CO2) emissions (International Energy Agency, & United Nations Environment Program, 2018). Infrastructure clearly has a significant role in reducing carbon emissions to acceptable levels.

Although not a focus of this Workshop, we also should acknowledge the loss of biodiversity. The population sizes of mammals, birds, fish, amphibians and reptiles reduced by 68% between 1970 and 2020 (WWF, 2022), and in 2020, anthropogenic mass exceeded overall biomass in the world (Elhacham et al., 2020).

The IPCC Sixth Assessment Report: Impacts, Adaptation and Vulnerability (IPCC, 2021) makes clear the “interdependence of climate, ecosystems and biodiversity, and human societies.” Climate-change risks should be assessed against non-climatic global trends, including “biodiversity loss, overall unsustainable consumption of natural resources, land and ecosystem degradation, rapid urbanisation, human demographic shifts, social and economic inequalities and a pandemic.”

2.3 EPSRC-NSF Infrastructure Workshop

The EPSRC-NSF Workshop, *Funding, Financing, and Emerging Technologies in Infrastructure to Improve Resilience, Sustainability, and Universal Access*. brought together a multidisciplinary group of international experts from academia, policy and practice to explore how to improve infrastructure delivery through innovative funding and financing as well as emerging technologies. This Report captures the discussion and narratives arising from the Workshop, which were framed by background papers and presentations prepared by the Workshop Planning and Organising Committee. It presents recommendations for industry, policy and research. Within the context of infrastructure funding and financing, the Workshop focused on resilience, net-zero carbon and social equity. Each of these topics is examined separately in this report. The complex interconnections across those issues are acknowledged throughout, with emphasis on the systems and systems-of-systems nature of those challenges.

[2] https://climateclock.world/

3.0

ENABLERS – FUNDING AND FINANCING

3.0 ENABLERS - FUNDING AND FINANCING

3.1. Distinguishing funding from financing

Resilience, net-zero carbon, and equity are only achievable if adequate funding and financing mechanisms are in place to support and incentivize critical investments in infrastructure. But, what exactly is the difference between infrastructure funding and financing?[3] Infrastructure funding is the underlying source of money (or revenue) used to pay for infrastructure. Transportation infrastructure funding in the United States offers one example, but this framework can be applied to many infrastructure sectors. Such funding typically comes from one of three broad categories. The first funding source is a direct user fee (e.g., tolls, mileage-based user fees, water/energy tariffs, etc.). These sources of funding are highly related to infrastructure use. Hypothecated gas or diesel taxes are in the spirit of a user fee, although they are becoming less correlated to use as alternative-fuel vehicles, such as electric vehicles, come into greater use. The second source of funding is a targeted tax that is less closely related to the infrastructure use, but still dependent on the value that infrastructure creates. A prime example of such a targeted tax is tax-increment financing (TIF), which relies on capturing increased land values resulting from infrastructure development (see Section 3.2.3). The third type of funding source is a broad tax that is effectively unrelated to infrastructure use. This could be a dedicated sales tax, property tax, or income tax at either the state/local or federal/national level. Importantly, these three broad types of infrastructure funding are not mutually exclusive and can be combined in various ways. For example, user fees can be combined with a subsidy from the general budget or dedicated taxes to partially cover those costs. The UK infrastructure funding model is relevant – regulated firms are required to make capital investments as a condition of license-holding, with the economic regulator determining the level of investment required. In economic terms, this is a concession, but it is a model that blurs public and private finance.

These three broad categories of funding link to social equity or fairness. When considering infrastructure funding sources, it is useful to distinguish between *horizontal* versus *vertical* equity. Horizontal equity refers to the principle of "equal treatment of equals." That is, all of those who use an infrastructure asset at the same intensity should pay the same amount. This concept is embedded in many economic relationships where consumers who wish to consume more of a product or service pay in proportion to their consumption. For example, a household that consumes 60 kilowatts of power per day pays twice that of a household consuming only 30 kilowatts of power. As a result, various funding sources can be ranked according to horizontal equity. That is, by how closely the amount paid is correlated to use of the infrastructure. Figure 3.1 illustrates this concept. In that figure, funding sources that are highly correlated with use are displayed at the far right of the figure. Those sources that are poorly or uncorrelated with use are at the left side. Funding sources at the far right closely measure and charge for road use. An extreme example is real-time, network-wide road pricing (Cramton et al., 2018, 2019). In that approach, drivers would be charged (almost) exactly for the road space used. Revenues from those charges would go directly to fund the transportation infrastructure used by those motorists. Such a charge would be positioned at the right side of the horizontal equity scale. Conversely for a dedicated, or hypothecated, sales tax, payment of the tax would be only weakly related to road use. Such funding would be positioned on the left side of the horizontal equity sale.

[3] Many of the definitions below were obtained from the website of the Federal Highway Administration's Office of Innovative Program Delivery, which was accessed on April 25, 2022. That website can be found at https://www.fhwa.dot.gov/ipd/.

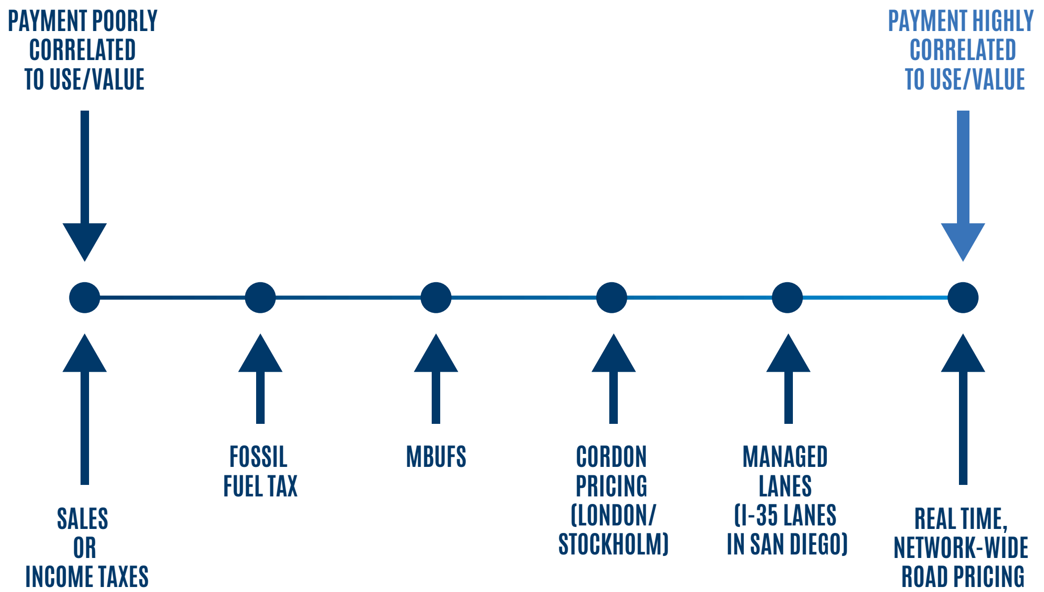


Figure 3.1: Road Infrastructure Funding Sources and Horizontal Equity (note – MBUF = mileage-based user fees/ road user charges) (Geddes, 2022)

In contrast, vertical equity refers to the payment of the funding source across income, or wealth, groups. In this case, there are three broad outcomes: (*i*) the rate, fee or charge is *progressive* if it results in people with higher incomes (or wealth) paying proportionately more; (*ii*) the rate, fee or charge is *proportional* if it results in people with higher incomes (or wealth) paying the same as other income groups; and (*iii*) the rate, fee or charge is *regressive* if it results in people with higher incomes (or wealth) paying less, and conversely for lower incomes. Discussions of equity in infrastructure funding mechanisms often focus on vertical equity. In doing so, detailed data are sometimes needed to determine the incidence of a particular funding mechanism across income groups.

Funding and Financing Recommendation (FFR) 1[4]: Consider adopting funding mechanisms that correlate closely with infrastructure use and that vary with the value of the facility.

Infrastructure finance, on the other hand, is distinct from infrastructure funding. Infrastructure financing describes the tools used to generate large upfront payments for the initial fixed costs of designing and constructing infrastructure facilities. Private financing generally falls under two broad categories: the financial equity and debt (or "fixed income") issued by the special purpose vehicle, as discussed below. This type of equity differs from the concept of equity described in Section 2.3. In financial terms, equity defines the property rights to the net cash flows, or residual claims, of an infrastructure project. Debt, however, usually takes the form of loans, bonds, revolving lines of credit or other securities. This credit eventually must be repaid via specified funding sources. When combined, these financing sources form the capital structure of an infrastructure project and can even be mixed with funding. For instance, a subsidy was allocated in the Spain-France trans-border High Speed Rail project, representing 57.4% of total construction costs. The remaining 42.6% was raised by private sources of capital, distributed between equity (4.3%) and debt (38.3%) (Bel, el al., 2017).

[4] Recommendations specific to each theme are provided throughout the Report and summarized in a table at the end of the Report.

Within infrastructure finance, there is also another important distinction between project finance and corporate finance. Under corporate finance, lenders rely on the borrower's creditworthiness, and the rights and obligations associated with an investment are supported by the company balance sheet. Project finance differs from this structure because it involves financing a specific investment using a special purpose vehicle (SPV). The SPV is set up to attract dedicated capital for the development and/or expansion of a specific project. Debt incurred by the SPV is backed only by project-specific revenues. The SPV is important for project financing because it ring-fences the cashflows generated by the project, thus ensuring the debt provided is on a non- or limited-recourse basis. This SPV structure is a central feature of most public-private partnerships (PPPs), which generally bundle several major project delivery elements (e.g. design, construction, financing, operations and maintenance) into a long-term contract and allocate risks between the public-sector project sponsor and the private partner (Casady and Geddes, 2016, 2019). In some cases, like the Pennsylvania Rapid Bridge Replacement Project,[5] PPPs wrap smaller projects together into one package to achieve scale. There is an opportunity to use this approach to fund some net zero (e.g. retrofit) and resilience projects that are smaller scale but nonetheless vital to achieving our planetary goals.

> **FFR 2: Bundling together facility design, construction and operation into one long-term contract can reduce the incentives to defer maintenance while enhancing incentives to adopt new technologies and improve life-cycle asset maintenance.**
>
> **FFR 3: Including an equity component in the financing structure of a PPP can provide an equity cushion that allows private investors to absorb risk while financing larger upfront amounts relative to debt-only financing structures. This is standard practice in the United Kingdom.**

Globally, public-private partnerships have assumed a greater role in providing infrastructure. There is, however, ongoing controversy about whether they convey lower costs and/or higher efficiency. PPPs will remain a critical source of financing for the foreseeable future in the US. Given that they account for only about five to ten percent of total investment, they are unlikely to be a panacea in addressing infrastructure gaps. More traditional forms of finance, such as public and corporate investment, will remain important.

3.2 Innovations in funding and financing: value capture, asset recycling, and tax-increment financing

Scale is important here because the global infrastructure funding gap is estimated to be about USD $15 trillion by 2040 (GIH, 2020), and as much as USD $18 trillion when we include investments needed to achieve UN Sustainable Development Goals. Importantly, these gaps only refer to infrastructure that directly influences the economy (e.g., transport, power, communications) and do not include investments in social infrastructure (e.g., hospitals, schools). Closing this gap would require annual infrastructure spending to increase from 3.0% to 3.5% of global GDP (OECD, 2017b), but limited infrastructure funding is an enduring challenge, and many governments are searching for alternative sources. Fortunately, existing infrastructure can offer an important latent source of funding, especially systems that may have been managed for decades without an eye for value creation. Innovations in funding and financing such as value capture, asset recycling and tax-increment financing are just some of the novel approaches being used to release this latent value in extant infrastructure. We describe each of these mechanisms in more detail below. It is important however to distinguished between the bundling together of various project elements discussed above from the bundling or wrapping of small projects together as discussed in Case Study FF1, The Pennsylvania Rapid Bridge Replacement Program as highlighted nearby.

> **FFR 4: Bundling or wrapping many relatively small but similar projects together into one large contract can attract international partners who have the expertise, capital and incentives to complete the project on time and on budget.**

[5] PennDOT wrapped 558 structurally deficient bridges (many small, rural) into one large PPP contract, valued at $899 million.

CASE STUDY FF1 - THE PENNSYLVANIA RAPID BRIDGE REPLACEMENT PROGRAM[6]

One daunting challenge to greater public-private cooperation in the United States is small project size. One-off projects placed out to bid by county, municipal, and sometimes state asset owners are often too small to justify the expense of a public-private-partnership (PPP) structure. The process of bidding on a PPP project often costs many millions of dollars, which renders bidding on small PPPs uneconomical.

One solution to that challenge is to bundle many similar projects together into a contract large enough to attract several international consortia. The canonical example of such creative bundling in the United States is the Pennsylvania Rapid Bridge Replacement Project. That Project will replace 558 structurally deficient bridges across Pennsylvania using a design-build-finance-maintain (DBFM) public-private partnership (PPP) availability-payment arrangement. Plenary Keystone Partners, the winning concessionaire, is responsible for demolishing the existing bridges, sustaining traffic during construction, and maintaining the bridges for 25 years following construction.

Project cost was estimated at $1.118 billion, which includes financing costs. The design-build contract was for $899 million. Private equity in the project was $59.4 million. Commercial close occurred on January 9, 2015, and financial close occurred on March 18, 2015. This was the largest road project in Pennsylvania's history.

Most of the bridges in the Program range from 40 to 75 feet in length and are in rural areas on the State's highway system. PennDOT chose the PPP structure to accelerate the replacement of the bridges and to capture efficiencies in the bridges' design and construction. Project bundling will allow each bridge to be replaced and maintained at an average cost of $1.6 million each versus $2 million if completed by PennDOT. It estimated that this would provide a 20 percent cost savings over the life of the concession period compared to PennDOT's replacing the bridges itself.

[6] https://www.penndot.pa.gov/ProjectAndPrograms/p3forpa/Pages/Rapid-Bridge-Replacement-Project.aspx

Image credit: Plenary Americas

3.2.1 Value capture

Value capture is most often associated with funding transportation infrastructure. Transportation networks and urban land values are closely linked. Transportation improvements increase accessibility and thereby make surrounding locations more desirable. These improvements also often increase the value of nearby land, benefiting landowners and developers. Value-capture techniques harness a portion of the increased property values to pay for infrastructure development as well as possible future investments. All told, there are a variety of mechanisms that may be used to derive monetary value from infrastructure improvements to help defray the cost of implementation. Several different forms of value capture used in the United States include air rights, impact fees, joint development, land value taxes, negotiated exactions, sales tax districts, special assessments and transportation utility fees. Massachusetts, for example, has used value capture extensively to fund transit projects (Metropolitan Planning Area Council, 2017).

Value-capture strategies can be used specifically to help pay for roadway and transit improvements by leveraging localized benefits. Although more common with transit projects, value-capture techniques may also be used for highway improvements, as is the case with the San Joaquin Toll Road in southern California and E-470 outside Denver, Colorado. In the United States, most value-capture revenue is generated at the state or local level, yet the federal government encourages these jurisdictions to look for new revenue sources to address funding shortfalls, such as additional motor fuel taxes, vehicle-related fees, and local option taxes. Importantly, value-capture strategies do not always have to be transportation oriented. In some cases, social infrastructure upgrades, such as for schools, can increase tax revenues by increasing surrounding property values.

The general concept of value capture applies to any infrastructure sector where value can be extracted via new technology and better management techniques. One example is simple optimization of real estate portfolios held by public owners. In some cases, land and office buildings could be sold or leased, with the proceeds funneled back into infrastructure owned by that public entity. Another important example is methane capture, where waste methane gas could be released into the atmosphere, but instead is captured and used to create electricity. If contracts are properly structured, then the savings in electricity from the capture can be borrowed against so that the capture technology can be installed at no cost to the public owner. Examples of facilities where methane capture has been used successfully include wastewater treatment plants, landfills and chicken farms, among others. Technological improvements are making such arrangements economic at smaller scales.

One important barrier to the more-widespread adoption of value capture lies in those who may be threatened by the required greater public-private cooperation. Private methane capture operators, for example, may threaten the jobs of public employees who have worked at a wastewater treatment plant for decades. In such cases, the concept of *value sharing* could be used. Value sharing is defined as sharing some of the value realized through value capture arrangements with groups that may be at risk or feel threatened by new technologies and management techniques. One approach, for example, would be to set up a fund using revenues from value capture to compensate employees if their jobs are lost, thus increasing their support for these innovative arrangements. Such funds could compensate employees based on seniority, with those holding more seniority receiving greater compensation.

3.2.2 Asset recycling

Asset recycling is another value-creation mechanism that public entities can use to derive revenue (or funding) from the value of existing infrastructure assets and invest it in new infrastructure (Casady and Geddes, 2020). This process typically involves leasing or selling government-owned assets to private-sector investors, but many other value-creation mechanisms can also be used. In the transportation sector, these assets are most often tolled highways, bridges or excess right-of-way. In addition to generating new revenue, typically in the form of upfront lease payments, asset recycling projects also require private-sector investors to make capital improvements or expand the capacity of leased facilities. In some cases, improvements can be made to unrelated infrastructure facilities or services. The upfront lease payments can also be used to pay off project debt in a new but currently unfunded project or program of projects.

Asset recycling has seen modest use to date. Australia developed a $5 billion Asset Recycling Initiative while the United States has seen five tolled highway and bridge facilities leased to private entities since 2004. Although several initial private-sector investors experienced challenges in realizing their expected return on investment in the near-term, public sponsors generally benefited from these long-term lease transactions. Even with several changes in lease ownership, no impacts on facility users or project sponsors have occurred. This is because provisions from the agreements, including commitments to operate and maintain roadways, remained in effect. They also followed established methods for toll-rate increases and profit sharing.

Other similar concessions in North America have been viewed less favorably. For instance, when the Ontario provincial government auctioned the 407 ETR (Express Toll Route), they did not reinvest (or recycle) the revenue they received into the development of additional transportation or social infrastructure. Instead, they used the proceeds to service a government budget deficit (McQuaig, 2020), thereby missing a value-creation opportunity.

> **FFR 5: Innovative approaches such as value capture and asset recycling can incentivize public asset owners to assess and extract value that may be latent in infrastructure after decades of traditional operation and management techniques. Value-capture projects that include environmental benefits such as methane capture and use should be a key focus.**

3.2.3 Tax-increment financing

Tax Increment Financing (TIF) is yet another innovative revenue tool that uses taxes on future gains in real estate values to fund, or pay for, new infrastructure improvements. In the United States, TIFs are authorized by state law in nearly all 50 states and begin with the designation of a geographic area, known as a TIF district. Implementing TIF financing is complicated and requires a public agency to administer the special district. A “finding of necessity” is first prepared that establishes the need for the TIF and formalizes the boundaries of the district. This finding is normally a detailed study demonstrating that the district meets the criteria contained in the enabling legislation. A redevelopment agency is then created by resolution or ordinance. This agency may be the governing body of a municipality, or it may be a new agency appointed by the governing body. Plans for specific improvements within the TIF district are then developed.

The TIF creates funding for public or private projects by borrowing against the future increase in these property-tax revenues. The intent is for the improvement to enhance the value of existing properties and encourage new development in the district. TIF districts are usually established for a period of 20 to 25 years, during which time all incremental real estate tax revenues above the base rate at the time the district is established flow into the TIF. Proceeds from the TIF can be used to repay bonds issued to cover upfront project development costs. Alternatively, they can be used on a pay-as-you-go basis to fund individual projects. In some cases, private developers may self-finance infrastructure improvements, with a municipality reimbursing them from the tax increment as tax proceeds are received. In many states, areas must be blighted to establish TIF districts. This ensures TIF is used to channel funding toward improvements in distressed, underdeveloped or underutilized areas where development might not otherwise occur.

Thousands of TIF districts have been established around the United States in cities of all sizes. The strategy is commonly used by local governments to promote housing, economic development and redevelopment in established neighborhoods. In Atlanta, Georgia, for example, the Beltline project’s formation of a special Tax Allocation District helped fund the development of public transit, affordable housing and other social infrastructure such as parks and walking trails (Nichols, 2012). Although TIF has not been used extensively (especially in the United Kingdom) to fund transportation infrastructure, some state laws specifically authorize the use of TIF for such purposes as asset recycling and other value-capture strategies. TIF is advantageous because the released value can often be used to pay for the redevelopment of existing facilities or invested in new infrastructure services.

One recurring theme in the United States regarding the innovative approaches to infrastructure described above is the public-sector asset owner's knowledge of, and comfort with, these new approaches. To capture the social benefits of these innovations, public-sector education and support is critical. That support may take the form of intensive public-sector-only executive education, as well as dedicated PPP units within government that advise asset owners on the social benefits and costs of various alternative delivery approaches. Many countries, such as Canada and Australia, have successfully used PPP units to protect the public interest while helping to improve infrastructure delivery.

> **FFR 6: Public-sector-only executive education can help ensure that innovative approaches such as PPPs, TIFs, value capture and asset recycling are in the public interest and can support public owners in the pursuit of new, socially beneficial approaches.**

3.3 Incentives for environmental, social, and governance (ESG)

Innovative yet proven funding and financing mechanisms are available to help improve community resilience, meet net-zero carbon targets, and create more equitable and accessible infrastructure services in ways that require little or no new capital commitments. Markets for decades have not routinely attempted to price this value creation. However, investors are increasingly adopting approaches to create value using Environmental, Social, and Governance (ESG) models and other impact-investing strategies (Vecchi et al., 2021). This trend is helping align private-sector interests with public-sector priorities. The growing emphasis of ESG-driven approaches to investing is also improving financial incentives. There are nevertheless drawbacks to ESG as currently practiced. Some firms have engaged in greenwashing whereby certain business practices are exaggerated to appear more environmentally friendly. Some oil companies, for example, have emphasized activities that reduce carbon emissions when the great majority of their practices promote carbon-based energy consumption. Concerns have been raised that the primary focus of companies is to support investors, even at the expense of adhering to ESG principles.

Yet, public and private actors still need to develop new ways of combining financial value with public value. Examples include: (*i*) public and private sector funding models need to adapt and evolve to deliver infrastructure that is more sustainable and meets societal needs while delivering a return to investors; (*ii*) these models need to move beyond traditional asset-based financing, while being consistent with a systems-based approach to infrastructure management and more flexible than traditional PPPs over the life of the investment/asset. These investments also need to deliver greater social impact in terms of resilience, carbon reduction, equity and driving innovation; (*iii*) the regulatory framework needs to adapt and become more flexible to accommodate these new approaches; and (*iv*) procurement methods will also need to change to deliver this. The Thames Tideway Tunnel offers one example of this approach. The tunnel will cost £4.3bn to complete and is paid for by Thames Water's 15 million wastewater customers through their bills, which will increase by around £25 per year. The project has an operating company backed by pension funds and other long-term investors. The financing model for Thames Tideway involves the financing of a single significant asset with suitable protection from the UK government against certain risks. Regardless of the funding and financing mechanisms, emerging technology will certainly play a leading role in how value is extracted and captured from our existing infrastructure systems.

4.0

ENABLERS – EMERGING TECHNOLOGIES

4.0 ENABLERS - EMERGING TECHNOLOGIES

4.1 What are emerging technologies?

There have been rapid technical advances in fields such as electronics, optics, material science and computer science. These technologies are referred to here as emerging technologies (ETs). Although there is no widely adopted definition of emerging technologies specifically targeting infrastructure applications, several general classifications do exist. For instance, Rotolo et al. (2015) describe an emerging technology as:

. . . a radically novel and relatively fast-growing technology characterized by a certain degree of coherence persisting over time and with the potential to exert a considerable impact on the socio-economic domain(s) which is observed in terms of the composition of actors, institutions and patterns of interactions among those, along with the associated knowledge production processes.

In addition, Rotolo et al. (2015) describe emerging technologies using five distinct attributes: (*i*) radical novelty, (*ii*) relatively fast growth, (*iii*) coherence, (*iv*) prominent impact, and (*v*) uncertainty and ambiguity. Halaweh (2013) adopts a slightly different set of characteristics to describe emerging technologies that focus on uncertainty, network effects, unseen social and ethical concerns, cost, limitations to specific countries, and an absence of investigation and/or research (i.e., novelty). Taken together, these definitions highlight an important feature wherein emerging technologies upset existing business models quickly and at scale, thereby radically accelerating social change.

4.2 Emerging technologies and infrastructure

New technologies related to materials, sensing, communication and computing are emerging at an accelerated pace compared to recent decades (Soga and Schooling, 2016). This has resulted in a spill-over of technologies from other fields into civil engineering, thus providing new opportunities for enhancing delivery and ensuring resilience in previously impossible ways.

Emerging technologies increase the timeliness and reliability of information about the current state of infrastructure. They support decision making and increase long-term infrastructure performance and return on investment. The data and insights generated from these technologies can empower decision-makers to improve design approaches and system resilience, decarbonize existing infrastructure networks and achieve more equitable service outcomes.

Augmented reality technology

4.3 Examples of emerging technology

Emerging technologies are being increasingly applied in infrastructure systems. Table 4.1 lists ETs that can be used for infrastructure applications.

Table 4.1 Key Emerging Technologies for Infrastructure

	Emerging Technologies	Remarks
1	Distributed sensors and network (satellite, fiber optics, wireless sensor network, etc.)	Sensors everywhere with 5G/IoT, creating hyper-connected networks
2	In-field autonomy (inspection, construction and maintenance)	Autonomy using drones, humanoids and robots
3	Off-site autonomy at sub-millimeter resolution	3D printing to self-assembly and operation at sub-millimeter resolution
4	From Building Information Modeling (BIM) to socio-technical digital twins	Infrastructure asset tracking to social behavior monitoring and modeling for digital visualization and extended reality
5	High-performance computing in the cloud	Multi-scale simulations and data interpretation from sub-millimeter scale to tens of kilometer-scale using Quantum computing
6	Virtual reality, augmented reality and mixed reality	Creating an immersive environment linked to digital twins using wearable technologies for training and operation under normal and extreme situations
7	Artificial intelligence and machine learning	Data analytics and human interpretation under normal and extreme situations, leading to the discovery of new materials and processes
8	Edge computing	Local decision making rather than centralized decision making
9	Ubiquitous and transparent security	Automating trust by blockchain, digital ethics and service integration
10	New materials	Zero- or negative- carbon, self-healing, sensing and adaptive
11	Platform-based approaches to infrastructure delivery	Industrialized precision manufacturing of infrastructure components based on standardized designs and specifications

Drones, humanoids, and other large robots are being deployed in the field to provide on-site autonomy for inspection, construction and maintenance tasks. At the same time, 3D printing, self-assembly, and other forms of pre-fabrication/modular construction are increasing off-site autonomy, even at sub-millimeter resolutions. Integrating structural sensing, environmental sensing and infrastructure usage can potentially yield more significant benefits than simple cost efficiency. The ubiquity of distributed sensors (satellites, fiber optics, wireless sensors, etc.), coupled with 5G/IoT, has created hyperconnected networks that can be used for long-term, real-time monitoring of infrastructure service performance and resilience. Such sensor systems are now being increasingly used by Network Rail in the United Kingdom to monitor performance of slopes and embankments, providing failure detection and reaction via alert alarm systems, as well as indicating possible precursors to failure (Mair, 2021). Sensors can now continuously monitor the strain, temperature and vibration profiles of pipelines along earthquake fault lines, improving our understanding of their adaptability to seismic activity (see Case Study ET1). Such monitoring has also been used to identify the nature of defects in rail lines, design remediation strategies and confirm the effectiveness of repairs (see Case Study ET2).

CASE STUDY ET1 - LONG TERM MONITORING OF HDPE PIPELINES USING DISTRIBUTED FIBER OPTIC SENSING (DFOS)

Seismically active faults pose a risk to buried water pipelines that can be complicated to quantify. Fault type, slip rate, pipeline geometry and soil conditions all factor into a complex soil-pipeline interaction. For critical pipelines that cross faults, high-density polyethylene (HDPE) has become an attractive material choice because of its accommodation of large deformations. Using HDPE increases the robustness of these pipelines, but it does not inform a utility about the actual deformed condition of a pipeline. This may be viewed as simply pushing a large break into the future when fault displacements are sufficient to rupture the pipe. At a site in Berkeley California, East Bay Municipal Utility District, a local water utility in the San Francisco East Bay, installed a monitoring system based on distributed fiber optic sensors to monitor their HDPE water pipelines crossing a strike-slip fault throughout its lifetime. The technology makes a single low-cost fiber optic cable into thousands of strain gauges, thermocouples or accelerometers. The sensor material itself, silica, is relatively inert compared to the life of infrastructure; it is ideal for long-term monitoring by embedding the fiber in structures. The goals of using this solution are to increase the robustness of the water system and to provide an information source that can be leveraged to make asset management decisions in the future, such as intervening measures to reduce stress buildup in a pipeline that has heavily deformed due to fault slippage. The technology can be a scalable distributed monitoring system for large infrastructure projects such as bridges, tunnels, foundations, dams, levees, deep wells, and surface or buried pipelines

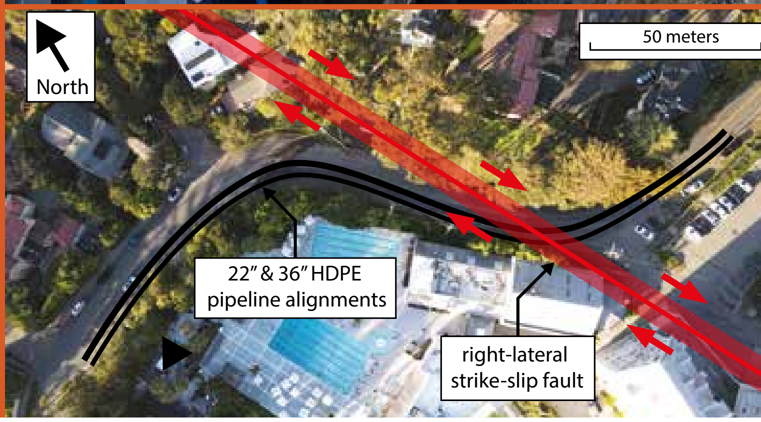


Image credit: Peter Hubbard, University of California, Berkeley © 2021

As the degradation of infrastructure is often governed by cyclic thermal loading (expansion/contraction), changes in moisture conditions (humidity, flooding, groundwater pressures) or changes in usage (heavier traffic, change in flow volumes and pressures, etc.), integration and communication between long-term value (structural health, future hazards, and degradation) and short-term value (operation, energy, etc.) provide efficiencies and profoundly shift how infrastructure projects are managed and maintained. However, due to different rates of technical development between monitoring and autonomy systems versus infrastructure usage, some data may be from older systems; some of the systems currently in use may be generating data that will be used in 10, 20 or 50 years' time.

> **Emerging Technologies Recommendation (ETR) 1: Intelligent sensor and autonomy systems must be designed for long lifespans or be adaptable for replacement.**

CASE STUDY ET2 - DEVELOPMENT OF A FIBER OPTIC INSTRUMENTED GEOGRID FOR EARLY DETECTION OF GROUND MOVEMENT

The serviceability of civil engineering assets can be adversely affected by ground movement due to differential settlement at earthwork/structure transitions, dissolution features or mining legacy voids. The number of methods for monitoring sufficiently large areas and providing early warning of the onset/development of ground movement is limited. The incorporation of distributed-fiber optic strain sensing (DFOS) systems into earthworks could provide important information on the commencement, location, origin and magnitude of ground movements in near-real-time for critical infrastructure over areas at risk. DFOS can provide high spatial resolution mapping of subsurface ground movement but accuracy is reliant on mechanical coupling between FO cables and the surrounding soil. The Cambridge Centre for Smart Infrastructure and Construction (CSIC), Huesker Gmbh and Epsimon Ltd have developed an instrumented geogrid in which FO cables are woven during the manufacturing process by substituting them for yarns of similar size. The performance of the instrumented geogrid was evaluated through extensive testing at CSIC and its capability for early warning of localized ground movement was verified during a series of controlled field trials at HS2's Chilterns Tunnel South Portal site in collaboration with Jacobs and Align JV. The results showed that the grid can detect ground movement from an early stage and at the sub-meter spatial scale as it is sensitive to small settlement. Following the successful field trials, the FO-instrumented geogrid was deployed on a 1000 sq.m. area at the Tilehouse Lane Cutting site of HS2 and is currently being used to monitor, in real-time, any potential sub-surface movement under a construction haul road, over which eventually the high-speed line will run.

Image credit: David Wright, Jacobs

With the advent of high-performance computing in the cloud, multi-scale simulations and data interpretations of system-wide impacts on road, rail and water networks are now possible. Because of the large number and manifold types of data collected by many sensing technologies, big data approaches are needed to interpret better and leverage content. The Digital Twin framework allows such data to be managed, understood and analyzed. Digital twins represent a 4D (3D + time) digital replica of the physical infrastructure, which can exchange information about asset operation and performance at the right time with the physical asset. The number of dimensions is now increasing beyond 4D by having additional performance indicators such as estimate/cost, project-lifecycle information, life-cycle and maintenance information, serviceability, sustainability, safety, etc. These analyses improve infrastructure delivery and network resilience and identify high-priority areas for efficiency gains and carbon-reduction interventions.

Problems of complex infrastructure systems cannot be solved without deeply analyzing the complex socio-economic and political considerations that affect different communities at different scales. There is also the possibility to include organizational infrastructure (human interactions) and informal infrastructure (unplanned) in the existing physical and digital infrastructure framework. The complexity of the social decision-making processes involved in mobilizing change requires the creative use of digital twin technologies. When the power of high-performance computing is paired with Building Information Modeling (BIM) and socio-technical digital twins, infrastructure asset modeling can be linked with social behavior to understand human interaction with physical infrastructure systems. These digital procedures are growing in use, including planning to identify evacuation corridors for residents living in communities threatened by wildfires. Digital twins for the water distribution system of Los Angeles and the auxiliary water supply system of San Francisco have also been used by system operators to make decisions about risks, network integrity and flows following a major earthquake (O'Rourke, 2010) (see Case Study ET3 below). Such models, including extensions of reality (e.g., virtual reality, augmented reality and mixed reality) using wearable technologies, are creating more immersive environments for enhanced training and operations under normal and extreme situations.

ETR 2: Autonomy in infrastructure construction and operation should be developed within the framework of a common data environment (CDE) with standardized data so that efficiencies in infrastructure systems can be achieved.

ETR 3: Using the framework of a socio-technical digital twin, infrastructure asset modeling should be linked to social behavior to understand human interaction with physical infrastructure systems.

There is a continued need for better tools to use infrastructure data more effectively for decision support. Emerging Machine Learning (ML) / Artificial Intelligence (AI) combined with high-performance computing (HPC) provides promising techniques to detect trends in high-dimensional data, which was not possible with traditional statistical techniques. This is particularly true for large-scale infrastructure with numerous data channels incorporating multiple measurement parameters, image-based sensing, or other non-contact sensing that generates large data sets.

Some AI/ML technology tools can become powerful interpolators to find complex patterns within multi-dimensional data that are not subject to predefined physical laws and assumptions. However, they may perform poorly in extrapolation problems where the conditions are outside the training boundaries. Prediction errors can lead to serious failure and unreliable predictions. Some models are prone to overfitting and may only perform reliably within the given training boundaries. A model that produces substantial errors due to a lack of generalization (i.e., ability to adapt to new data) or data perturbation (e.g., outliers, noises) cannot be accepted. This is one of the main current limitations of ML/AI for infrastructure applications.

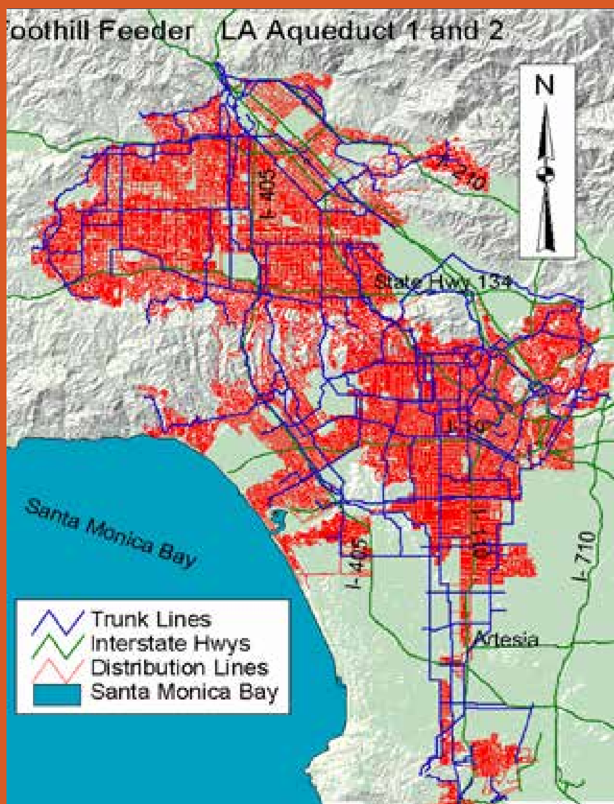
ETR 4: There is a need for machine learning and artificial intelligence to address prediction accuracy and prediction reliability of infrastructure system performance.

AI and ML are further extending human capabilities in data analytics and interpretation, both under normal and extreme conditions, leading to the discovery of new materials and processes. These discoveries, especially in materials science, are increasingly zero (or negative) carbon, self-healing, sensing, and adaptive. At the same time, the proliferation of renewable technologies for energy generation and storage is accelerating the low-carbon transition in an era of edge computing where decision making and energy provision is becoming increasingly local and distributed rather than centralized. These increasingly distributed systems are, however, being integrated and secured in a ubiquitous and transparent way via digitization and the use of blockchain.

CASE STUDY ET3 - DIGITAL TWIN OF THE (LADWP) DISTRIBUTION SYSTEM

A digital twin was developed using the Los Angeles Department of Water and Power (LADWP) distribution system, as shown in the figure. It simulated all of the nearly 12,000 km of trunk and distribution pipelines and related facilities (e.g., tanks, reservoirs, pressure regulation stations, etc.) in the network (O'Rourke, 2010; Bonneau and O'Rourke, 2009; Rose et al., 2011). The digital twin accounted for the aggregated seismic hazard in Los Angeles through an ensemble of 59 scenario earthquakes. The 59 scenario earthquakes provide a library, from which engineers and managers select specific scenarios or combinations of scenarios. The digital twin worked with risk and reliability assessment tools to provide metrics of system performance. The computer simulations could account for the interaction of water and electric power. The model output was used to evaluate the regional economic and community impacts of water losses. All system input and output was visualized through GIS with advanced query logic and web-based features. The simulations accounted for loss of service as tanks and local reservoirs lose water over time through leaks and breaks in pipelines. The analysis also accounted for non-steady state flow through a special computer program. Because of the numerous locations of damage, flow in the network needed to be modeled as non-steady (Lui and Guoping, 2013; Muranho et al., 2014; Kise et al., 2017; WINTR, 2021).

The model allowed for interaction between academic researchers and LADWP engineers and managers. There was much learned about the corporate culture at LADWP, and what methods of modeling worked for the best practical results. The digital twin was used for policy decisions by LADWP management, thereby emphasizing the social and economic aspects of the model.



General Dwight Eisenhower said, "In preparing for battle I have always found that plans are useless, but planning is indispensable." Like conflict planning, the LADWP digital twin allowed for experimentation. Researchers, engineers, planners and managers obtained multiple results from the simulations. Although no result is likely to match the actual outcome, it is the combination of results that teach improvisation. Those who use digital twins learn to improvise through experimentation with many scenarios and can therefore adapt to changing conditions. Such improvisation is a distinguishing characteristic of a resilient organization.

Image credit: Professor Tom O'Rourke, Cornell University

4.4 BARRIERS TO ADOPTION

Emerging technologies are beginning to experience far-reaching applications in the infrastructure value chain. However, such transformations do not happen overnight, and many barriers to adoption exist. Both the public and private sector can be reluctant to adopt new, emerging technologies. Reliability and safety in the provision of services are taken extremely seriously by both private and government organizations. They do not want to lose their reputation for service quality by deploying relatively unproven technologies, especially when technology companies tend to come and go. In particular, public agencies are looking for long-term stewardship. Depending on only one company, especially a startup, is a risky proposition. At the same time, these agencies need to show savings (i.e., reductions in cost), but they often lack the skills required to adopt cost-saving technologies. Unions will resist automation and employment reductions. In-house technology adoption also tends to be slow because there is a delay in labor skill development, and it is often difficult to redefine roles to work on new activities. Moreover, both agency and service structure tend to differ across sectors. The siloed nature of these complex industries makes adoption bespoke to specific infrastructure systems and networks. It also means that deployment is more expensive, and the value of innovation is difficult to map. Hence, public agencies are resistant to change and tend to pursue small pilots first with relatively minor impacts. This creates long lead times before certain, well-established technologies are fully adopted at scale.

4.5 Technology adoption cycles for infrastructure systems

A new technology is adopted because it generates a perceived benefit, which can generate a new function or improve the performance of a system designed by the technology producer and can be reasonably expected by the adopter. There are two popular approaches for describing technology adoption cycles: (*i*) measure of market share; and (*ii*) technological expectations accompanied by lifecycle phases.

Rogers (2010) defines five successive phases based on the demographic characteristics of technology stakeholders. These five phases include early innovators, early adopters, early majority, late majority and laggards. Another popular approach to assessing the lifecycle adoption of technologies is the Gartner Hype Cycle (Gartner, 2022). The Gartner chart asserts that the process of technology adoption consists of five phases: innovation trigger, peak of inflated expectations, trough of disillusionment, slope of enlightenment and plateau of productivity. Differing from Rogers's curve, the measure is not market share but a psychological measure of market expectations.

For technological maturity, there are popular NASA technology readiness levels (TRL) (NASA, 2012). There are nine NASA TRLs, ranging from "basic principles observed and reported (level one)" to "actual system flight proven (level nine)." As for organizational readiness to adopt a technology, the American Association of State Highway and Transportation Officials (AASHTO) Transportation Asset Management Guide presents five maturity scales: initial, awakening, structures, proficient and best practice (AASHTO, 2011). In a National Cooperative Highway Research Program (NCHRP) report, Olsen et al., (2016) evaluated technologies that can be used for inspection, marking and coding of transportation structures. They defined three categories for all technologies that can be used for transportation structures, which include: (*i*) commonly used; (*ii*) available for use; and (*iii*) emerging. For a technology to be categorized as "commonly used", it must be at a TRL of nine according to NASA (2012) and either be proficient or best practice according to AASHTO (2011). The same requirements apply to the category of "available-for-use". Emerging technologies are defined as being at or above TRL 6 ("system/subsystem model or prototype demonstration in a relevant environment", NASA, 2012) and in the awakening or structured level of organizational maturity (AASHTO, 2011). However, specific equipment and special training are still needed. This means organizations need to get comfortable with new technologies, find first movers and initially adopt technologies that do not affect delivery, all while enhancing worker safety.

The benefits of new technology can only be realized when it is widely diffused and when that diffusion results from decisions that encompass its uncertain benefits (Hall and Khan, 2003). Should uncertainties be mitigated or even removed, the diffusion and adoption process would be facilitated or even accelerated. When assessing the maturity level of an emerging technology for an infrastructure system, challenges arise from significant uncertainties associated with benefits that span many physical, organizational and economic dimensions. There is no standard or straightforward measure for explicitly defining the maturity of an emerging technology for infrastructure applications. To adopt a technology in infrastructure systems, one must consider two types of maturity: technological and organizational. These maturity types differentiate between a technology provider and an adopter. It is inevitable that emerging technologies will go through periods of inflated expectations. It is thus crucial to assess whether contributions of these technologies to improved delivery, resilience, net-zero carbon and equity objectives are also inflated. Objectively, separating proven performance from exaggerated claims is critical for successfully assessing the viability of emerging technologies. Moreover, quantitative measures of value that an emerging technology can bring to a socio-technical system are only realized after a trial, or set of trials, that are spurred on by a qualitative understanding of technological advancement and the potential benefits that the technology can offer. This is especially true in the complex ecosystem of civil infrastructure socio-technical systems.

4.6 Expectations of emerging technologies

Although end-users tend to view the adoption of ETs as universally beneficial for improving service performance, accessibility and life-cycle reliability/resilience, the value of specific emerging technologies must be assessed contextually. The effects of ETs on resilience, net-zero carbon and equity can also be difficult to quantify and therefore are not fully appreciated. Accelerating the use of emerging technologies will only occur if these technologies can be directly linked to broader resilience, net-zero carbon and equity objectives. A challenge to ET adoption is a communications disconnect between those technology companies and infrastructure owners who desire to accelerate our ability to improve infrastructure resilience and equity on the global pathway to net-zero carbon. Proactive versus reactive steps make infrastructure more adaptive, while performance-based design and operations help improve the quality of infrastructure delivery and services throughout the lifecycle. Technology can also substantially enhance recovery efforts after exogenous events.

Unless we create a large market for smart infrastructure, it will be difficult to adopt emerging technologies in our everyday practice. It is thus important first to build trust with infrastructure owners and community members and develop a dialogue defined by shared values. We must then demonstrate the value and maturity of emerging technological applications, and organizational readiness for their adoption.

> **ETR 5: Through innovations in materials and construction/maintenance processes, future infrastructure systems must be designed to generate their own energy or rely exclusively on renewable energy, realizing a net-zero or negative carbon system.**
>
> **ETR 6: There is a need to develop a commonly shared approach to evaluate emerging technology contributions for improved delivery, resilience, net-zero carbon and equity objectives of infrastructure systems. The framework needs to be used to enhance communication between infrastructure owners and technology developers.**
>
> **ETR 7: A large market for smart infrastructure should be created and developed by innovative policies and financial incentive mechanisms.**

5.0

RESILIENT INFRASTRUCTURE

5.0 RESILIENT INFRASTRUCTURE

5.1 What do we mean by resilience?

The word resilient comes from the Latin *resilere*, meaning to leap back (*salire* being to leap). Its dictionary definition (Chambers) is "elastic, physically or in spirits". Applied to infrastructure, the term resilient implies the ability to recover function rapidly after some damaging event (Rose, 2007). We expect more from infrastructure than this, however. As Bruneau et al. (2003) point out, we expect our infrastructure to be robust ("stout, strong and sturdy") in resisting damage from use or abuse and to have properties of redundancy (enabling functionality even though some components fail), rapidity in recovery, and restoration of functionality and resourcefulness (i.e., the capacity to recover and meet performance goals). We also look to infrastructure to be adaptable "for a purpose or in conditions … other than those … originally intended".

Numerous definitions for resilience have been proposed, some of which have been summarized by the American Society of Civil Engineers (Ayyub, 2021). The House of Lords Select Committee on Risk Assessment and Risk Planning report *Preparing for Extreme Risks: Building a Resilient Society* (2021) uses the definition from the United Nations Office for Disaster Risk Reduction (UNDRR, 2021) as "The ability of a system, community or society exposed to hazards to resist, absorb, accommodate, adapt to, transform and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions through risk management." In societal terms, resilience may be "the ability of a community to withstand and recover rapidly from disruptions and to adapt to changing conditions" (White House, 2011). Other definitions of resilience are offered in *Disaster resilience: A national imperative* (National Research Council, 2012).

Infrastructure provides the resources and services that sustain communities. It includes key public and private-sector buildings, transportation facilities, energy generation and delivery systems, water supplies, telecommunications, and waste conveyance and treatment networks. Resilient infrastructure, however, involves much more than the protection and emergency operation of core facilities. It involves complex interactions between the government agencies and utilities that operate it, the companies and businesses that design and build it, the institutions that finance and fund it, and the people who depend on it for safety and economic security (NIST, 2016).

We increasingly expect our infrastructure to be sustainable, in the sense of "meeting the needs of the present without compromising the ability of future generations to meet their needs" (Brundtland, 1987), and to contribute to reducing greenhouse gas emissions and improving society through equitable provision of and access to infrastructure services and levelling up[7]. These are important boundary conditions that must be considered when making infrastructure services more resilient.

The importance of resilience is explicitly stated in UN Sustainable Development Goal 9: "Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation…. A functioning and resilient infrastructure is the foundation of every successful community." Resilience embraces uncertainty about the future, emphasizing the need to acknowledge and respond to uncertainty in our assessment of risk. It helps us comprehend possible futures and how we make sensible decisions that will help us anticipate, prepare for, and respond to these possibilities. The UN Sendai Framework for Disaster Risk Reduction 2015-2030 (UNDRR, 2015) outlines seven clear targets and four priorities for action to prevent new and reduce existing disaster risks. The four priorities are: (*i*) understanding disaster risk, (*ii*) strengthening disaster risk governance to manage disaster risk, (*iii*) investing in disaster reduction for resilience and (*iv*) enhancing disaster preparedness for effective response, and to "build back better" in recovery, rehabilitation and reconstruction.

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[7] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1095544/Executive_Summary.pdf

5.2 Types of threats and events

Resilience, by definition, implies a certain level of responsiveness to some form of disruptive force. In the context of infrastructure, types of disruptors include:

- Internal, owing to changes in the infrastructure itself (e.g., ageing and end-of-engineered life)
- Sudden and unexpected (e.g., extreme natural hazards such as earthquakes, tsunamis, fires, pandemics, etc.; or extreme man-made events, such as terrorism and war), and/or
- Gradual and externally driven (e.g., climate or demographic change; changing operations or usage patterns resulting from evolving technological and/or societal expectations).

Acute (sudden) events which are anticipated must be planned for as much as possible, while bearing in mind that the presumption of knowledge about what is most likely has often resulted in a lack of preparedness for what *actually* happens. Repurposing, or disposing of, infrastructure at the end of its design, engineering or useful life raises new questions about the utility of infrastructure beyond its original purpose or original design life. In each of the scenarios presented below, there is an opportunity to shape a more-resilient future.

Throughout this discussion of possible disruptors, it is important to consider for which events planning is reasonable. Is it more useful to understand the effect/impact of an event than predict the cause? It may be better to plan for the right capability rather than focusing on the cause. What information do we need to ensure that we have a good understanding of how assets in a system are affected by a range of events and what are the results downstream? Given that asset managers must deal with the unplanned consequences, their skills need to be enhanced to better cope with increased uncertainty and perturbations. The goal is to avoid a disproportionately large impact due to damage to and/or loss of a previously unidentified critical node.

5.2.1 Internal changes

Infrastructure gradually deteriorates over time and with use, and to keep it functioning reliably requires a strict regime of inspection, maintenance and renewal. This is sometimes problematic because infrastructure can last decades if not centuries; what was actually built is often not accurately recorded, and records have been lost over time. Detailed physical inspection is not always possible, making it difficult to detect loss of function. For example, earthworks (cut slopes and embankments) can suffer a form of fatigue failure due to annual seasonal cycles of moisture-content-induced shrinkage and swelling. Likewise, a combination of corrosion, detailing defects and increased loading have led to catastrophic bridge failures, especially of those that were not adequately maintained – e.g., the 2007 I-53W bridge collapse over the Mississippi River; the 2018 Ponte Morandi steel cable-stayed bridge collapse in Genoa, Italy; and the 2022 Fern Hollow Bridge in Pittsburgh, Pennsylvania.

Some infrastructure also becomes obsolete (e.g., abandoned mines, utilities, manufactured or town gas plants, wind- and watermills, etc.) because society no longer finds it useful. In these instances, infrastructure may be either abandoned, torn down or repurposed. Although some major pieces of infrastructure are often lost in this way,[8] others are re-used in novel ways that bring different benefits to society (e.g., “rails to trails”[9]), making adaptability an important feature of resilience as infrastructure needs change over time.

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[8] Mass rail line closures in the UK during the 1960s and 1970s resulted in the destruction of bridges across the Severn estuary at Sharpness and Solway Firth as well as spectacular iron-decked viaducts at Crumlin and Belah and masonry viaducts at Thorpe Thewles, Little Water of Fleet and Crowhurst. Other parts of this network were converted into a national long-distance cycle path network, using some of the original bridges and viaducts (see note 2).

[9] “Redundant” railways in both the US and UK have been repurposed as greenways for cycling and walking.

5.2.2 Sudden and unexpected events

Past experiences of acute shocks, whether related to natural hazards or man-made, have heightened awareness of vulnerabilities in the built environment and have acted as catalysts for improvements in policies, standards and management practice. Examples of these events include extreme weather impacts, physical and cyber-attacks, and pandemics.

Extreme weather – Climate change is increasing the volatility, frequency, and severity of extreme weather events, making them more commonplace or even the norm going forward. In fact, mega-disasters from the combination of more severe natural hazards and greater exposure due to growing cities are occurring with increasing frequency (IPCC, 2022).

In 2017 alone, Hurricanes Harvey, Irma and Maria collectively caused direct damage of $265 billion. The latter devastated electrical power in Puerto Rico, which took approximately 328 days to restore. In 2020, there were also more than 30 named storms and hurricanes in the North Atlantic, exceeding the 28 that occurred in 2005. Also, the 2019-2020 Australian bushfire season resulted in one of the worst wildlife disasters in modern history with almost 3 billion koalas, kangaroos and other animals estimated to have been killed or displaced (Slezak, 2020).

Earthquakes and resulting tsunamis pose a significant threat to infrastructure. During 2004-2014, three of the 10 highest magnitude earthquakes occurred, including the 2004 Sumatra-Andaman earthquake and tsunami (third highest), 2011 Tohoku earthquake and tsunami (fourth highest), and 2010 Maule earthquake (sixth highest). Approximately 228,000 and 16,000 people were killed by the Sumatra and Tohoku earthquake and tsunami, respectively. The sheer severity and far-ranging consequences of these and similar events are establishing a new normal for natural disasters while posing a corresponding challenge to the engineering profession to help develop more resilient infrastructure to mitigate the impacts of these natural hazards.

New York subway during Hurricane Sandy in 2012

Table 5.1 summarizes examples of infrastructure systems damaged by sudden events, together with historical comparators for context.

	Location	Year	Type of event / brief description[10]
Extreme weather	United Kingdom	1990	Extensive flooding and property loss from Burn's Day Storm; costliest weather event for insurers in British history; $5 Bn direct damage
	New Orleans, USA	2005	Flooding due to overtopping/failure of Hurricane Protection System in New Orleans by Hurricane Katrina; $125 Bn direct damage
	New York City Metro Area	2012	Extensive flooding, including Lower Manhattan, from Hurricane Sandy; closure of the New York Stock Exchange for two days; $68 Bn direct damage
	Houston, Texas	2017	Extensive flooding and inundation around Houston, Texas, by Hurricane Harvey; $125 Bn direct damage
	Puerto Rico	2017	Extensive flooding and wind damage from Hurricane Maria; massive electric power system destruction; $90 Bn direct damage
	Europe	2021	Major flooding owing to extreme rainfall (notably in Germany)
Earthquake & Tsunamis	Los Angeles, California	1994	Northridge earthquake; destruction of buildings, roads, water supply, electric power, etc.; $46 Bn direct damage
	Sumatra-Andaman Earthquake & Tsunami	2004	>228,000 fatalities. Massive damage in Indonesia, Thailand, Sri Lanka, India, & Africa
	Canterbury, New Zealand	2010-2011	Four major earthquakes affecting the Canterbury region, New Zealand, including Christchurch; 185 fatalities; buildings, roads, water/energy supply etc. destroyed several times in multiple earthquakes; $30 Bn direct damage
	Japan	2011	Massive earthquake and tsunami destruction from Tohoku earthquake; 16,000 fatalities; loss of Fukushima-Diachi Nuclear Power Plant; 54 nuclear reactors shut down as a response to the disaster
Fire	California	2018	Massive destruction by the Camp Fire; 90% of Paradise, CA lost; $13.5 Bn victims' trust fund established by Pacific Gas & Electric Company
Volcano	Krakatoa, Indonesia	1883	Massive volcanic eruption that destroyed >70% of the island of Krakatoa and its surrounding archipelago; together with the ensuing tsunamis, it is thought to have been responsible for >36,000 fatalities
	Eyjafjallajökull, Iceland	2010	Volcanic eruption emitting clouds of fine-grained ash that remained suspended in the atmosphere over a very wide area, disrupting commercial air traffic around the world
Terrorism	New York City, New York	2001	World Trade Center Disaster: 2,977 fatalities: 25,000 injured; loss of US GDP of $145 billion; massive building destruction; led to worldwide disruption
	London, UK	2005	Simultaneous bombings at three London Underground locations and one bus stop; significant damage and disruption of infrastructure
Anthropogenic landslide	Aberfan, Wales	1966	Catastrophic collapse of a colliery spoil tip that had been deposited on a mountain slope on top of a natural spring. Rising pore pressures within the tip following heavy rain led to a sudden slide, which engulfed the village school killing 116 children and 28 adults
	Stava, Italy	1985	Two mine tailings dams above the village of Stava failed owing to poor operational practice which led to the decant pipe in the upper dam becoming ineffective. The resulting debris slide killed 268 people and destroyed 63 buildings and eight bridges
	Brumadinho, Brazil	2019	Failure of a mine tailings dam resulted in a mudslide that destroyed farms, roads and houses, and killed 270 people

10 Costs estimated in US dollars at the time of the event.

Pandemics – The devastating effects of the COVID-19 pandemic exposed the vulnerability of major healthcare systems around the world. Although vaccines have mitigated its worst consequences (at least in the developed world), its effects extend far beyond healthcare. The effect of the pandemic on infrastructure was not directly physical, but through changes in people's needs and behaviors. Citizens travelled less and used telecommunications infrastructure much more. Critical infrastructure services (e.g., energy, water and wastewater, solid waste disposal, etc.) were fortunately relatively unaffected, but supply-chain disruptions were severe, especially during the early weeks of the crisis.

Cyberattacks – Finally, a serious threat facing infrastructure today is cyberattacks on critical infrastructure such as power networks, water treatment, electricity production and other interconnected services. In December 2015, the world witnessed the first known power outage caused by a malicious cyberattack. Three utilities companies in Ukraine were hit by BlackEnergy malware, leaving hundreds of thousands of homes without electricity for six hours. In May 2021, a ransomware attack against the Irish Health Service Executive (HSE) disrupted Irish healthcare IT networks and hospitals for more than 10 days, causing consequences to patients and their families. The HSE, which provides health and social care services in Ireland, shut down national and regional networks the same day to contain the incident. Many other sectors are vulnerable to cyberattack and the problem is likely to increase with growing digitalization and the advent of the IoT. Confidence in data and systems security is key if society is to realize the benefit that digitalization brings.

Government agencies have been set up to oversee the impacts of these sudden events. In the wake of the terrorist attack on the World Trade Centre towers and the Pentagon on 11 September 2001 (i.e. 9/11), new policy was established in the United States to protect critical infrastructure, and the Department of Homeland Security was created. In 2005 after Hurricane Katrina, US policy was expanded to include resilient communities. US policy today is a composite of both protecting infrastructure and creating resilient communities. The United States has recently proposed legislation to make software developers responsible for cybersecurity (Voltz et al., 2023).

In the United Kingdom, the Centre for the Protection of National Infrastructure (CPNI), founded in 2007 from the merger of two security organizations, is a government authority that provides protective security advice to businesses and organizations across UK national infrastructure. It aims to reduce the vulnerability of the national infrastructure to terrorism and other threats. UK policy related to the work of CPNI includes the National Security Strategy, National Risk Register and Counter Terrorism Strategy.

5.2.3 Gradual, externally driven change

Currently, the most obvious and arguably the most urgent externally driven changes are related to climate change. Our infrastructure needs to be made more resilient and robust in the face of increasing volatility in weather patterns (e.g., more intense rainfall possibly interspersed with periods of drought; increased numbers and magnitude of storms; more frequent high winds and waves). The impact of flooding and wildfires as a result of changing climate was discussed in Section 3.2.2. Additionally, drought is becoming increasingly significant. The water level in Lake Mead (the reservoir impounded by the Hoover Dam on the Colorado River in Nevada and Arizona, which supplies water to Las Vegas) recently fell to its lowest level ever. In late 2022 a record drought in the southwestern United States forced the federal government to announce a severe water shortage in the region. In the United Kingdom, July 2022 was England's driest July since 1935 with only 35% of the average rainfall for the month and the Government declared parts of southern, central and eastern England to be in drought, with "hosepipe bans" being enacted in parts of the United Kingdom. Infrastructure slopes subjected to increased seasonal cycles of wetting and drying as a result of more volatile and extreme weather conditions will suffer the effects of fatigue more quickly, leading to earlier, potentially catastrophic, failure. Changes that initially were gradual are occurring at increasing rates.

5.3 Strategies for transitioning to a resilient and sustainable infrastructure system

Our infrastructure systems have a crucial role to play in both adapting to and mitigating the impacts of climate change. They must be transitioned to deliver a low-carbon economy that is more resilient and sustainable. This transition needs a long-term strategy that encompasses the targeted enhancement of vulnerable critical infrastructure while taking advantage of routine maintenance and renewals to make improvements more generally. However, other external drivers, such as technology and societal expectations, directly influence this sustainable transition, sometimes in contradictory ways. For example, the advent of air travel and growth in personal car use in the 20th century unwittingly popularized unsustainable forms of transportation. This makes transitioning infrastructure a multi-faceted challenge.

The advent of digital technologies is important for both asset enhancement and resilience, and also as the means of achieving strategic network interconnection and enabling a systems-based approach to infrastructure management. However, there is a separate issue around digital resilience, i.e., ensuring the integrity of data and security of systems for storing, analyzing and exchanging data. In the future, this will extend to preventing autonomous systems and infrastructure-related assets such as robots being compromised.

Apart from the community and institutional dimensions discussed in Section 5.4, most infrastructure systems have many physical elements, and it is practically or financially impossible to change them all at once. Hall et al. (2016) describe these transition challenges for a variety of systems, including energy, transport, water, wastewater, solid waste and digital communications/information. They conclude that traditional "predict and provide" approaches based on incremental capacity enhancement or efficiency improvement are neither feasible nor sustainable. This is partly because supply generates rather than sates demand and over-reliance on an infrastructure service reduces resilience as well as leading to unsustainable resource use.

Furthermore, the interdependencies between sectors are neither acknowledged nor exploited in a traditional sector-by-sector approach. The more radical system restructuring approach is considered likely to be the most robust strategy over the long term because it enables major reductions in demand, but it may also bring a high degree of investment uncertainty. The study by Hall et al. (2016), among others, shows that a future-focused, systems of systems “decide and shape” approach to planning, is essential for a successful transition to a resilient and sustainable infrastructure future. Our infrastructure needs to support fundamental societal goals in terms of resilience, sustainability and social benefit; we need to decide what those goals are and then shape our infrastructure to support delivering them.

How do we transition our infrastructure approaches to such a desired future? We can challenge ourselves to improve resilience beyond known ranges by implementing better scenario planning and testing what will happen outside current ranges. Programs such as the Financial Stability Board’s (FSB) Task Force on Climate-related Financial Disclosures (TCFD) are helpful to achieve this goal. We need to adopt a whole-system approach, moving beyond the traditional four priorities of scope, cost, risk and time to include a further four priorities: biodiversity, social value, climate resilience and carbon & the environment. These eight priorities need to be considered at all stages of infrastructure development, from developing the strategic brief through to delivery and end of life.

> **Resilience Recommendation (RR) 1: Adopting frameworks such as the Task Force on Climate-related Financial Disclosures (TCFD) can drive thinking about possible future scenarios across a number of different variables and improve and increase reporting of climate-related financial information.**

Forecasts cannot provide specific and accurate predictions about climate impacts on infrastructure assets and systems. We must plan in a way that is informed by considered thinking about a range of possible futures, rather than assuming we know what the most likely one will be, and then build in measures that allow the plan to be adapted as further information emerges and the sophistication of modelling techniques improves (see Case Study R1 below). The pragmatic use of digital twins of infrastructure systems will help inform scenario planning, but there are limitations. There are points where the unpredictability of human behaviour becomes too challenging to model quantitatively, since some variables may be too complex and uncertain to allow meaningful results.

RR2: Use scenario planning and modelling and a whole-system approach to explore a range of possible futures and design resilient solutions that can be adapted as the underlying data and boundary conditions become clearer.

CASE STUDY R1 - AN ADAPTIVE STRATEGY: THAMES ESTUARY 2100 PLAN[11]

In 2012, England's Environment Agency and its partners published the first Thames Estuary 2100 Plan. This sets out a strategy for managing tidal flood risk in the Thames Estuary to the end of this century and beyond. The Plan is a frontrunner of the adaptation pathways approach. It sets out a series of possible pathways for managing tidal flood risk in the Thames Estuary. This includes a decision-making framework for switching between pathways, using the latest climate projections as a basis for those decisions. It is the first strategy in the United Kingdom to set out recommendations for managing tidal flood risk for a range of possible climate futures.

The Thames Estuary 2100 Plan is reviewed and updated as new data, scientific evidence and climate change projections become available. This ensures the Plan continues to set out the most effective way to manage tidal flood risk. The review process assesses what has changed in the estuary. This information could suggest either switching pathways, revising the recommendations for managing flood risk, or changing the deadlines for delivering those recommendations. For example, if the projected rate of sea level rise increases, the deadlines for raising defences would be brought forward. However, if it decreases, later deadlines would be possible. If projections increase significantly, alternative options or pathways for managing the increasing risk of flooding would be considered. By following this approach, the most cost-effective solutions will be implemented at the right time.

Now, ten years into the Plan, the latest review found that sea level in the Thames Estuary has risen over the last century, and the rise has been accelerating over recent decades. The 10-Year Review found that the strategy continued to set out a robust approach to future flood risk. It also found that some tidal defences needed to be raised earlier than originally thought, some within the next 20 years.

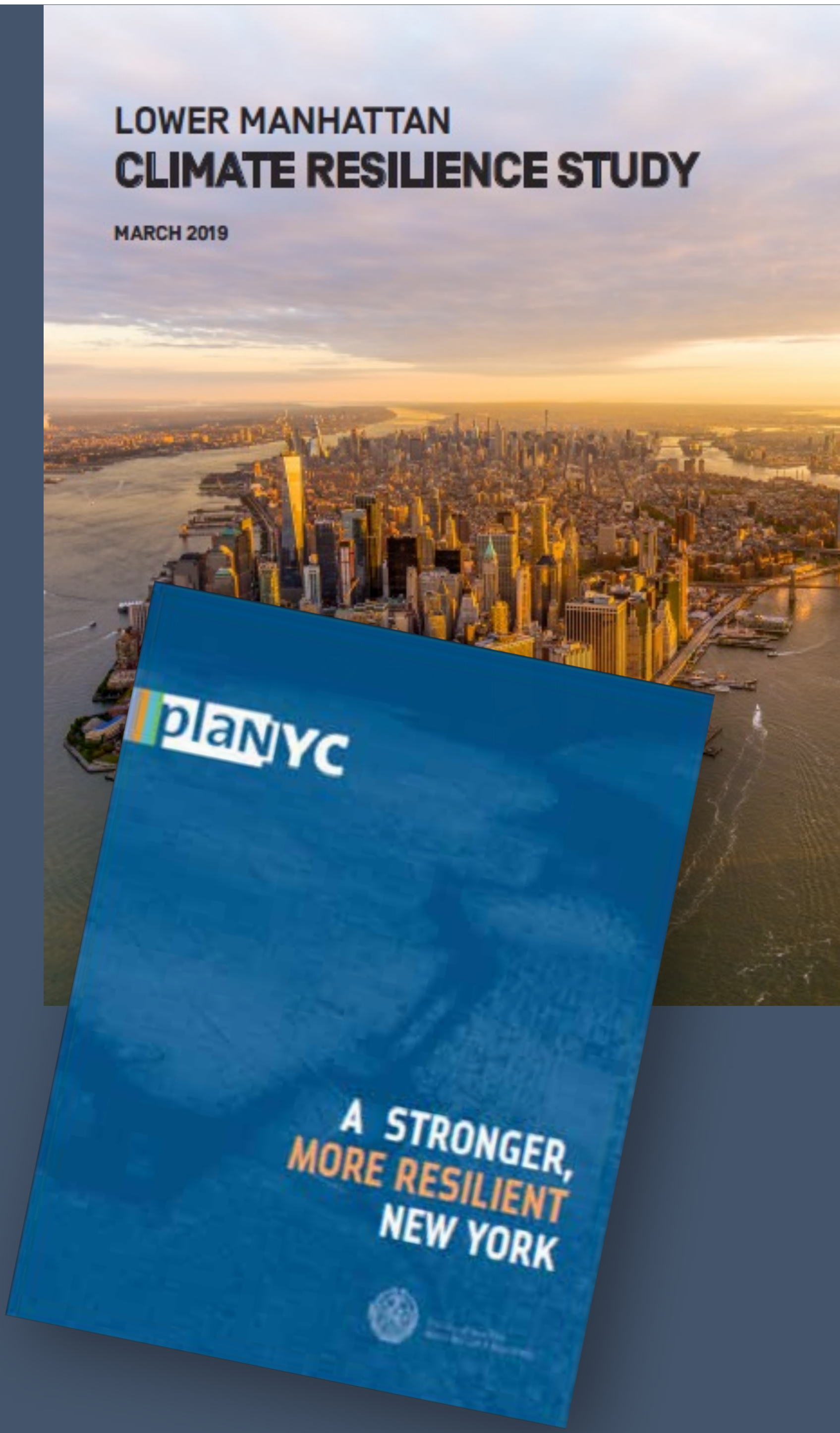
[11] https://www.gov.uk/government/publications/thames-estuary-2100-te2100/thames-estuary-2100-key-findings-from-the-monitoring-review#executive-summary

Digitalization of infrastructure will enable the gathering of data about both disruptive events and the operation of assets during natural and operational cycles. This will provide opportunities to inform and shape our future infrastructure. Lessons learned from these events offer an opportunity to build better by implementing performance-based-design principles using real data.

> **RR3: Use lessons learned alongside better data and information from emerging technologies to update design standards and develop policies to ensure adherence to the updated standards.**

CASE STUDY R2 - NEW YORK CITY RESILIENCE

In October 2012, New York City was hit by Hurricane Sandy, which generated a 12-ft surge on top of a 2-ft high tide, inundating large parts of the Metropolitan Area. Direct damages were $68 billion. The city recorded the hurricane's effects and developed measures for flood defense, much of which is described in two reports: *A Stronger, More Resilient New York* (City of New York, 2013) and *Lower Manhattan Climate Resilience Study* (City of New York, 2019). The first report documents the hurricane's impacts as well as interdependencies among geographically distributed infrastructure, including the transportation, steam, electrical and wastewater systems. A general procedure for developing a resilient city is described, including potential inundation zones combined with critical infrastructure and the engagement of various neighborhood communities to identify and rank projects. Before the hurricane, the New York City Panel on Climate Change (NPCC) presented to the city government general climate projections. After the hurricane, NPCC review and input are required for each major project. A plan for creating a resilient shoreline in Lower Manhattan is presented in the second report. The plan calls for deployable flood protection, using HESCO bastions (sand-filled geotextile units) and tiger dams (water inflatable hose-like barriers), and the creation of elevated esplanades to serve as local barriers to flooding. Improvements have been realized for the location and protection of diesel generators, full tanks and fuel lines. Flood doors, mechanical closure devices, hatch doors and watertight manhole covers were developed to prevent storm water penetration of the subway system.



5.3.1 Nature based solutions

Nature-based solutions for resilience enable both adaptation and, over time, mitigation of the impacts of climate change. This forms a key aspect of the transition to a resilient and sustainable infrastructure system. Sustainable urban drainage systems (SUDs) are being used for vulnerable, eroding coastal areas; this entails allowing rivers to temporarily flood adjacent areas without causing lasting damage and, in some areas, pursuing a policy of managed retreat. Green infrastructure – e.g., mangrove vegetation, wetlands and swamps – is increasingly being deployed to reduce the effects of natural hazards.

In Louisiana, for example, the creation and maintenance of wetlands is important for greater coastal resilience against hurricanes. Jamaica Bay in Long Island is likewise a key regional asset for reducing storm surge and flooding associated with hurricanes affecting the New York City area. In the United Kingdom, the Natural Flood Management Programme (Environment Agency, 2021) is utilizing measures such as restoring salt marshes, mud flats and peat bogs, creating "leaky barriers" to slow water flows from streams and ditches, and covering the ground with plants and trees to reduce surface water runoff. Development of parkland and green roofs can reduce the urban heat island effect, decreasing the intensity of heat waves in cities and towns, while also providing habitats for birds and insects as well as amenities for residents. These co-benefits such as increased biodiversity alongside creating a public amenity provide a triple dividend, delivering benefits even when disaster doesn't strike. From a funding perspective, building in these co-benefits that are delivered irrespective of disasters helps to mitigate the perception that funding to increase resilience for rare events is not good value.

One example of this is the Value Toolkit,[12] developed in the United Kingdom by the Construction Innovation Hub (CIH). There is a shift by the UK government to focusing on value, through the Social Value Framework, and as set out in the UK Government's Construction Playbook. The government is also framing legislation such as the Climate Change (for carbon) and Environment Acts (for biodiversity). The Value Toolkit enables clients and policy makers to work with their supply chains to make informed, value-based decisions, driving better social, economic and environmental outcomes. It embeds value definition and measurement into contracts, providing value definition and measurement tools to enable the definition and quantification of value across the four capitals: natural capital, social capital, human capital and produced capital.

> **RR4: Utilize nature-based solutions to deliver improved resilience with increased biodiversity and public amenities, building in valuation of these co-benefits as part of the business case.**

5.4 Community and institutional factors

5.4.1 Resilience is a socio-technical problem and requires engagement with users

As pointed out by O'Rourke (2019), resilience is both a societal and a technical problem. Infrastructure policy and progress must address the combined social and technical dimensions of infrastructure, including interdependencies among the physical, social and economic systems on which communities depend. A key part of the socio-technical approach involves effective public engagement. Consumer behaviour can improve resilience, but we need better communication and engagement as well as building of trust to change behaviour, developing a whole-of-society approach that values listening to the public as the users of infrastructure services, or as customers who have information about how well assets are operating.

Effective public engagement can also enable a better understanding of risk among infrastructure users. The public perception of risk can be different to the engineering interpretation. Even if there might be agreement on the level of risk, it does not mean that there is agreement over the

[12] https://constructioninnovationhub.org.uk/our-projects-and-impact/value-toolkit/

appropriate action to take. The Institution of Professional Engineers New Zealand (IPENZ – Now Engineering New Zealand) book *Engineering Risk* published in 1983 describes three versions of risk: engineering risk, public perception of risk and actual risk. Effective public engagement programs can enable infrastructure users to understand risks and make a more informed response to events. However, we must also be mindful that the customer will have other concerns, such as the cost of energy and food, particularly as we face challenging economic circumstances. Better public participation and engagement also means that consumers are more likely to adopt changes when required e.g., disaster-response protocols. This is an area where industry/research collaboration could expand.

> **RR5: Develop effective community engagement strategies that help communities to understand risk and resilience, alongside equity, financing and other issues. This would enable collaborative evolution of appropriate responses to potential events, through research and consultation.**

New technologies are enabling more inclusive communication between asset owners and users. For example, vTaiwan,[13] an online-offline consultation process, enabled all stakeholders to contribute to policymaking via social media and helped lawmakers implement decisions with a greater degree of legitimacy. New technologies can also be used to engage citizens in capturing data during or after events to inform the government response. The Kyiv Digital[14] smartphone app used for purposes such as paying utility bills and parking tickets was repurposed during the Ukraine conflict by the government to capture information regarding bomb damage as well as to provide citizens with vital information on the location of shelters, humanitarian assistance and healthcare. The concept of gamification can be another effective way to engage the customer/public. Metaverse, for example, has the potential to provide a vivid scene to experience an event and help to anticipate, understand and prepare for future possible disasters. Gamification and social media can provide insights into how a customer might respond to hazards to inform planning for resilience and understanding the range of possible responses.

> **RR6: Engage with stakeholders using simulation and social media to help citizens and asset managers visualize a potential event and develop response strategies, provide feedback to authorities and receive services from authorities prior to, during and after events.**

5.4.2. Promoting ownership of solutions by local communities

Physical infrastructure and technology are rarely the whole problem or solution. Resilience issues often stem from constraints on governance and institutional capacity, especially the management of available infrastructure services in the face of existential challenges. Addressing these challenges requires engagement with the communities ultimately responsible for implementing infrastructure resilience policies. When local communities feel that they have genuine ownership or influence over decisions impacting their lives, they are more likely to support the intended direction of those decisions. Methods such as the *WeValue* approach, developed by the Values and Sustainability Research Group at the University of Brighton, help elicit and crystallize the *in-situ* shared values of groups, which provides a portrait considered to be authentic by participants, but concise enough to communicate to outsiders what is important locally (Sethamo et al., 2020; Odii et al., 2020). This can then be incorporated into a hierarchy of actions for establishing consensus and guiding future actions. For example, a sustainable travel hierarchy is a tool to facilitate thinking about improving the impact of journeys. The higher up the hierarchy, the more sustainable and greener the travel option.

> **RR7: Government at all levels should be required to demonstrate how decisions made in relation to infrastructure support local communities, are consistent with the UN Sustainable Development Goals, and improve the performance and resilience of infrastructure assets and systems.**

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[13] https://info.vtaiwan.tw

[14] https://time.com/6163708/kyiv-digital-technology-app

5.4.3 Risk-informed decision making for assessing community resilience

A risk-informed decision-making approach is often essential for assessing community resilience and enhancement (Ellingwood et al., 2019). The US National Institute for Standards and Technology (NIST) issued a community planning guide for buildings and infrastructure systems to help communities identify factors that make them resilient, assess likely hazards and develop risk-informed strategies to optimize recovery planning from natural hazard events (NIST, 2016). This last point is particularly important because recovery is commonly overlooked in discussions of resilience in the traditional engineering sense, which has focused on improving physical robustness as the main trait of resilience. Much attention is focused on withstanding acute events, such as hardening and redundancy (mitigation), while accelerating recovery efforts is another critical means to reduce overall losses in communities impacted by extreme events.

5.4.4 Resilience in the culture of operating institutions and among professionals

Operating institutions must have an appropriate culture – including improved codes and standards, land-use policies, incentives such as tax credits and insurance discounts, and educational programs – to enable an effective response to the many threats facing infrastructure. Since agencies with geographically distributed infrastructure (e.g., water, energy distribution, and waste or wastewater collection networks) are frequently the first movers following a disaster, it is important for these organizations to create a culture that thinks about resilience constantly, not just in a crisis. Local Resilience Forums or equivalent Civil Defense networks can provide a basis for this.

> **RR8: The capacity for managing resilience in operating organisations needs to be strengthened to become a core capability. This will entail more collaborative approaches within and between sectors that help to mitigate risk at a system-of-systems level.**

An example of this is the CREDO[15] project carried out by the UK's Digital Twin Hub, which brought together energy, water and telecoms network providers for a climate change adaptation digital twin project to provide a practical example of how connected data can improve climate adaptation and resilience across a system of systems.

> **RR9: There is a need to equip resilience professionals with the right tools and skills that allow them to be adaptive in the face of unexpected challenges. A broader-based body of knowledge for future infrastructure resilience professionals should be defined.**

If we recognise that uncertainty will always be present, we can focus on preparing communities and institutions not for disaster avoidance, but for proactive change management.

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[15] http://digitaltwinhub.co.uk/credo

5.5 A whole-life value and system-led approach to identifying vulnerabilities

The way we operate infrastructure has a role in both enabling resilience and rapidly recovering functionality following a disruptive event. The disastrous results of inadequate or inappropriate operations and maintenance have already been highlighted (Section 3.2.1), but we find time and time again, especially with interdependent systems, that the cumulative impact of shocks is what pushes infrastructure over the edge. The resulting failure propagation is where we realize there are additional vulnerabilities.

Identifying these vulnerabilities and understanding value in the system is critical but the value of infrastructure systems is often latent and hard to quantify. Short-termism in funding cycles and the conception of infrastructure as a series of projects rather than a system of systems, coupled with the tension between comprehensive risk avoidance and efficiency, also makes measuring this value even less of a priority. Through an industry-led initiative, Project 13, the United Kingdom infrastructure sector has recently focused on moving away from a transactional relationship to an enterprise relationship across supply chains in order to build resilience (See Case Study R3 below)[16]. Rather than seeing an individual project as a transaction where you try and get the best value out of that transaction, the focus shifts to assessing the optimal action to take to maximise value over the long-term. This will help measure current risks, identify emergent ones and quantify the opportunity costs of alternative solutions (including doing nothing). Such metrics are also important for attracting investment and will enable more economic analysis of the downstream impact of asset failure.

> **RR10: There is a need to reassess on a regular basis the value of critical infrastructure because the concept of value and highest/best use of infrastructure will evolve over time. Good quality system-level metrics (and data) are needed both to understand the true impact of these systems and for benchmarking existing performance.**

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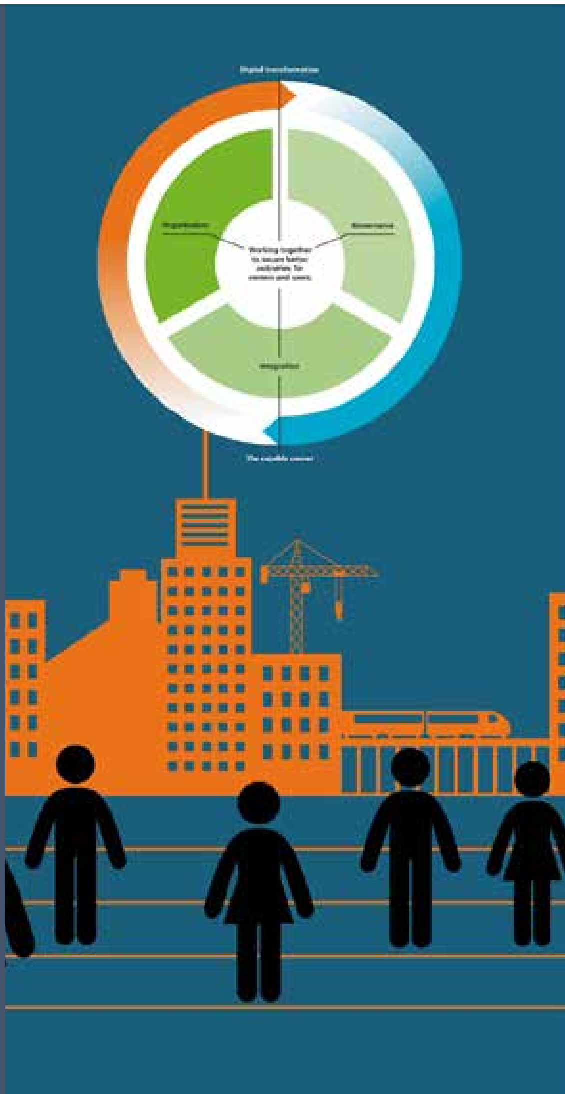
[16] https://www.project13.info/

CASE STUDY R3 - MOVING TOWARD ENTERPRISE RELATIONSHIPS: PROJECT 13

Project 13 is an industry-led movement to improve the way high-performance infrastructure is delivered. Core to Project 13 is the role of infrastructure investment in delivering better outcomes for people and place. Once the Capable Owner has articulated the desired outcome, it first considers whether this can be achieved by optimizing or modifying what already exists before deciding to construct something new. The more mature the Capable Owner, the more they are able to articulate the outcome at all levels: from global and national strategic priorities, through local requirements, to investment decisions for individual interventions. To understand local requirements, some form of community engagement is required.

Project 13 advocates integrated collaborative Enterprise models, bringing together the right capabilities and technologies in longer-term relationships. All parties are incentivized to achieve the outcomes and therefore work together to find a solution and to resolve problems along the way. By managing projects as interventions on our existing built systems rather than stand-alone siloed projects, Project 13 enables the improvement of the overall performance of infrastructure across the whole life of the asset. There are several formal and informal Project 13 adopters putting the Project 13 Principles into practice both in the United Kingdom and globally.

Image credit: Project 13.



Making our infrastructure more resilient requires a renewed perception of the risks associated with our existing infrastructure systems, using whole-life thinking to optimize the long-term operations and maintenance of these systems and manage their interdependencies. We need frameworks to anticipate events and develop a systems-based approach to managing resilience, using models that consider the interdependency between different infrastructure components and systems. This requires a robust communication system among all parties involved in promoting infrastructure resilience and a process for engaging stakeholders in this endeavour.

5.6 Distributed vs centralized and connected vs fragmented infrastructure systems - implications for resilience

Distributed and multi-connected infrastructure is intrinsically more resilient than highly centralized or fragmented infrastructure. Increased resilience of distributed infrastructure is true at numerous levels including physical infrastructure, digital infrastructure (including not being tied to proprietary solutions but using open or interoperable solutions), and organizational as well as intra-organizational infrastructure. After Hurricane Sandy, the report *A Stronger, More Resilient New York* (City of New York, 2013) included recommendations for micro-grids, which are neighborhood scale networks for the distributed generation of electric power. The adoption of de-centralized power through distributed generation improves resilience by increasing electricity sources that, as a whole, are more resistant to the effects of flooding than a centralized power system. The integration of decentralized energy into traditional systems poses challenges, but the energy sector seems to be moving forward with it (Plumer, 2023).

The National Digital Twin programme in the United Kingdom is an example of distributed and multi-connected data infrastructure. The implications for resilience of distributed versus centralized infrastructure systems, and connected versus fragmented infrastructure systems, should be better understood, tested and evidenced. If true, it should become a guiding principle to provide a better model irrespective of what causes the disruptive shock.

By developing new protocols/standards for resilience assessment, we can strengthen organizational capacity in the process, highlight the benefits of distributed yet connected networks, and begin to pursue both hard engineering and natural solutions to resilience challenges. This is not a suggestion that existing centralized systems should be abandoned, but that they are strategically developed to create a more flexible system (Saxe and MacAskill, 2021).

5.7 Role of funding and financing, procurement and insurance in addressing resilience challenges

Over the past decade, resilience has emerged as a key orienting concept for evaluating critical infrastructure planning and investment decisions. Exposure to (and the costs of) disasters are increasing dramatically around the world. We have various data such as insurance loss trends from Swiss Re and tracking of billion-dollar disaster events in the United States by the National Oceanic and Atmospheric Administration (NOAA). It is not feasible to invest in physical robustness against all possible shocks and stresses on critical infrastructure systems because we simply do not have the resources to do so.

There are four crucial elements that need to be considered. Capital expenditure (capex) and operational expenditure (opex) budgets need to account for the need to build all components of resilience as infrastructure is built or modernized. How resilience can be incorporated into a value assessment needs to be identified. Procurement needs to focus on whole-life value and whole-life carbon performance, and not to entrench the artificial capx/opex split. And, finally, the insurance sector needs to become a driver of better infrastructure design, management and maintenance linked to resilience, and to push for assets to meet current best practice performance, with lower premiums for those that do and higher for those that don't.

6.0

ACHIEVING NET ZERO/ NET NEGATIVE CARBON EMISSIONS FROM INFRASTRUCTURE

6.0 ACHIEVING NET ZERO/NET NEGATIVE CARBON EMISSIONS FROM INFRASTRUCTURE

6.1 Context - Global emissions and net zero

The climate crisis is compelling governments, businesses, and third-sector organizations to find ways to significantly cut their carbon emissions (CO2 eq). These policies and initiatives form the basis of global pathways to net-zero carbon[17], but time is running out to address carbon emissions. The IPCC report published in 2021 calculates that if we are to have a 67% chance of limiting warming to 1.5°C, the estimated remaining carbon budget that can be emitted into the atmosphere from the beginning of 2020 is 400 GtCO2e. If we aim for an 83% chance, this budget reduces to 300 GtCO2. Using estimated global annual emissions of CO2 as 42.2 Gt per year and assuming constant emissions, the allowable budget will be expended by mid-2029 (at 67% chance) or early-2028 (at 83% chance). If we are going to prevent dangerous warming, we need to drastically reduce emissions. The most significant reductions are required in the next decade.

There are two ways to approach how we reduce carbon emissions: the first is to consider how this total global carbon budget of 400 GtCO2e is allocated across the whole of society, accounting for emissions of every country, sector and subsector. Although different models have been suggested, there is currently no mechanism for allocating this overall budget to various countries. Each country develops its own targets and actions. For example, in the United Kingdom, the Climate Change Act of 2008 was amended in 2019 to legally require the United Kingdom to achieve net zero by 2050. This is managed through carbon budgets, which quantify the allowable emissions for each five-year period, setting the trajectory to net-zero based on historic emissions. The 6th Carbon Budget (Climate Change Committee, 2020) sets out the emissions for 2033 to 2037, with an interim target to reduce emissions by 78% by 2035 compared to 1990 levels. Although this is an ambitious target, there is no check to ensure that this national carbon budget is consistent with the global budget.

Working from a top-down allocation using a simple equal distribution per capita, the UK population is approximately 0.88% of global population, meaning that the pro-rata share of the remaining global budget should be 3.52 GtCO2 from the beginning of 2020. Similarly, the US population is 4.30% of the global total, so the carbon allowance would be 17.2 GtCO2. Summing up the emissions from 2020 to 2050 in the “Balanced Net Zero Pathway” of the UK’s Climate Change Committee’s 6th Carbon budget equates to just under 7 GtCO2e, almost double the simple budget allocation. Additionally, the Committee has recently expressed concerns that progress is lagging the policy ambition (Climate Change Committee, 2022). In this context, current plans to cut emissions are clearly inadequate to address the climate crisis.

6.2 Infrastructure carbon emissions and achieving net zero

The built environment is a significant contributor to national and global emissions, both from the provision of infrastructure and services required for the development of society (both new-build and retrofit), as well as from the ongoing energy needed to heat and power buildings and infrastructure. Emissions in the context of infrastructure should be understood from a whole-life, systems-thinking approach: how design influences operational carbon and user carbon as well as capital carbon, and how investment in infrastructure impacts emissions in other sectors (e.g., de-carbonized energy for operation of buildings). Understanding the impact of infrastructure should also be from a systems perspective – the relationship between different networks and systems as well as the assets and activities they support. This should encompass the direct emissions associated with construction and operation as well as how infrastructure facilitates low-carbon behaviors (or not) and therefore plays a role in moving our societies toward net-zero carbon. Global and national carbon budgets provide a ceiling for allowable emissions. Asset and project-level targets demonstrate the progress being made and provide a mechanism for supporting decisions on how best to invest in de-carbonization.

[17] In this paper net zero refers to reducing anthropogenic emissions of a programme of works to zero or to a residual level that is consistent with reaching net-zero emissions at a systems-level in eligible 1.5˚C pathways and neutralizing the impact of residual emissions (if any) by permanently removing an equivalent volume of carbon.

6.2.1 Capital and embodied carbon

The whole-life emissions of infrastructure assets consist of capital/embodied carbon, operational carbon, and user carbon. Capital carbon refers to the Green House Gas (GHG) emissions associated with the creation, refurbishment and end-of-life treatment of a network or asset but excluding maintenance, whereas embodied carbon refers to the GHG emissions associated with the creation, maintenance, refurbishment and end-of-life treatment of an asset (sometimes referred to as "embedded carbon"). Reductions in capital and embodied carbon can be achieved in various ways, including design efficiency (i.e., improving and refining existing design practices, reducing overspecification), material selection (including use of low-carbon alternatives or reuse of existing materials), and construction processes and site efficiencies (i.e., reduced waste – both in materials and in temporary works, electrification of plant, etc.) (UK Green Building Council, 2021). Reductions in embodied carbon can also be achieved through improved maintenance regimes, based on condition monitoring and leading to a risk-based "predict and prevent" approach to asset management.

6.2.1.1 Reducing What We Build

The lowest-carbon infrastructure project is the one we do not build. If we can get more from our existing infrastructure and extend its life, or reduce demand so that new assets are not required, then we can avoid the need for capital investments, and the resources and carbon they consume.

> **Net Zero Recommendation (NZR) 1: Review every capital project proposal to ascertain whether reducing demand for infrastructure services or refurbishing existing infrastructure are viable and to assess options to reduce carbon.**

If we do choose to build, we must tackle carbon as early as possible in the project process (see Figure 6.1) to build less, build clever or build efficiently (HMG Infrastructure Carbon Review, 2013). Woetzel et al (2016) estimated that from 2016 through 2030, the world needs to invest about 3.8 percent of GDP, or an average of $3.3 trillion a year, in economic infrastructure (i.e., infrastructure that directly influences the economy) just to support expected rates of growth. Crucially, they noted that improved management of existing assets could translate into 15% savings. However, this may require clients, consultants and contractors to rethink some of their business and procurement models, which are typically based on the creation of new assets and the amount of time and effort required for design and delivery (Construction Innovation Hub Value Toolkit, 2022).

> **NZR2: Procurement should focus on low- or zero-carbon solutions as well as refurbishing waste materials. Include residual value/residual carbon to encourage use of novel materials.**

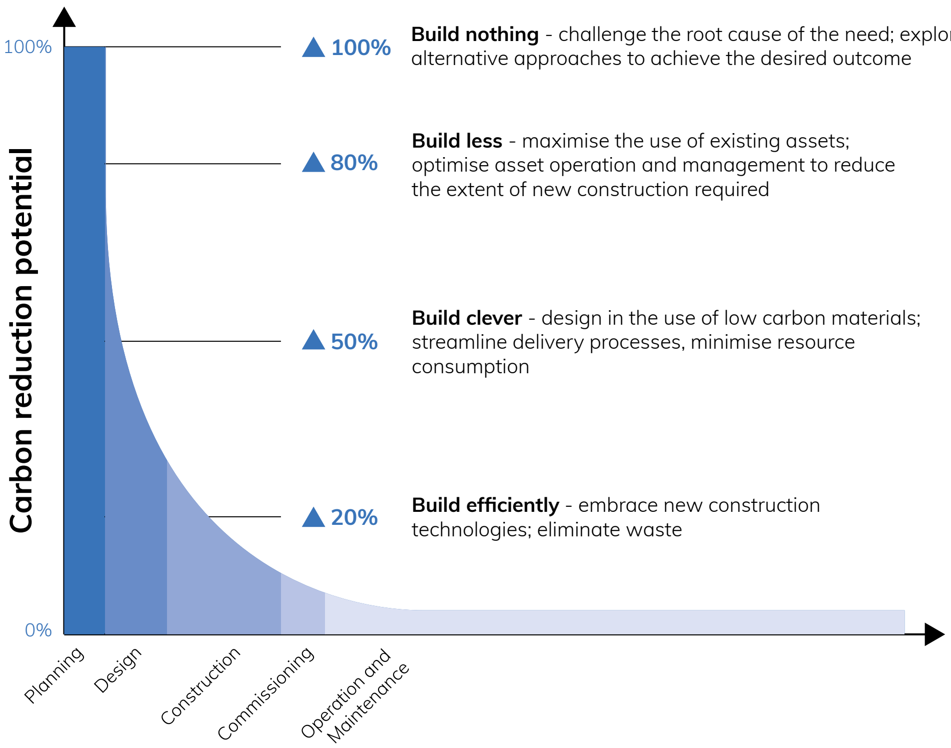


Figure 6.1: Carbon Reduction Curve (HM Treasury, 2013)

6.2.1.2 Designing efficiently

Given that most materials used in construction, particularly concrete and steel, are carbon intensive, using material more efficiently is an important way to reduce embodied carbon. However, most designers rely on the use of generally conservative structural design codes (e.g., Eurocode: Basis of structural Design; BS EN 1990:2002), leading to structures that are inefficient for the amount of material they use. For example, Moynihan and Allwood (2014) found in a survey of 10,000 steel beams in existing buildings that the average utilization was only 40%. Orr et al. (2019) also found that a wide variety of cultural and regulated behaviors contribute to habitual overdesign, including not questioning the suitability of previous methods, and perceived risk of construction errors. Reducing these inefficiencies could yield immediate carbon savings as high as 50%. This would also help to accelerate the transition to lower-carbon materials.

> NZR3: Review and revise design codes to reduce conservatism in design and resultant overuse of material.

6.2.1.3 Using Lower-Carbon Materials

The fundamental materials challenge in the construction industry is the use of concrete and steel, both of which have significant carbon-emission factors. Cement, a key component of concrete, is responsible for 8% of GHG emissions globally (ICE, 2022), while steel production is responsible for a further 8%, with half of all steel used in construction and infrastructure (Drewniok, 2021). Material efficiency in design and construction, alternative manufacturing processes, the use of alternative cements in concrete and the development of circular economies (see Section 6.4) are examples of strategies being explored to address the challenges of these carbon-intensive materials. However, it should be noted that the chemical reactions that happen during the manufacturing processes for steel and cement also release carbon dioxide (CO2): primary steel production releases CO2 from the process of reducing iron ore with carbon, whilst CO2 is released in the process of converting limestone to clinker for cement. Therefore, even if the manufacturing industries switched entirely to renewable sources of energy, CO2 would still be emitted. Achieving net zero while still using these materials means that these emissions need to be balanced by some type of removal or offset.

NZR4: Academic and industry research into low- and zero-carbon materials, such as improved cements, should be scaled up and accelerated to deliver replacement products as rapidly as possible. Reuse of products such as steel beams should be encouraged. It is important to understand how these materials may age and to manage residual risk in adopting these new materials and to scale up supply chains.

Strategies for addressing the challenges of these carbon-intensive materials relate to material efficiency in design and construction, circular economy (especially relevant for steel), alternative manufacturing processes, and use of alternative cements in concrete. Academia and industry are also investigating the appropriate use of low-carbon materials such as timber (Allwood et. al., 2019).

6.2.1.4 Reducing carbon and waste in the construction process

The construction industry has long been criticized for perceived low productivity. The United Kingdom's National BIM survey in 2018 reported that up to 30% of building materials are wasted (NBS, 2018), while a 2019 WRAP report indicated that of the 400MT of materials used in construction each year, 100MT is wasted. This represents a direct carbon-and-resource impact which could be substantially reduced or eliminated. Defects and rework are also a major cause of waste in construction, with the total cost of rework estimated to be 5-10% of the construction cost. Other causes include over-ordering of concrete, measurement errors and use of concrete in temporary works (see Case Study NZ1 below).

Alongside this measured waste, there is a range of hidden excess carbon. For example, a recent study of concrete strength for a major UK construction project found that the average 28-day strength test for concrete across all cubes tested was 30% over specification. Given that strength is directly proportional to cement content, this represents 30% additional carbon emissions. That suggests carbon-emission values based on designs and specifications are likely to be substantial underestimates of the true values. Better measurement and management of materials use in construction is therefore vital for net-zero carbon targets and is likely to result in significant cost savings. Technology has a role to play in waste reduction. Readily available solutions can make an immediate impact. Examples include digital logging of materials arriving on site and their storage locations, which can help avoid materials being lost, spoiled or damaged while enabling accurate inventory management and capture of material use.

The Get It Right Initiative (GIRI) in the United Kingdom is a group of construction industry experts, organizations and businesses actively improving productivity, quality, sustainability and safety in the construction sector by eliminating error in design and construction from inception, through operation, to completion.

NZR5: Processes should be developed for capturing and analyzing greenhouse gases, including carbon-based data and the integration of this information with existing digital technologies and processes (e.g., BIM models, digital twins).

CASE STUDY NZ1 - IDENTIFYING CARBON BLIND SPOTS - WHAT IS WASTE?

Current research at CSIC applies the concept of waste from lean manufacturing to redefine waste across the construction industry using zero-loss yield analysis (ZLYA) to identify inefficiencies in the material value chain. By comparing actual performance to a first principle best performance, ZLYA reveals processes that would otherwise be overlooked, such as over-specification or over-ordering of concrete, thus identifying carbon blind spots. This is achieved by collecting data with digital tools to analyze the differences between characteristics and material volumes required at the design stage to that used in an asset or structure. The discrepancy between the values highlights how much of the concrete used is providing value in the system (i.e., meeting the design requirements) and identifies data gaps. This research has highlighted several issues including over-ordering, rework, rejected concrete, over-specification, concrete batching accuracy and waste. Results show inconsistencies between design volumes and concrete consumed, with a yield of 61-97% for individual components and delivered strengths more than double the design strengths. These inefficiencies result in waste, increased carbon emissions and higher costs. These valuable data insights can immediately inform better carbon choices, improve construction practice and reduce the associated cost of using more materials than necessary.

6.2.2 Operational carbon

Operational carbon emissions for infrastructure arise from energy used by the asset and associated systems during normal operation (including maintenance) and from water used and its treatment. Reductions in operational carbon can be achieved by reducing demand for energy together with decarbonization of the electricity grid. Because most infrastructure systems that will be in existence in 2050 have already been built, two main opportunities for reducing operational emissions are created:

- Reducing carbon emissions resulting from the operation of these assets through maintenance and retrofit; and
- Addressing locked-in operational constraints and inefficiencies.

All infrastructure asset operations and maintenance plans should address the requirement to achieve net zero carbon and ensure that assets are suitably retrofitted to meet this objective. Where refurbishment works are undertaken, these should make use of the opportunity to improve the performance of the whole system and not only the specific aspect being addressed. The constraints of existing urban form may make improving overall system performance difficult. Hence financial incentives may be needed to deliver improvements at scale. Existing infrastructure may also need to be managed differently to circumvent operational constraints and address built-in inefficiencies.

> **NZR6: Require maintenance, refurbishment and renewal projects to demonstrate substantial reductions in both operational energy and carbon-based use throughout the system.**
>
> **NZR7: Develop financial incentives such as grant schemes to support carbon-efficiency retrofit programs.**

6.2.2.1 Maintaining infrastructure to support net-zero carbon

Effective maintenance of existing infrastructure contributes meaningfully toward a net-zero carbon built environment. The European Green Deal requires the worst performing 15% of the building stock of each member state to be upgraded by 2027 for nonresidential buildings and by 2030 for residential. This provides a clear, firm target, but the capacity required to deliver on these targets is huge. The current rate of refurbishment to existing buildings is low and buildings are ahead of infrastructure. Technology has a key role here, especially when it comes to understanding asset condition through, for example, asset-health monitoring, to extend the residual capacity and design life of existing infrastructure in a less carbon-intensive way.

Many infrastructure assets are built to last for 100 years but poor maintenance can lead to defects and problems that prevent longevity of service. In the United States, the current system makes federal government funds available for new construction. There is no scrutiny, however, of the operations and maintenance (O&M) work to support long-term performance. Linking O&M programs to federal dollars could avoid the cycle of new construction by introducing eligibility criteria to secure funding for new capital expense based on management of existing assets. In addition, asset owners can find themselves locked into O&M contracts for 30 years. This is true in public-private partnerships. If the economic climate changes and asset managers need to allocate maintenance dollars elsewhere or change the way an asset is maintained, a program locked to PPP contracts is not helpful unless flexibility is facilitated by the contract. One way to achieve this is to include future proofing in the contract, as described above.

> **NZR8: Deploy asset-heath monitoring and assessment widely across the asset base to facilitate condition-based and risk-based approaches to asset maintenance and capacity assessment to enable life extension of assets and targeted deployment of maintenance resources. Develop O&M contracts that avoid lock-in to specific technologies, by using outcome-based specifications to encourage innovation during the contract.**

In the United Kingdom, the political culture encourages new construction over maintenance and refurbishment. Considerations and approaches to promote O&M include the following:

- If the required O&M standard can be identified, local authorities who meet the standard to maintain and document condition could receive payment.
- Monitoring helps to reduce maintenance costs and avoid the potentially big capex costs from recovering from disaster or major defects that occur due to underinvestment in maintenance or the lack of early detection of intervention needs. Monitoring provides valuable data to inform better decisions for repairs, upgrade or refurbishment. Data are valuable assets that are useful to a range of stakeholders.
- Limited appreciation of risk and the consequences of failure may be considered as an explanation for why assets are not being monitored and maintained optimally. Keeping infrastructure and the built environment in optimal condition enables more efficient operation and brings associated reduction in carbon. Use of whole-life, risk-based portfolio management, with risks allocated to parties best placed to manage them, can help to address this and make the case for wider deployment of monitoring technologies, while helping to focus investment on assets most critical to operation (Hadjidemetriou and Parlikad, 2022). The whole-life, risk-sharing features of long-term PPP contracts provide important lessons for traditional procurement models and future innovative approaches. Allocating risks to the parties that are best placed to manage them can incentivize operators to achieve more efficient and operation in financial and carbon terms. This requires careful monitoring, enforcement and management of contracts, and effective wider infrastructure governance. Incentives need to be identified and embedded in contracts to drive better asset management decisions.

6.2.3 User carbon

Unlike embodied carbon or operational carbon, user carbon is largely beyond the direct control of asset owners and operators. However, in some infrastructure systems, notably highways and airports, user carbon is by far the dominant source of whole-life emissions and the ability to reduce or eliminate user carbon emissions can be substantially influenced by the design of the assets and systems. In other contexts, operational and user carbon are very closely linked. For example, in buildings the use of heating and cooling systems can be regarded as both operational (delivered by facilities management) and user (as the user may choose to increase or decrease the heat in a specific room or building for reasons of comfort). In this context, user carbon also relates to user habits and preferences.

Reducing or eliminating these emissions depends largely on the design of these systems as well as the choices and capacity of individuals to adopt lower-energy solutions. Electric vehicles, for example, require up-front investment, which may be out of the reach of many households, as well as adequate charging infrastructure and additional grid capacity. The use of energy-efficient fixtures, windows, and heating/cooling systems can reduce energy demand in buildings, especially when users are encouraged to adopt more energy-efficient habits and preferences.[18] However, changing user preferences is difficult and retrofitting can be complex, particularly for older properties. This makes the scalability of user carbon reductions more complicated.

NZR9: Develop a one-stop-shop service to support householders and small businesses to retrofit their buildings for energy efficiency.

6.3 Opportunities and challenges for carbon reduction and removal

6.3.1 The measurement and management of whole-life carbon

One of the most significant challenges for whole-life carbon management in infrastructure is consistent and reliable measurement of carbon emissions across the lifecycle of the asset using accurate carbon data and standard reporting methods. Currently, there is no mandated requirement to measure whole-life carbon and industry reporting is mostly voluntary.

NZR10: Industry benchmarks and best practice need to be developed, refined and adopted to measure whole-life carbon and provide the evidence to set targets and establish financial incentives for carbon reduction. Identify incentives for whole-life, risk-based management approaches, with risks allocated to those best able to manage them. Embed such incentives in contracts to drive the adoption of monitoring approaches and motivate better-informed asset management decisions.

In addition, successful whole-life carbon assessment requires accurate carbon measurement by stakeholders across the project lifecycle. These carbon data must then be evaluated in accordance with a consistent and transparent reporting framework. Sharing the data also promotes bench-marking and opportunities for performance improvement through learning. In the United Kingdom, initiatives such as the Built Environment Carbon Database are working to provide these mechanisms for accessible carbon data and reporting, and the PAS2080 standard (Nguyen and Beer, 2023) for managing carbon in buildings and infrastructure provides a process to actively manage carbon during delivery and operation.

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[18] Octopus Energy in the United Kingdom is trialing a system that sends text messages to customers to ask for changes in energy behavior, who are then rewarded for adjusting their behavior to smooth demand.

An accounting system for carbon would allow carbon costs to be integrated into everything we do. Such a shadow carbon price on materials would fundamentally change agents' economic calculus and provide a legitimate way to account for carbon. One way to implement this could be adding a carbon metric label on materials and products to influence better choices and make it easier to count the cost of carbon. Although reducing carbon on projects is a welcome priority for the UK government, change also needs to happen at the systems and network level, which requires incentives.

NZR11: Implement an accounting system for carbon and prices that will appropriately value the impact of carbon on the environment both now and in the future (natural capital accounting). Consider developing a carbon metric label for materials and products.

6.3.2 Assessing embodied carbon in existing infrastructure

Part of the challenge in ensuring a holistic understanding of whole-life carbon in infrastructure is understanding the value of extending the life of existing infrastructure and maximizing its benefit. Since carbon is already committed to these existing systems, getting the most out of this infrastructure is critical. However, valuation models and project assessments often do not account for this embodied carbon.

The Gross Replacement Carbon footprint (GRCf) toolkit, commissioned by the Welsh Government to promote a better understanding of the embodied carbon in the bridges in their network, is just one example of how embodied carbon might be measured in practice (Trump, 2021). This toolkit calculates the equivalent embodied carbon if the structure were to be replaced on a like-for-like basis with a new structure, which is presented alongside Gross Replacement Cost and categorized by structure type and current condition. Such a toolkit provides valuable information that can be used to allocate funding for maintenance or replacement by illustrating the embodied carbon associated with replacing those structures in the worst condition. This introduces carbon into the discussion of asset management and provides a mechanism for communicating with stakeholders.

NZR12: Adopt a scheme such as the Gross Replacement Carbon footprint (GRCf) toolkit to account for the embodied carbon of existing assets in option selection.

6.3.3 Mitigation, adaptation, and land use

Reducing carbon emissions in infrastructure to mitigate the effects of climate change is in some ways inextricably linked to the issues pertaining to resilience outlined above. There is frequently a perceived tension between mitigation, adaptation and resilience, but infrastructure development offers an opportunity to find a balance. Getting to net zero by a target date will not turn the tide of change immediately. Even if the targets are achieved, significant adaptation for resilience will have been necessary leading up to that and for many years thereafter. Getting to net zero is a necessary, but not a sufficient, response to climate change. Investment for appropriate adaptation measures should be progressively increased, and appropriate and structured adaptation programs planned and budgeted.

Infrastructure development should consider the most beneficial use of the land on which the development is proposed. Currently, project assessments do not require an assessment of carbon-storage capacity (current and future) of any natural systems that will be impacted by the construction of new assets. Examples include the need to remove existing woodland or peat bogs. Nature-based solutions and green infrastructure systems enhance biodiversity, sequester carbon and provide mitigation against the impacts of major climate events. Reducing carbon in concrete or improving energy efficiency is only part of the change required to achieve meaningful decarbonization at scale.

The definition of net zero requires that all residual emissions are offset. Carbon capture and engineered GHG removals are not sufficiently developed at the scale necessary to account for current emissions.[19] Land regeneration for sequestering carbon therefore is essential, and it brings potential benefits such as the creation of recreational spaces. While land-use change and LULC (land use/land cover) are, strictly speaking, part of lifecycle carbon assessments, they are used inconsistently when it comes to project assessments. Yet, such changes in land use are not commonplace and require more consideration (and widespread application) in the construction industry.

> **NZR13: Recognize, prioritize and protect the role of nature as a complex and interconnected natural system and develop frameworks which favor nature-based solutions over hard engineered solutions when possible.**

6.3.4 Behavior change

Behavior change will play a key role in carbon reduction in the infrastructure sector. How can we catalyze a step-change toward zero-/negative-carbon to be as effective and comprehensive as the shift to health and safety in construction? The latter required regulation and all parties were morally obliged to take part. Smoking indoors is another example of once-common behavior in the United States and the United Kingdom that is now seen as unacceptable. A tipping point is required to shift the carbon dial.

Consumers need more information to make better decisions, but this process requires trust in the source of the information. The cost-of-living crisis is putting strain on many households. Understanding the benefits of low- and no-carbon decisions will be key to engagement. Demonstrating benefits delivered locally and at scale could help win hearts and minds. Behavioral economics can help to nudge people with reminders to alter patterns of consumption. For example, as mentioned in Section 6.2.3, UK energy company Octopus trialed an energy-use tariff, “Agile Octopus”, that rewarded customers for adjusting behavior to support smooth demand.[20] Methods to drive behavior change at all levels in the system are required. For example, personal or community-level carbon budgets could be introduced to make carbon visible and incentivize action. The intent here is to have a non-enforceable, but visible, carbon budget for communities or individuals to be aware of their use vs the remaining (planetary) carbon budget.

Examples are needed in the building sector that demonstrate ways to change energy use at low or no cost. For example, improving efficiency of windows in a city’s building stock would make financial sense if all the buildings were wrapped together into one contract, taking advantage of the benefits of purchasing at scale.

6.3.5 Perceived cost of net zero

There is a common perception that carbon reduction measures inevitably result in increased costs. However, this is frequently found not to be the case. Although in some cases up-front costs may be higher, whole-life costs are typically lower, and in many cases even initial costs are found to be lower.

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[19] Offsets: payment to receive credit (and compensate GHG emissions) for certified emission reduction or removal projects outside of the asset or network boundary, carried out by others. NOTE: Priority should be given to removals over offsetting. Offset is a last resort mechanism accepted only in particular cases when certain programs of work demonstrate that all carbon reduction opportunities have been exhausted to meet a net zero carbon target.
Carbon Capture/Carbon Removal: carbon removed from the atmosphere and permanently stored within or beyond the asset or network boundary to counterbalance the impact of emissions that remain unabated.

[20] https://octoenergy-production-media.s3.amazonaws.com/documents/agile-report.pdf

Subsidies for low-carbon energy technology have been shown to be a sound investment (Way et al., 2022), with projected economic benefits estimated to be in the trillions of dollars in net savings in energy costs compared with fossil fuels, even without taking into account the costs of climate-change impacts associated with the burning of fossil fuels. Accounting for damage avoided only increases these benefits. It has also created entirely new industries providing clean-tech jobs, which more than replace the jobs lost in sectors related to mining and carbon-intensive energy production, with more than 10 million net new jobs anticipated by 2030 compared with 2.7 million jobs lost in the fossil fuel sectors (Wallach, 2022).

In major infrastructure construction projects, the pursuit of carbon reduction strategies have resulted in reduced capital costs. The UK's National Grid found that for every 2% of carbon saved, there was a 1% reduction in capital cost. Anglian Water delivered a 61% reduction in capital carbon alongside a significant reduction in capital cost over the period 2015-2020 (NCE, 2018). An example of this is shown in Case Study NZ2 below.

CASE STUDY NZ2 - FOCUS ON CAPITAL CARBON REDUCTION AND REDUCE CAPITAL COST

Anglian Water in the United Kingdom has been at the forefront of carbon reduction in the water industry, reducing capital carbon by 61% in their capital programs in 2020 from their original 2010 baseline and reducing operational emissions by 34% from a baseline set in 2014/2015. These emissions reductions have resulted in reductions in capital and operational costs, demonstrating the direct relationship between carbon reductions and cost reductions. An example of this is the Marston Water Recycling Centre (WRC), near Grantham in Lincolnshire, which currently recycles water for a population of approximately 63,500. This is expected to rise to 76,000 by 2031, with significant new housing developments in the area. The capacity at the Marston WRC was insufficient to cater for this growth, and the works was at the limit of its ability to remove ammonia to the required discharge water quality standards. The tertiary treatment process at the Marston WRC consists of four large grass plots covering 64 acres. Initially, the plan was to stop using these existing grass plots and build a new pumping station and nitrifying sand filter, which would involve erecting new concrete structures, phasing out the natural cleaning process and increasing operational energy consumption (and therefore carbon emissions). However, the area is a designated Local Wildlife Site, and home to an abundance of wildlife, so the Anglian Water team came up with a revised plan to remodel the grass plots to provide greater treatment capacity and climate resilience instead. Completed in December 2019 after 12 months on site, the project delivered an efficiency saving of £1,957,000 (39%) and a 90% capital carbon saving (534tCO_2 e), while newly planted trees help offset the site's carbon footprint further (Anglian Water, 2021).

Image credit: Anglian Water.

6.3.6 Financing carbon reduction initiatives - Green Banks

Green banks have been set up by a number of countries, states and also privately. Such banks use public and private funding to incentivize the transition to clean energy and address climate change. Green banks use financing, not grants, meaning that capital is eventually expected to be returned or repaid[21] thus focusing on markets where there is potential for payback. This generally means that they finance proven, technically viable projects that are well past the research and development stage. Financing can be done in tandem with other market-development activities. Examples include the UK Infrastructure Bank, and multiple state-level finance authorities in the US.

Climate bonds specifically finance projects that reduce carbon emissions or alleviate the effects of climate change, while green bonds represent a broader category of instruments related to projects with a positive environmental impact. Such bonds have been in use for over a decade, with over $90 billion in new green bonds issuances since 2010.[22] The Climate Bonds Initiative is a global partnership of governments, businesses, investors and civil society actors with more than 230 institutional investor members in 52 countries.

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[21] https://coalitionforgreencapital.com/what-is-a-green-bank/

[22] https://www.esgthereport.com/what-is-the-climate-bonds-initiative/

Peat bog on Isle of Skye in Scotland

6.4 Circular economy in the built environment

6.4.1 Overview of principles

One of the strategies that is promoted to reduce carbon emissions in the built environment is the adoption of a circular economy. Such an economy is defined by Geissdoerfer et al. (2020) as an economic system in which resource input and waste, emission, and energy leakages are minimized by cycling, extending, and intensifying material and energy loops. Construction is responsible for over half of virgin material extraction and over 60% of waste disposed in the United Kingdom, and it therefore has a responsibility to use materials efficiently and maximize the value obtained. Circular-economy principles promote changing our approach regarding the use of materials from a linear process of extract-make-use-dispose to a circular approach where all possible opportunities to reuse materials are explored before down-valuing them through recycling or disposal. A visual representation is shown in Figure 6.2.[23]

A circular economy reduces emissions associated with the extraction and processing of raw materials, limiting them to the emissions from reprocessing and distribution of materials.

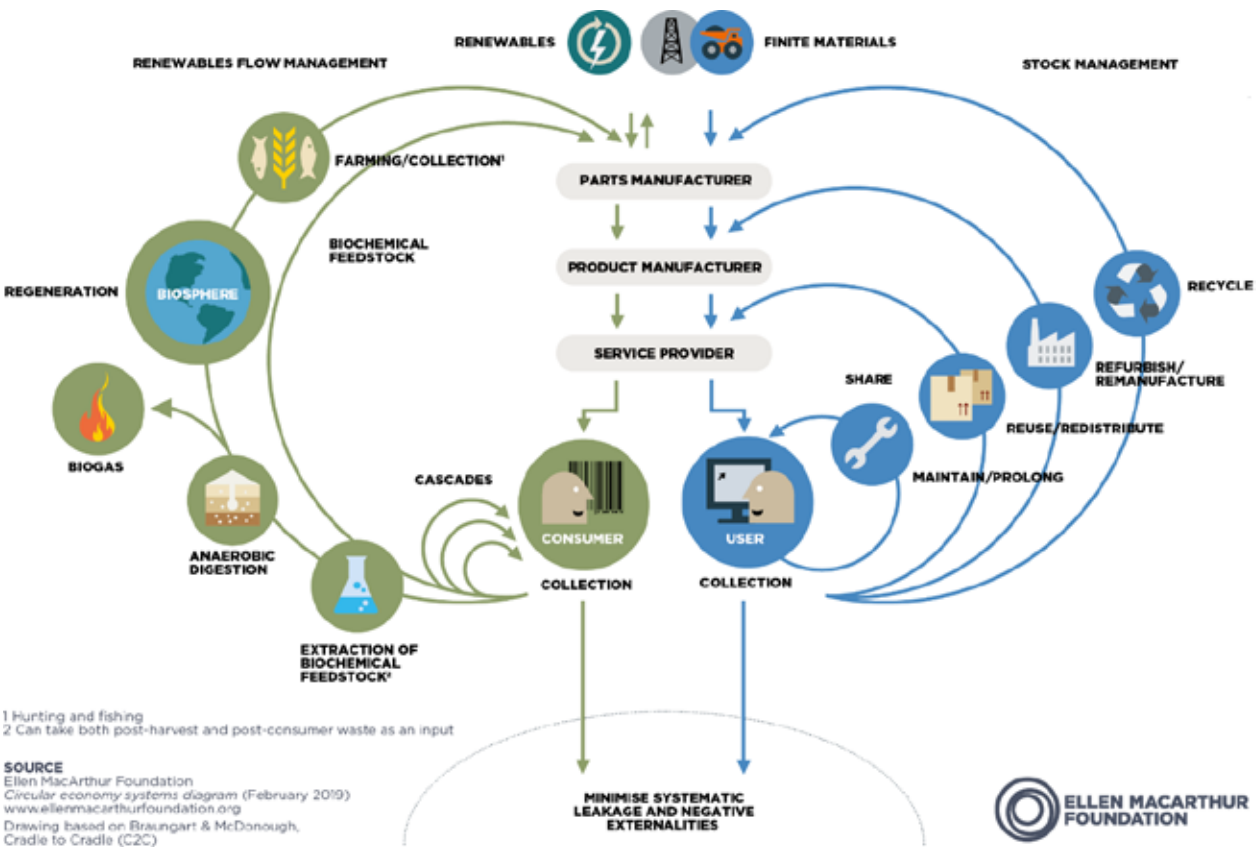


Figure 6.2: The Circular Economy (Ellen MacArthur Foundation, 2019

In the construction industry, circular economy can be achieved, for example, by adapting existing buildings or infrastructure to extend serviceable life. A circular economy is also achieved by reusing building components; deconstruction instead of demolition to salvage materials and components (e.g., by selling through material exchange platforms), and design for deconstruction to allow for future reuse of elements (see Case Study NZ3 below).

[23] https://ellenmacarthurfoundation.org/

To establish a circular economy in the built environment, many elements are required to develop both supply and demand for materials, including:

- Pre-demolition audits on existing structures to understand the value of materials locked into buildings and assets,
- A design-for-deconstruction-and-reuse approach to design and construction of new assets,
- Accurate as-built information that details material specifications and quantities which could be accessed upon refurbishment or demolition,
- A system of materials verification and tracking to verify and certify material quality and condition for reuse,
- A marketplace for materials – including tracking materials supply alongside materials demand to match potential providers with users.

Digital technologies, such as BIM, play an important role as tools for storing this information and transferring it to relevant stakeholders, who can use the information to maximize reuse of materials and components.

To enable the practical requirements above, there is also a need to create an ecosystem including reputable resellers, and assessors who can evaluate competently assets prior to demolition. There is also a need for funding and financing mechanisms to take on board a new type of material and certification, and to understand any risks involved (or ideally, to find that risk is not increased), including risks regarding quality of material and supply availability. Likewise, the reinsurance industry will need to recognize the balance between the risk of reusing materials against the risks imposed by the higher carbon emissions of virgin materials.

NZR14: Continue to invest in circular-economy research and innovation initiatives to develop technologies, processes and a marketplace for material reuse and repurposing.

CASE STUDY NZ3 - REPURPOSING WIND TURBINE BLADES: BLADE BRIDGE[24]

Thinking beyond the constraints of the built environment reveals innovative examples of the relationship between infrastructure and the circular economy. Blade Bridge, a pedestrian and cycle bridge in Ireland, was constructed in January 2022 using repurposed blades decommissioned from wind turbines. It is the second such bridge to be built in the world. The blades form the structural span of the bridge and are joined by a steel deck. Wind-turbine blades have a design life of approximately 20 to 25 years and cannot be recycled due to the materials used historically for their construction. Finding alternative uses for the blades saves them from being landfilled and reduces the need for new materials in the construction of the asset (Deeney, et al., 2021).

Image credit: Re-Wind Network (© Re-Wind Network)

[11] https://www.rte.ie/brainstorm/2022/0804/1287943-what-can-you-do-with-used-wind-turbine-blades/

6.6 Carbon from conflict and military operations

Carbon emissions from conflicts and military operations may be substantial. Conflicts in the Near East and the Ukraine invasion have involved carbon releases associated with bombing, shelling, building and facility destruction, burning of oil fields, and fuel consumption by land and air-based military vehicles. There are substantial carbon emissions associated with building defense facilities, equipment production, and personnel resources and travel. The carbon footprint of these conflicts is largely unknown. Carbon releases result from (1) active military operations and (2) rebuilding structures and facilities either destroyed or partially damaged. It is important to understand and quantify the carbon released from these activities so that its impact can be evaluated and compared relative to other sources of carbon release. Military-related carbon emissions would also delay the dates for various milestone reductions, and thus offset the timeline for achieving net-zero carbon.

> **NZR15: Evaluate the effects of military operations on carbon released to the atmosphere. Estimate delays in carbon reduction milestones and provide plans either to adapt or estimate the cost associated with carbon-reduction milestone delays.**

6.5 Beyond net zero

The IPCC Sixth Assessment Report in 2022 has made it clear that we need to aggressively pursue carbon reduction, with 50% reductions by 2030 if we are to limit global warming to 1.5 to 2o C. However, it is also clear that even this may not be enough to avoid serious damaging effects from climate change. Therefore, research and development into carbon capture, utilization and storage (CCUS) opportunities are required in parallel. This includes deploying nature-based solutions to store carbon, such as restoring wetlands, alongside more technology-focused solutions. Current examples of such technologies include: developments in carbon negative cement, where traditional Portland cement is directly replaced by novel cementitious materials; carbon capture algae, where waste CO2 from industrial processes is bubbled through tubes of algae and brine, with the resulting dried algae potentially being sold as feed for chicken or fish; or permanent geological storage of captured CO2. Initiatives that create the potential for infrastructure projects to capture more carbon than they emit should be prioritized.

7.0

EQUITY IN INFRASTRUCTURE PROVISION AND OPERATION

7.0 EQUITY IN INFRASTRUCTURE PROVISION AND OPERATION

7.1 Defining equity in the context of infrastructure

Equity in the context of infrastructure has multiple dimensions that support the underlying principle that infrastructure should be available, accessible and affordable to all (Littman, 2022). In terms of financial investment in infrastructure development, equity is equated with ownership and risk allocation. In terms of socio-economic development, equity relates to the practice of fairness and impartiality. In recent years, the pursuit of equitable outcomes for all individuals has become a key point of focus to address past inequities and influence future development trajectories. Infrastructure is critical to delivering these desired outcomes because it has distributional impacts. It can reconfigure consumption and production patterns, influence the spatial development of places, and directly contribute to whether public services are fairly or unfairly accessible.

Infrastructure provision is not value neutral. It can create or exacerbate inequities. It is therefore crucial that the notion of universal service is embedded in our infrastructure system, and that equity considerations underpin the development process of all types of infrastructure (OECD, 2017a). Postal services, energy generation, water provision, wastewater treatment and transportation networks all have historical universal-service obligations (USOs), which define what types of services must be provided to citizens in areas where they live and work. That said, the concept of universal service is a dynamic issue and its connection to equity is based on regulatory, social and technological developments. It also varies across users, sectors, and regions and at different scales – e.g., local versus international. These variations notwithstanding, universal service is likely the most well-defined and measurable manifestation of equity in infrastructure provision (United Nations Environment Program, 2021), regardless of whether the services themselves are provided using public, private or PPP delivery models.

> **Equity Recommendation (ER1): Guidance, tools and incentives are needed to enable engineers and planners to link desired outcomes and project-appraisal processes with locally relevant solutions.**
>
> **ER2: Decision makers should take into account the importance of equity in relation to economic viability – ensuring all communities have infrastructure that enables people to be productive and contribute to the future.**

7.2 How does the concept of equity differ in the United States and United Kingdom?

Equity has different socioeconomic, geographic, racial/ethnic and gender connotations that capture the legacy consequences of past decisions. Fundamentally, equity considerations recognize the lack of inclusivity in the inputs considered for current systems, which is reflected in the resulting outputs and outcomes. The United States and the United Kingdom are illustrative of how past institutional practices have entrenched inequities of access to infrastructure in different ways. As a result, differences are evident in how equity in infrastructure access has been regarded in the United States and the United Kingdom, respectively.

In the United States, infrastructure has "racial inequities built into" it (Marin, et al., 2021). Traumatic legacies of racial inequality, marginalization and *de facto* segregation in urban redevelopment have forced the infrastructure community to consider deeply the marginalization and restriction of spatial access to selected community groups. Additionally, the supply of infrastructure in the United States remains very uneven, because decision-making occurs at the local level, and municipalities have very different interests and access to resources. This means that the types of infrastructure services provided to communities vary considerably (see Case Study E1 below). Does everyone need access to specific infrastructure facilities (e.g., railways or airports)? Not necessarily, because every community has different service needs. However, in terms of transport infrastructure, mobility itself should be the underlying service obligation (Casady, 2020).

ER3: Real-time accounting and appraisal systems are required to better understand equity needs as well as outcomes, and to ensure that the changing dynamics shaping our societies are captured.

In the United Kingdom, equity considerations are focused on regional inequality, most recently framed as the policy slogan “levelling-up”. The resulting discourse relates to addressing the North-South divide and overcoming the perception that most infrastructure development, services and technology have disproportionately benefited London and the Southeast (UK DfT, 2021). The National Infrastructure Commission in the United Kingdom has also more aggressively identified equity concerns within the energy transition, expansion of digital infrastructure networks and climate resilient infrastructure (NIC, 2019). Although the primary focus on inequity in the United States and the United Kingdom may be different, the consequences appear to be similar: that certain communities are being left behind.

Elevated freeway through New Orleans

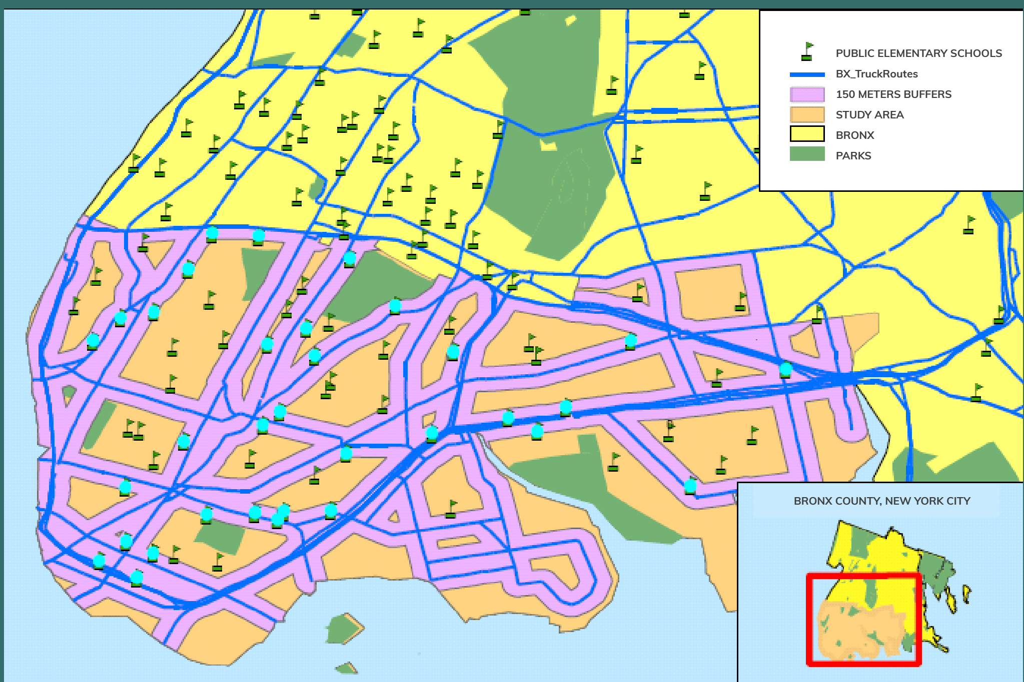
CASE STUDY E1 - EQUITY AND INFRASTRUCTURE RESILIENCE

Equity and social justice are central to infrastructure resilience (Tierney, 2014; Vale, 2014). Waste management infrastructure (landfills, waste transfer stations, Superfund sites) historically were analyzed for disproportionate adverse health and economic population impacts (Zimmerman, 1993, 1994), later emphasizing other infrastructures (Bullard, 2007), and natural hazard and climate threats (Foster et al., 2019; Walsh et al., 2014; Wei et al., 2022).

Equity includes accessibility, availability, affordability and health inequities. Availability and access occur where routes and stations are located in underrepresented neighborhoods but not serving them, e.g., Washington DC-suburban Maryland green line (Schrag, 2006). Electric power equity (Farley et al., 2021) was identified for poorer NYC housing providing renewable solutions (Zimmerman et al. 2019: 201). Communications disparities such as digital divide emphasize uneven access to information technologies and training (Lythreatis, 2022). Affordability arises for transit (Fehr 1991; Heathcott, Soffer and Zimmerman, 2022) and general energy funding allocations (Greenberg, Irving and Zimmerman, 2009). Environmental and health equity covers traditional and green infrastructure (Grabowski, McPhearson and Pickett, 2023). Flint, Michigan, exemplifies health-related water disparities (Bodin, 2019).

Two transportation cases illustrate infrastructure equity at different geographic scales. First, Zimmerman (2012: 14) evaluated US Census nationwide data for differences in worker travel mode by poverty finding greater public transportation use and less car use at lower-income levels. Second, locally, vulnerable population proximity to roadways occurred in the relatively lower income South Bronx, NY, using GIS-based analysis co-locating roads and schools, where twenty percent of pre-kindergarten to 8th grade students were in schools near major highways ("within 150 meters or 500 feet or less") (Restrepo and Zimmerman, 2007: 92, Figure 11). Infrastructure-related equity issues encompass many disadvantaged groups (Peek, 2018; Rodriguez, 2018). Case-based statistical and spatial analyses provide tools to identify and evaluate disparities across different groups to shape infrastructure policies.

Image credit: Dr. Zvia S. Naphtali



Map produced by Dr. Zvia S. Naphtali, Wagner Graduate School of Public Service, NYU for C.E. Restrepo and R. Zimmerman, editors (December 2007) "South Bronx Environmental Health and Policy Study, Public Health and Environmental Policy Analysis: Final Report for Phase IV, Environmental Planning, Zoning, Land Use, Air Quality and Public Health," New York, NY: New York University Wagner Graduate School of Public Service, Institute for Civil Infrastructure Systems, Figure 11, p. 92. Note: 150 meters is roughly 500 feet or about 2 city blocks (assuming 20 blocks per mile). Blue dots indicate schools within the 150-meter buffer around major roads.

The COVID-19 pandemic placed a new emphasis on digital infrastructure. The need for broadband access and technology to keep workers connected during the pandemic opened the door to new opportunities, especially remote/hybrid work. However, these opportunities were not applicable to all job roles, and therefore not open to all, highlighting the inherent disparities and vulnerabilities in the digital economy (Fairwork, 2020). The main beneficiaries were those in higher-skilled, higher-status employment – but with some exceptions by job type. Those in lower-skilled roles/socioeconomic levels were typically most exposed to pandemic risks in the workplace as well as due to their domestic arrangements.

Although variations in demand changed conceptions of access for certain types of infrastructure (e.g., railways and buses), the pandemic highlighted existing inequities in internet connectivity both in the United Kingdom and the United States. Existing estimates of broadband service availability likely underreport the true extent of gaps in coverage, making assessments of service provision and equity difficult to determine. However, during the pandemic the need for children to attend classes online highlighted substantial inequities of access both to computer hardware and to internet connectivity, prompting urgent campaigns to source and distribute computers and broadband tokens. Many cities, such as Liverpool, now have digital inclusion strategies (Liverpool City Regions, 2021). In the USA, the national government addressed this issue, among other infrastructure equity matters, with the passage of the Infrastructure Investment and Jobs Act (IIJA) (The White House, 2021). However, there is a risk that longer-term trends around working practices, healthcare and the delivery of and access to digital infrastructure both embed and deepen these social divides, and this challenge should be recognized and addressed by future infrastructure planning.

7.3 A just transition - a global perspective on equity

A recently published report by the IPCC (2022) on impacts, adaptation and vulnerability notes that, in addition to being effective and feasible, climate-oriented solutions should conform to principles of justice. That is, they set out the moral and legal principles of fairness and equity in the way people are treated, often based on the ethics and values of society. Climate justice involves addressing the underlying drivers of vulnerability and emissions by placing emphasis on: (*i*) the protection of vulnerable populations from the impacts of climate change; (*ii*) mitigating the effects of low-carbon transformations; and (*iii*) ensuring an equitable decarbonized world. Developing infrastructure in adherence to the principles of climate justice therefore encompasses:

- *Distributive justice:* the allocation of infrastructure-related benefits and burdens are fair and equitable across individuals, nations, and generations;
- *Procedural justice*: fairness and equity are reflected in who decides and participates in infrastructure decision making; and
- *Recognition justice:* robust engagement is undertaken with basic respect and fair consideration of diverse cultures and perspectives.

To understand the drivers of vulnerability and emissions, we need to examine past and present models of development. Infrastructure has been shaped by economic, social and cultural factors that often prioritized the interests of powerful groups at the expense of minorities or less-valued groups. Prevailing developmental theories for most of the 20th century were also based on assumptions about patterns of development, where societies move from an agrarian economic model to an industrial one, then finally to a services-based economy, each characterized by higher levels of internal and external trade over greater distances. This resulted in development of carbon-intensive infrastructure such as fossil-fuel based energy and road-based transport. Historically, this infrastructure has supported powerful economic actors, without explicitly requiring the needs of minority or disadvantaged groups to be addressed. Modernizing this legacy infrastructure to address societal needs and achieve net zero requires embedding new assets in existing complex systems while changing infrastructure design and delivery policies (O'Neil et al., 2018).

Wealthier countries also export the carbon problem to countries with less environmental regulations, weaker policy environments around carbon emissions and poorer industrial practices around waste, social justice and equity issues (Partnership for Market Readiness, 2015). The net result is an increase in emissions in jurisdictions beyond the reach of carbon-pricing policies, and worsened conditions for those regions and people who are already highly vulnerable to climate hazards. Hotspots include places with development constraints in West-, Central- and East Africa, South Asia, Central and South America, Small Island Developing States and the Arctic. As the IPCC reports, between 2010–2020, human mortality from floods, droughts and storms was 15 times higher in highly vulnerable regions, compared to regions with very low vulnerability. Addressing this vulnerability in these places requires the urgent provision of basic infrastructure services that account for changing climate conditions. This improved access will ultimately enhance lives and livelihoods, particularly of low-income and marginalized groups. In the absence of collective action (Ostrom, 2014), there is a risk that vulnerable populations are left unprotected from the impacts of climate change and harmed by low-carbon transformations, leading to persistent or worsening inequalities and disparities. Recognition of these issues led to the agreement in principle at COP27 of a loss and damage fund to support poorer countries in the adaptation of their infrastructure to increase resilience to climate change.

As a complement to targeted interventions, there is a clear need to advance our understanding of how best to achieve equitable infrastructure in all regions across the world (Global Infrastructure Hub, 2019). Infrastructure should enhance positive outcomes in social inclusivity and ensure no individual, community, or social group is left behind or blocked from the benefits of improved infrastructure services. Indeed, universal service, or universal access, has been the focus of infrastructure policy for decades. Transportation policy focused on providing paved roads to all communities, telephone policy focused on providing all communities with a basic level of service, and power connectivity ensured that no communities were without a source of power, no matter how rural.

> **ER4: To achieve equitable outcomes from infrastructure investments, develop effective partnerships between governments, society, and private-sector organizations, to facilitate the adoption of support mechanisms.**
>
> **ER5: Inclusive, integrated and long-term planning is needed at local, municipal, sub-national and national scales, together with effective regulation and monitoring systems.**

Finally, the costs associated with the low-carbon transition will be transferred to individuals – i.e., users of infrastructure and taxpayers. The challenge is how to ensure this cost is equitable and manageable across society. The pandemic and the war in Ukraine have created supply-chain disruption and exacerbated inflationary pressures. Equitable access to infrastructure must therefore reflect the costs borne by users, especially those from lower-income communities, who are likely to face challenges in accessing these services. Lack of demand density and/or unaffordability in small population areas where socioeconomic conditions are unfavorable has always placed a major constraint on universal service obligations. Economic measures may be needed to help expand universal access and avoid entrenching inequity.

7.4 Addressing equity outcomes

Society is not a homogenous group and identifying the infrastructure needs and equity outcomes of different communities is not an easy task, but it is necessary. Distributional analysis in the context of infrastructure provision is especially important because such investments can fundamentally change the spatial make up of places. That notwithstanding, infrastructure is only one aspect of the wider socioeconomic picture. A focus on equity in outcomes that takes a systems perspective is required. Some communities suffer multiple deprivations, such as health and education, that call for infrastructure provision to be complemented with locally relevant social policies and interventions. Especially in historically disadvantaged communities, there is a need for a shift towards equity in outcomes (for example, Case Study E2 below).

> **ER6: Equity considerations should be included in systems perspectives and should be implemented in planning and delivery of infrastructure and services.**

CASE STUDY E2 - FUNDING TO REDRESS INEQUITY IN WATER SUPPLY

Water supply often involves equity with respect to universal access by all, regardless of race, nationality, disability status and economic characteristics. Flint and Brenton Harbor, Michigan, have been the focus of lead service pipe replacement after high levels of lead were found in their water distribution systems. Substantial state and US federal government funding has been used to replace lead services, often with copper pipelines that are safe with respect to contamination. In Flint, Michigan, the source of city water was returned to the Detroit water system in 2015. Flint victims of the water supply crisis were awarded over $600 million in damages, and several government officials, including the previous governor, were charged with felony counts and misdemeanors. Federal support of $600 million was directed to repair the water supply system in Jackson, Mississippi, where flooding in 2022 damaged the main water treatment facility, adding to disruptions already experienced because of many years of deferred maintenance. The President of the NAACP pointed out that emergency funding to address the availability of safe drinking water should be "celebrated as a promise of equitable infrastructure services."

To ensure infrastructure meets the needs of the communities it seeks to serve, citizen engagement in the processes and decision-making from the start of an initiative is critical. For example, a transport link to a city will only be useful if people have the money to use it as well as jobs and other amenities to travel to. Historically, some of these communities are not engaged during the process of planning and developing infrastructure on account that they are "harder to reach", or they have only been consulted when all material decisions have been made. However, if we are to address equity gaps and legacy challenges to raise outcome standards, citizen engagement must be secured from the outset.

ER7: To ensure infrastructure meets the needs of the communities it seeks to serve, citizen engagement should be sought from the outset, and this requires a shift in focus to the citizen. Equity considerations need to be community-specific and outcome-driven.

ER8: Develop guidance and policy for early citizen engagement in developing equity-related initiatives and associated metrics.

Digital tools can help engage citizens in decision-making at an early stage and identify the right means to achieve the desired ends. Digital tools can also help model and simulate scenarios that communicate impact and thus make the decision-making process more meaningful. This process includes engaging and enabling communities to share ownership in addressing problems and identifying appropriate solutions (see the vTaiwan example above in Section 5.4). Achieving these benefits, however, cannot be oversimplified because there are important considerations to be made.

Accompanying the present era of growing use of digital technologies is a transition to an era of data abundance. The goal is to turn data into accurate and reliable information that is available on an equitable basis. As new digital technology increasingly shapes the services on which people depend, the potential social impacts must be considered; there is risk of inequity if tech-based solutions are expected to be picked-up universally. It is important to ensure digital tools do not ignore the needs of disadvantaged or under-represented groups. We cannot assume that all groups in society will have equal access to digital systems and technologies, or the skills to use them. For real social value to be achieved through the delivery of infrastructure projects, such problems should be tackled up front with digital systems and technologies designed with a range of users in mind.

Early consideration and planning for social impacts can be integrated in delivering infrastructure projects with an approach that begins by anticipating, evaluating and managing societal risks, impacts and effects from digitalization. To this end, new technologies can be used as tools to widen citizen participation to include underrepresented groups as stakeholders. Although this is a useful approach, there is yet another layer of inequity that will persist. The pervasive digital divide, which was starkly revealed at the peak of the COVID-19 pandemic in many developed and developing countries alike, shows that there are citizens who are faced with material, skills and usage access barriers when it comes to digital engagement. In the truest sense, therefore, achieving equity will be significantly impaired if viewed through a lens of technology-optimism bias.

The utilization of new technology to deliver and accelerate the attainment of social equity through infrastructure project delivery would be best approached as a process of coevolution with addressing the digital access barriers that face the underrepresented in society. The adoption of such approaches could be incentivized by creating an ecosystem to enable the growth of scalable technologies that can both push for the delivery of transitional technologies (in addressing the digital divide) and pull advanced technologies towards adaptability to ensure widened citizen participation. Implementing such a dual approach can lead to realizing benefits of using digital tools to accelerate and deliver equity with real social gains without further deepening exclusion in the society.

ER9: Planners need to use digital tools which can help to engage citizens in decision-making at an early stage, while also addressing persistent digital access barriers.

7.5 Measuring equity needs and outcomes

How do we measure equity returns on investments and bring environmental, social and governance (ESG) credentials to investment decisions? Metrics are needed to assess the outcomes of infrastructure investments in reducing inequity and delivering improved quality of life. There is an opportunity to use participative processes, enabled by digital tools, to codevelop metrics with the communities who are expected to benefit, engaging the public in cocreating both the solutions and the key performance indicators. It is important to give a voice to all those stakeholders involved, potentially including the natural environment (via wildlife and conservation organisations), and to create a balanced set of metrics that take a broad view of the concept of value and return on investment (ROI) and address the United Nations Sustainable Development Goals.

In addition, real-time accounting and appraisal systems are required to better understand equity needs and outcomes, and to ensure that the changing dynamics shaping our societies are captured. Technologies such as digital twins are starting to be used to monitor the key performance indicators (KPIs) in real time and provide an analysis platform for assessing outcomes. Examples include Space Syntax,[25] which can produce socioeconomic maps showing over- and under-provision of services and inequality, but we need to ensure that we do not focus solely on what can be measured and treat it as important purely for that reason. We need to understand how digital twins can support effective decision-making on a system wide basis, and that this includes social and organizational systems as well as physical ones.

> **ER10: Infrastructure sponsors would benefit from the development of digital tools for monitoring environmental and social outcomes of interventions, and guidance regarding the ethical requirements surrounding such tools.**

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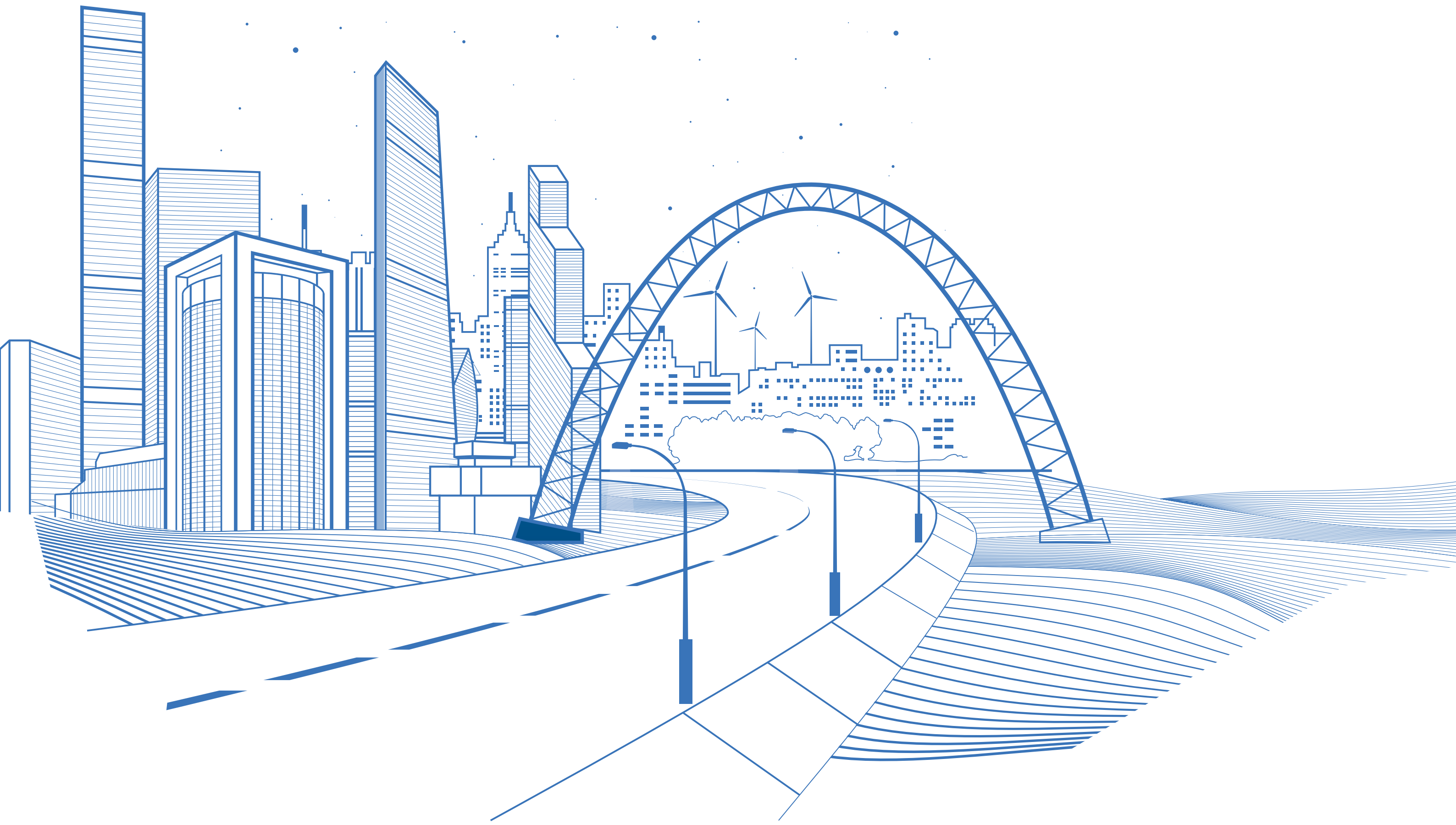
[25] https://spacesyntax.com



8. SUMMARY OF RECOMMENDATIONS

This section provides a summary of recommendations for policy, industry and research that have been developed on the basis of the Workshop. The recommendations are listed according to the main Workshop topics. Funding and Financing, Emerging Technologies, Resilience, Net Zero and Social Equity are listed as FFR, ETR, RR, NZR and ER, respectively. The main focus of each recommendation is shown with a colored box that links the recommendation with policy, industry, and/or research.

	Recommendation	Policy	Industry	Research
	Funding and Financing			
FFR1	Consider adopting funding mechanisms that correlate closely with infrastructure use and that vary with the value of the facility.	■		
FFR2	Bundling together facility design, construction and operation into one long-term contract can reduce the incentives to defer maintenance while enhancing incentives to adopt new technologies and improve life-cycle asset maintenance.	■	■	
FFR3	Including an equity component in the financing structure of a PPP can provide an equity cushion that allows private investors to absorb risk while financing larger upfront amounts relative to debt-only financing structures. This is standard practice in the United Kingdom.	■		
FFR4	Bundling or wrapping many relatively small but similar projects together into one large contract can attract international partners who have the expertise, capital and incentives to complete the project on-time and on-budget.	■	■	■
FFR5	Innovative approaches such as value capture and asset recycling can incentivize public asset owners to assess and extract value that may be latent in infrastructure after decades of traditional operation and management techniques. Value-capture projects that include environmental benefits such as methane capture and use should be a key focus.	■	■	■
FFR6	Public-sector-only executive education can help ensure that innovative approaches such as PPPs, TIFs, value capture and asset recycling are in the public interest and can support public owners in the pursuit of new, socially beneficial approaches.	■		■
	Emerging Technology	**P**	**I**	**R**
ETR1	Intelligent sensor and autonomy systems must be designed for long lifespans or be adaptable for replacement.		■	■
ETR2	Autonomy in infrastructure construction and operation should be developed within the framework of a common data environment (CDE) with standardized data so that efficiencies in infrastructure systems can be achieved.	■	■	■
ETR3	Using the framework of sociotechnical digital twin, infrastructure asset modelling should be linked to social behavior to understand human interaction with physical infrastructure systems.	■	■	■
ETR4	There is a need for machine learning and artificial intelligence to address prediction accuracy and prediction reliability of infrastructure system performance.		■	■

ETR5	Through innovations in materials and construction/maintenance processes, future infrastructure systems must be designed to generate their energy or rely exclusively on renewable energy, realizing a net-zero or negative carbon system.			
ETR6	There is a need to develop a commonly shared approach to evaluate emerging technology contributions for improved delivery, resilience, net-zero carbon, and equity objectives of infrastructure systems. The framework needs to be used to enhance communication between infrastructure owners and technology developers.			
ETR7	A large market for smart infrastructure should be created and developed by innovative policies and financial incentive mechanisms.			
	Resilience	**P**	**I**	**R**
RR1	Adopting frameworks such as the Task Force on Climate-related Financial Disclosures (TCFD) can drive thinking about possible future scenarios across a number of different variables and improve and increase reporting of climate-related financial information.			
RR2	Use scenario planning and modelling and a whole-system approach to explore a range of possible futures and design resilient solutions that can be adapted as the underlying data and boundary conditions become clearer.			
RR3	Use lessons learned alongside better data and information from emerging technologies to update design standards and develop policies to ensure adherence to the updated standards.			
RR4	Utilize nature-based solutions to deliver improved resilience with increased biodiversity and public amenities, building in valuation of these co-benefits as part of the business case.			
RR5	Develop effective community engagement strategies that help communities to understand risk and resilience, alongside equity, financing and other issues. This would enable collaborative evolution of appropriate responses to potential events, through research and consultation.			
RR6	Engage with stakeholders using simulation and social media to help citizens and asset managers visualize a potential event and develop response strategies, provide feedback to authorities and receive services from authorities prior to, during and after events.			
RR7	Government at all levels should be required to demonstrate how decisions made in relation to infrastructure support local communities, are consistent with the UN Sustainable Development Goals, and improve the performance and resilience of infrastructure assets and systems.			
RR8	The capacity for managing resilience in operating organisations needs to be strengthened to become a core capability. This will entail more collaborative approaches within and between sectors that help to mitigate risk at a system-of-systems level.			
RR9	There is a need to equip resilience professionals with the right tools and skills that allow them to be adaptive in the face of unexpected challenges. A broader-based body of knowledge for future infrastructure resilience professionals should be defined.			
RR10	There is a need to reassess on a regular basis the value of critical infrastructure because the concept of value and highest/best use of infrastructure will evolve over time. Good quality system-level metrics (and data) are needed both to understand the true impact of these systems and for benchmarking existing performance.			

	Net Zero	P	I	R
NZR1	Review every capital project proposal to ascertain whether reducing demand for infrastructure services or refurbishing existing infrastructure are viable and reduce carbon options.	■	■	
NZR2	Procurement should focus on low- or zero-carbon solutions as well as refurbishing waste materials. Include residual value/residual carbon to encourage use of novel materials.	■	■	
NZR3	Review and revise design codes to reduce conservatism in design and resultant overuse of material.	■	■	
NZR4	Academic and industry research into low- and zero-carbon materials, such as improved cements, should be scaled up and accelerated to deliver replacement products as rapidly as possible. Reuse of products such as steel beams should be encouraged. It is important to understand how these materials may age and to manage residual risk in adopting these new materials and to scale up supply chains.		■	■
NZR5	Processes should be developed for capturing and analyzing greenhouse gases, including carbon-based data and the integration of this information with existing digital technologies and processes (e.g., BIM models, digital twins).		■	■
NZR6	Require maintenance, refurbishment and renewal projects to demonstrate substantial reductions in operational energy as well as carbon-based use throughout the system.	■		
NZR7	Develop financial incentives such as grant schemes to support carbon-efficiency retrofit programs.	■	■	
NZR8	Deploy asset heath monitoring and assessment widely across the asset base to facilitate condition-based and risk-based approaches to asset maintenance and capacity assessment to enable life extension of assets and targeted deployment of maintenance resources. Develop O&M contracts that avoid lock-in to specific technologies, by using outcome-based specifications to encourage innovation during the contract.		■	
NZR9	Develop a one-stop-shop service to support householders and small businesses to retrofit their buildings for energy efficiency.	■		
NZR10	Industry benchmarks and best practice need to be developed, refined and adopted to measure whole-life carbon and provide the evidence to set targets and establish financial incentives for carbon reduction. Identify incentives for whole-life, risk-based management approaches, with risks allocated to those best able to manage them. Embed such incentives in contracts to drive the adoption of monitoring approaches and motivate better-informed asset management decisions.		■	■
NZR11	Implement an accounting system for carbon and prices that will appropriately value the impact of carbon on the environment both now and in the future (natural capital accounting). Consider developing a carbon metric label for materials and products.	■		
NZR12	Adopt a scheme such as the Gross Replacement Carbon footprint (GRCf) toolkit to account for the embodied carbon of existing assets in option selection.	■	■	
NZR13	Recognize, prioritize and protect the role of nature as a complex and interconnected natural system and develop frameworks which favor nature-based solutions over hard engineered solutions when possible.	■	■	■

NZR14	Continue to invest in circular economy research and innovation initiatives to develop technologies, processes and a marketplace for material reuse and repurposing.			
NZR15	Evaluate the effects of military operations on carbon released to the atmosphere. Estimate delays in carbon reduction milestones and provide plans either to adapt or estimate the cost associated with carbon reduction milestone delays.			
	Equity	**P**	**I**	**R**
ER1	Guidance, tools and incentives are needed to enable engineers and planners to link desired outcomes and project appraisal processes with locally relevant solutions.			
ER2	Decision makers should take into account the importance of equity in relation to economic viability – ensuring all communities have infrastructure that enables people to be productive and contribute to the future.			
ER3	Real-time accounting and appraisal systems are required to better understand equity needs as well as outcomes, and to ensure that the changing dynamics shaping our societies are captured.			
ER4	To achieve equitable outcomes from infrastructure investments, develop effective partnerships between governments, society, and private-sector organizations, to facilitate the adoption of support mechanisms.			
ER5	Inclusive, integrated, and long-term planning is needed at local, municipal, subnational and national scales, together with effective regulation and monitoring systems.			
ER6	Equity considerations should be included in systems perspectives and should be implemented in planning and delivery of infrastructure and services.			
ER7	To ensure infrastructure meets the needs of the communities it seeks to serve, citizen engagement should be sought from the outset, and this requires a shift in focus to the citizen. Equity considerations need to be community-specific and outcome-driven.			
ER8	Develop guidance and policy for early citizen engagement in developing equity-related initiatives and associated metrics.			
ER9	Planners need to use digital tools which can help to engage citizens in decision-making at an early stage, while also addressing persistent access barriers.			
ER10	Infrastructure sponsors would benefit from the development of digital tools for monitoring environmental and social outcomes of interventions, and guidance regarding the ethical requirements surrounding such tools.			

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APPENDIX

Conduct of the Workshop

The workshop was held in the Verizon Executive Education Center at Cornell Tech, located on Roosevelt Island in Manhattan, New York City. Taking place from the 10-15th July 2022, significant time was scheduled for breakout sessions and open discussions, as well as invited talks and short presentations by selected participants. The full workshop agenda is included below.

Workshop plan

To meet Workshop objectives, organizers commissioned the development of five briefing papers covering the sub-themes of:

1. funding/financing,
2. emerging technology,
3. resilience,
4. net zero carbon, and
5. equity.

These briefing papers were primarily used as background reading for the participants but also aided the development of prompts for the various breakout sessions held during the weeklong event. These focused interactive discussion periods were a central part of the Workshop. Significant time was scheduled to discuss the key thematic items and identify the most promising paths forward for resilience, net zero carbon, and equity in infrastructure.

Additional online discussion sessions focused on the themes above were held during the workshop to increase the diversity of thought. The online sessions were focused on early career researchers and industry practitioners, but anyone interested was welcome to attend. Additionally, several of the plenary sessions were streamed live or available on demand during the workshop to increase the reach of participants and ideas.

After the Workshop, organizers and a few selected participants remained in New York for an additional day to expand the group's perspectives as well as distil and synthesize the results of the Workshop. These results, coupled with insights from the briefing papers, form the basis of this Workshop Report.

Report Recommendations

Report recommendations were developed from workshop particpant's input especially from those who are expert in the relevant area. Recommendations were discussed and agreed by those preparing this report.

Workshop organization

Workshop Planning Committee

The Workshop Planning Committee included faculty members and staff from Cornell University in the US and the University of Cambridge in the UK The lead Workshop organizers are delineated below:

US Workshop Chairperson:
Professor Tom O'Rourke
Dept. of Civil & Environmental Eng.
Cornell University
Ithaca, New York, USA

US Workshop Co-Chairperson:
Professor Rick Geddes
Jeb E. Brooks School of Public Policy
Cornell University
Ithaca, New York, USA

US Workshop Program Manager:
Richard Coyle
Jeb E. Brooks School of Public Policy
Cornell University
Ithaca, New York, USA

UK Workshop Chairperson:
Professor Lord Robert Mair CBE
Dept. of Engineering
University of Cambridge
Cambridge, UK

UK Workshop Co-Chairperson:
Dr Jennifer Schooling OBE
Dept. of Engineering
University of Cambridge
Cambridge, UK

UK Workshop Program Manager:
Dee Dee Frawley
Dept. of Engineering
University of Cambridge
Cambridge, UK

International Organizing Committee

The planning committee solicited input on workshop preparations from a larger international organizing committee. This organizing committee included the following members:

- Professor Germà Bel, Professor of Economics and Public Policy at Universitat de Barcelona
- Professor Richard Dawson, Director of Research in the School of Engineering at Newcastle University
- Professor William Powrie, Professor of Geotechnical Engineering at the University of Southampton
- Dr Eoin Reeves, Professor of Economics, University of Limerick, Ireland
- Professor Kenichi Soga, Donald H. McLaughlin Chair and a Chancellor's Professor at the University of California, Berkeley.
- Richard Threlfall, Global Head of Infrastructure, Government and Healthcare, KPMG
- Dr Michael Samuelian, Founding director of the Jacobs Urban Technology Hub at Cornell Tech
- Professor Veronica Vecchi, Professor of Public Management and Business Government Relations at Bocconi University School of Management.

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Kunqi Zhang, University of Maryland
Dr. Mingliang Zhou, Tongji University

Workshop Program

Monday 11 July

Welcome	Welcome – **Prof Lord Robert Mair**
Session 1- Funding and financing infrastructure and the role of technology - Part 1	Plenary chair: Prof Eoin Reeves, University of Limerick • Funding and financing infrastructure – **Prof Rick Geddes**, Cornell University • Emerging technology in infrastructure – **Prof Kenichi Soga**, University of California, Berkley • Funding and financing infrastructure – EU context, **Prof Veronica Vecchi**, Bocconi • Emerging technology in infrastructure – UK context, **Ann-Marie Friel**, Pinsent Masons • Panel Discussion and Q&A
Session 2 - Resilient infrastructure	Plenary chair – Prof Rae Zimmerman • Resilience US context – Prof Tom O'Rourke, Cornell University • Resilience UK context – Prof Richard Dawson, University of Newcastle Followed by breakout session
Breakout session	

Tuesday 12 July

Session 3 - Net zero/Net negative Infrastructure	Plenary chair – Dr **Jennifer Schooling**, University of Cambridge • Net Zero/Net Negative US context – **Steve Beatty**, KPMG • Net Zero/Net Negative UK context – **Dr Heleni Pantelidou**, Arup Followed by breakout session

Wednesday 13 July

Session 4 – Equity in infrastructure provision and operation	Plenary chair – **Richard Threlfall**, KPMG • Equity US context – **Reuben McDaniel**, DASNY • Equity UK context – **Prof Philip McCann**, University of Manchester Followed by breakout session
Session 5 - UK and US lessons learned for infrastructure research and delivery	Plenary chair – **Sue Lee**, Ernst & Young • Lessons learned from delivery of large research programmes - **Prof Tom O'Rourke**, Cornell University • Panel discussion: **Prof William Powrie**, University of Southampton**; Dr Jennifer Schooling**, University of Cambridge; **Mark Enzer**, Mott MacDonald; **Fergus Harradence**, UK Department for Business, Energy and Industrial Strategy (BEIS); **Scott Zuchorski**, Fitch Ratings, **Stephen Beatty**, KPMG; **Maisie England**, EPSRC; **Prof Yueyue Fan**, NSF/University of California, Davis; **Dr Daan Liang**, NSF/University of Alabama • Panel discussion, Q&A (1 hour)

Thursday 14 July

Session 6 - Technology adoption - Part 2 **What is the role of technology, how can/will it get adopted? Based on sessions 2-5.**	Plenary chair – **Prof Kenichi Soga**, University of California, Berkley • Outputs of resilience breakout session • Outputs of net zero breakout session • Outputs of equity breakout session • Panel discussion and Q&A
Session 7 - Funding and financing infrastructure - Part 2 **What funding and financing models are needed? Based on sessions 2-5.**	Plenary chair – **Raymond DiPrinzio**, Sumitomo Mitsui Banking Corporation • Outputs of resilience breakout session • Outputs of net zero breakout session • Outputs of equity breakout session • Panel discussion and Q&A
Session 8 - General discussion and workshop summary	Plenary chair – **Robert Mair** • Panel of delegates reflect on the key points from the week. • Panel discussion and Q&A
Session 9 - Future planning and next steps	CPIP – **Prof Rick Geddes**, Cornell University CSIC – **Dr Jennifer Schooling**, University of Cambridge Thanks and Closing – **Prof Tom O'Rourke**, Cornell University

Online program

Plenary presentations in Sessions 1, 2, 3 and 4 (above) were available for online participants to watch live or recorded prior to the following facilitated online breakout sessions.

Monday 11

- Online breakout session 1 – Resilient Infrastructure

Tuesday 12

- Online breakout sessions 2 – Resilient Infrastructure
- Online breakout sessions 3 – Net zero Infrastructure
- Online breakout sessions 4 – Net zero Infrastructure

Wednesday 13 July

- Online breakout sessions 5 – Equity and the Role of Infrastructure
- Online breakout sessions 6 – Equity and the Role of Infrastructure

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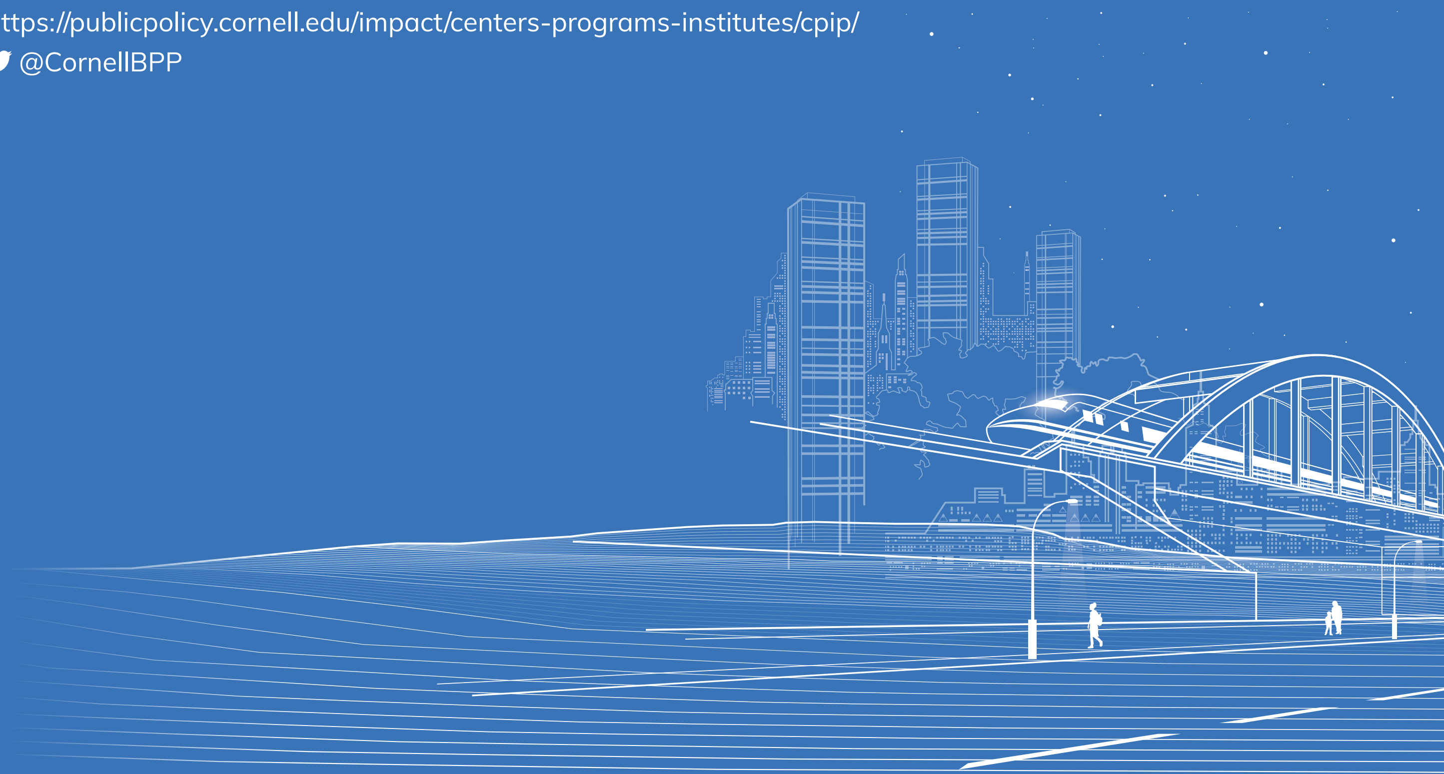

Engineering and Physical Sciences Research Council

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