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ANALYSIS
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Infrastructure for sustainable development

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Infrastructure systems form the backbone of every society, providing essential services that include energy, water, waste management, transport and telecommunications. Infrastructure can also create harmful social and environmental impacts, increase vulnerability to natural disasters and leave an unsustainable burden of debt. Investment in infrastructure is at an all-time high globally, thus an ever-increasing number of decisions are being made now that will lock-in patterns of development for future generations. Although for the most part these investments are motivated by the desire to increase economic productivity and employment, we find that infrastructure either directly or indirectly influences the attainment of all of the Sustainable Development Goals (SDGs), including 72% of the targets. We categorize the positive and negative effects of infrastructure and the interdependencies between infrastructure sectors. To ensure that the right infrastructure is built, policymakers need to establish long-term visions for sustainable national infrastructure systems, informed by the SDGs, and develop adaptable plans that can demonstrably deliver their vision.

From its origins as a specialist term within early twentieth century railway construction, the word 'infrastructure' has broadened to describe the myriad structures that underpin modern society[1]. Although there is no unique definition of infrastructure, common categorizations[2,3] almost always include networked systems that deliver services including energy, water, waste management, transport and telecommunications. Broader definitions also include social infrastructure, such as social protection systems, healthcare systems (including public health), financial and insurance systems, education systems, and law enforcement and justice. All of these are complex socio-technical systems, because they consist of accumulations of physical technology that are embedded within human systems and are operated on behalf of society[4,5]. This interplay between the physical and the social components provides the potential for lock-in, whereby long-lived assets shape future patterns of behaviour and development[6]. For example, construction of highways will affect preferences for modes of transport[7] and lock-in patterns of urban development.

The fact that practically all infrastructure services are delivered by complex socio-technical networks has profound implications. Networks can be characterized by economies of scale: they yield progressively increasing benefits as they get bigger; however, they are costly and risky to initiate. Some infrastructure, such as flood-protection systems, have the characteristics of public goods, because it is hard to exclude people from benefitting from flood protection, and the benefit received by one person does not detract from the benefit received by others. Most infrastructure have the characteristics of merit goods: they are regarded as being desirable by society, but would be underproduced in a free market, and thus require some form of public intervention to provide for the needs of society. In that sense, infrastructure systems have much in common with the SDGs and, therefore, it is not surprising that infrastructure and the SDGs are intimately intertwined in ways that we will elucidate in this Analysis.

Infrastructure provides for and supports vital human capabilities[8]. Most fundamentally, infrastructure provides essential services to people, such as water and energy, and protects them from hazards, such as floods or the pathogens in sewage. Infrastructure also enables people to access other services, such as healthcare and education, and participate in the economy, by accessing markets and travelling to work. Infrastructure provides essential factors of production (energy, water and access to labour markets), whereas unreliable infrastructure systems limit the productivity of businesses and public services[9] and costly infrastructure services add to production costs, undermining business competitiveness. Infrastructure that enables communication (that is, transport and telecommunications) has further diffuse benefits by widening product and labour markets and promoting innovation through the exchange of ideas, which seems to be most productive when large agglomerations of people and businesses are able to co-exist in cities, as a result of infrastructure provision[10,11].

Of course, infrastructure systems do not just have beneficial impacts. The social and environmental impacts of infrastructure can be profoundly harmful—both directly during construction and in more systemic ways, within and beyond the lifetime of assets. The construction of infrastructure displaces people and, although it provides employment, it can expose people to hazardous working conditions. Fossil-fuel power stations are responsible for harmful air quality and greenhouse gas emissions. Construction of transport infrastructure (roads, railways, airports, ports and inland waterways) can destroy and fragment habitats, and provides access that enables the overexploitation of natural resources. On the other hand, infrastructure is essential to minimize the impact of humankind on the environment, in particular enabling concentrations of people to live in cities, by providing wastewater treatment and waste collection, recovery and disposal systems. There is increasing interest in the possibility of substituting 'grey infrastructure' with 'green infrastructure'[12], for example, by using ponds and reed beds to treat sewage[13], wetlands to help recharge groundwater aquifers[14] and afforestation to substitute for flood protection[15].

Infrastructure can also increase vulnerability to natural and human-made hazards—for example, by enabling development in hazardous locations, such as floodplains and mountain sides. Given their central importance to the functioning of economies and

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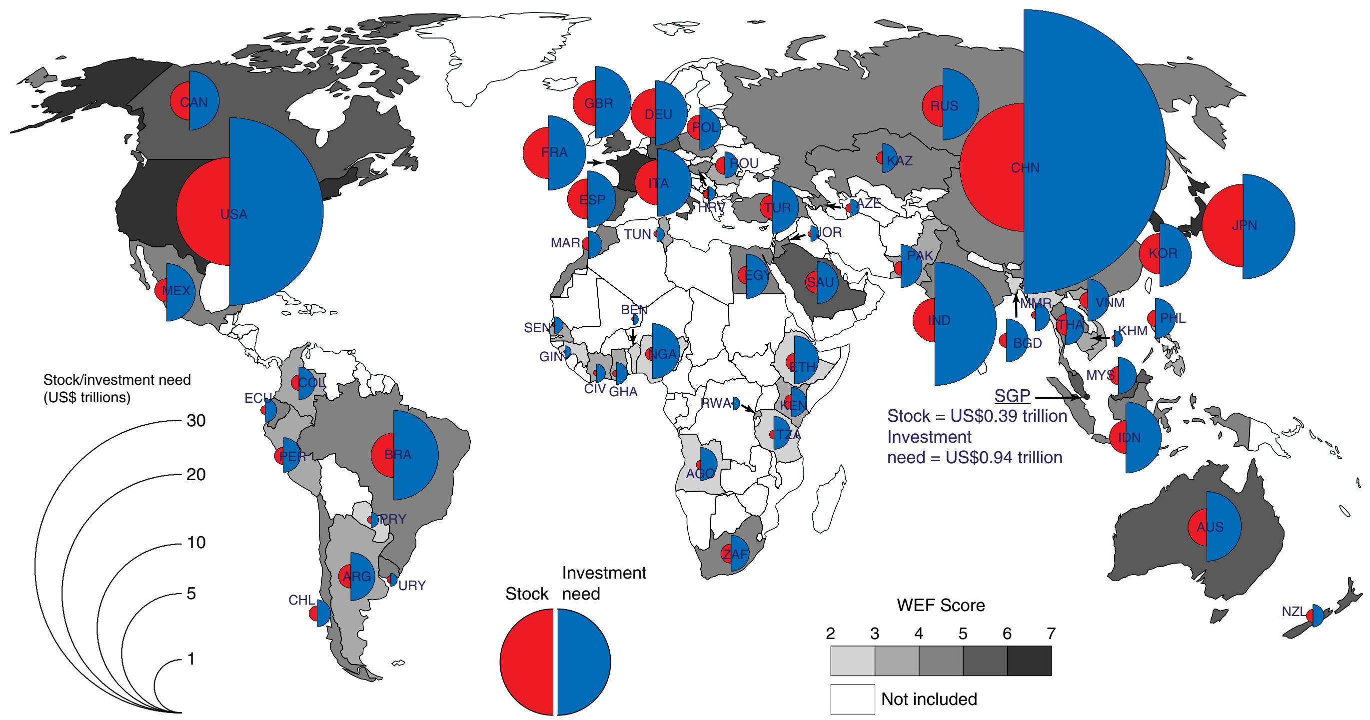

Fig. 1 | Current infrastructure stock and forecast future needs to 2040. Current stock and forecast future investment needs (2016–2040) were obtained from a previous study[19]. Current infrastructure status using the World Economic Forum (WEF) composite infrastructure score was obtained from a previous study[54], with full country names given in Supplementary Table 1.

societies, infrastructure network systems represent particular points of vulnerability to natural hazards and targets for security threats[16]. Dependence on infrastructure is growing rapidly, as a result of the digitization of societies worldwide. Information and communications technologies are now embedded in all other infrastructure sectors, meaning that there are complex interdependencies between sectors with potential for cascading failure[17]. The increasingly ubiquitous dependence on electricity as the main energy vector for modern societies (which is, in part, a consequence of action to mitigate carbon emissions) is also increasing interdependencies. At the same time, technological trends towards decentralization—for example, through the widespread uptake of distributed renewable-energy-generation technologies (photovoltaic panels and wind)—may be enhancing the resilience of infrastructure networks[18]. However, these decentralized technologies are embedded within multiscale coupled socio-technological systems. Physical networks that operate at multiple scales rely on governance systems to establish infrastructure policies and priorities, mobilize finance, and procure, operate and regulate infrastructure networks.

At approximately US$2.3 trillion per year, global capital infrastructure investment is now at an all-time high[19]. One estimate suggests that US$94 trillion of capital investment will be required by 2040 for both new and replacement infrastructure[19] (see Fig. 1 for national-scale forecasts), which is more than the value of the world's existing infrastructure (approximately US$50 trillion)[20]. To cite an example of the scale of developments under way, the China–Pakistan Economic Corridor—which was announced in 2015—involves US$62 billion of Chinese investment, which is more investment in infrastructure than has occurred since the creation of the state of Pakistan. The China–Pakistan Economic Corridor is part of the Belt and Road Initiative[21], which seeks to provide new marine and land connectivity between China and Europe, spanning 65 countries. Infrastructure has emerged as an investment asset category, with private investments in capital infrastructure now amounting to an estimated US$93.3 billion in low- and middle-income countries alone in 2017[22], dwarfing the investment resources of multilateral development banks such as the World Bank (which invests about US$24 billion per year in infrastructure)[23] and national and/or regional investment banks, such as the European Investment Bank (which invests about US$21.5 billion (€19.1 billion) per year in infrastructure)[24].

Notwithstanding the huge sums that are being mobilized for the investment in infrastructure, there is still a shortage of funding for infrastructure that is urgently needed in the poorest parts of the world—for example, to provide basic energy, water and sanitation services. In those places, investors are deterred by weak governance, high political and financial risks, and very limited capacity of people to pay for the services that they desperately need.

The massive investments in infrastructure that are now taking place are being driven by rapid urbanization, population growth and industrialization of developing economies. In most high-income countries, there is a large stock of ageing infrastructure assets that are in need of replacement, rehabilitation or removal, meaning that major investments are needed even in countries with relatively well-developed and mature infrastructure networks. In many instances, these investments are not primarily motivated by sustainability. They are intended to enhance a narrow range of outcomes, often focusing on economic development. Whether that development proves to be sustainable or not depends upon how the huge amount of infrastructure development that will take place in the next few years is planned, implemented and regulated. Investment in unsustainable infrastructure can bequeath future generations with debt. Indebted countries have benefited from debt relief; however, in Africa debt is now creeping up again, in part as a consequence of a plethora of infrastructure investment in some countries[25]. Infrastructure investments also commit future generations to the costs of operation and maintenance, which can consume large proportions of constrained national budgets[26]. Wasteful investment in

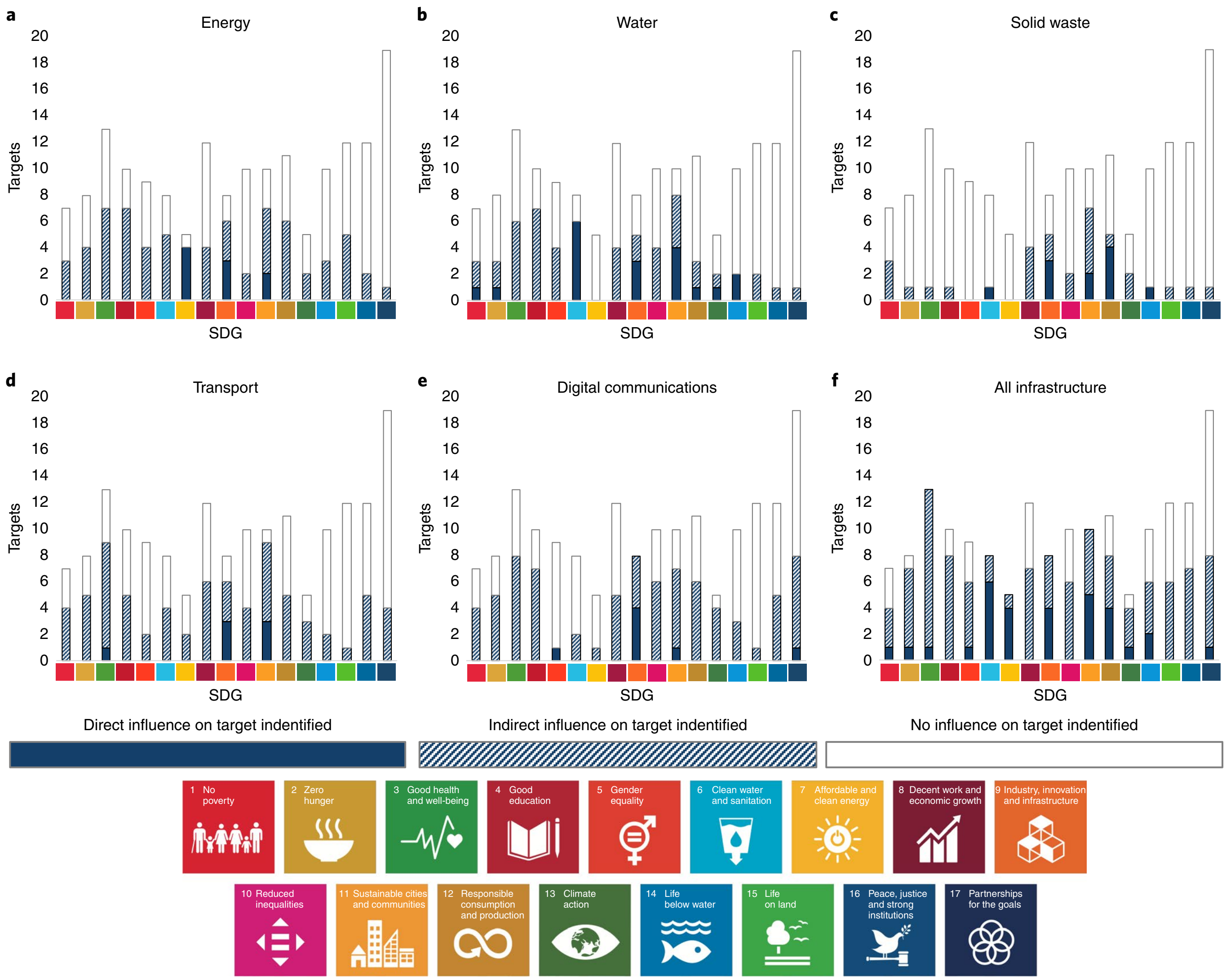

Fig. 2 | The direct and indirect roles of infrastructure in influencing the targets of the SDGs. a–f, Each goal is subdivided according to the number of targets, and each target has been assessed to establish direct or indirect influences from provision of the five categories of infrastructure considered in this analysis: energy (**a**), water (**b**), solid waste (**c**), transport (**d**) and digital communications (**e**) (see Methods). **f**, All infrastructure shows the combined influence on SDGs and targets of the five infrastructure sectors: here a target is included if it can be influenced by one or more of the five infrastructure sectors; in cases in which a target is both directly and indirectly influenced by different infrastructure systems, it is classified as direct.

vanity projects undermines trust in public institutions and public commitment to taxation. Given the potential for lock-in, there is an urgent need to embed the principles of sustainable development in infrastructure decision-making.

Infrastructure and the SDGs

Infrastructure is part of SDG 9 (industry, innovation and infrastructure), but is recognized to have much wider sustainable development benefits[27,28]. Figure 2 presents the results of an analysis (see Methods) in which we estimated the extent to which infrastructure systems influence sustainable development outcomes, as defined by the targets of the SDGs. Infrastructure either directly or indirectly influence all 17 of the SDGs, including 121 of the 169 targets (72%). For 5 of the 17 SDG goals (SDGs 3, 6, 7, 9 and 11), all of the targets are influenced by infrastructure, whereas for 15 of the SDGs more than half of the targets are influenced by infrastructure. The water and energy infrastructure sectors have the largest direct influence on individual SDGs: 6 (clean water and sanitation) and 7 (affordable and clean energy). Water infrastructure includes wastewater and sanitation services, and infrastructure systems to protect against flooding, as well as water supply, and has therefore, overall, the largest direct influence across all SDG targets. Transport infrastructure enables access and participation in society and the economy, and has therefore a wide indirect influence. The increasingly pervasive role of digital communications in enabling delivery of a wide range of services, from hazard warnings to remittance transfers, is demonstrated by this sector having the largest overall influence across the SDGs when indirect effects are taken into account. Across all sectors, there are three times more indirect influences compared to direct influences. Given that in the case of indirect influences the relevant infrastructure sector is not mentioned in the target's description, these policy levers may be overlooked by decision-makers, leading to potentially missed opportunities to realize sustainability-related outcomes.

Although we demonstrate that provision of infrastructure systems and services is fundamental to achieving the SDGs, it is also a potential threat to them. Badly planned infrastructure can have harmful impacts on people's health (SDG 3; for example, through air

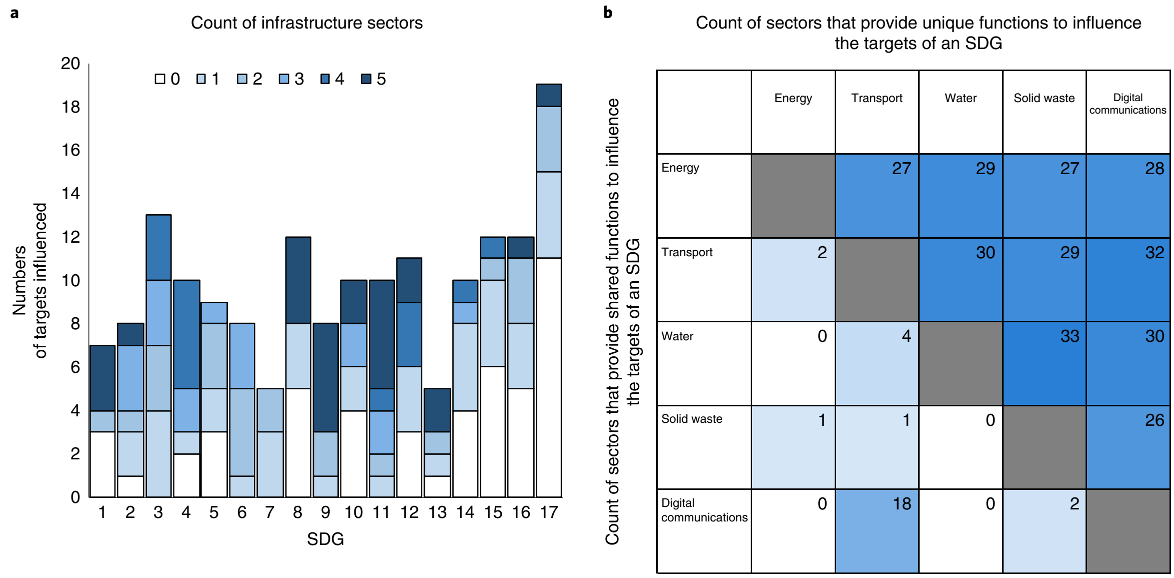

Fig. 3 | SDG infrastructure interdependencies. a, Counts of the number of different infrastructure sectors that influence the SDG targets (where 5 is the maximum) that are identified as being able to influence different targets of the SDGs. **b**, Counts of the number of interdependencies, which are identified when more than one sector can influence a target. Interdependencies are classified as unique when different sectors influence a target in a different way (top right) and shared when different sectors influence a target in the same way (bottom left). See Methods for details.

pollution, water and soil contamination, or disease transmission)[29] and on aquatic and terrestrial ecosystems (SDGs 14 and 15) and destroy culturally important sites (SDG 11). Estimates suggest that there is already enough carbon-emitting infrastructure to exceed the carbon budget agreed in the Paris Agreement (SDG 13) unless that infrastructure is abandoned or repurposed before the end of its life[30]. The allocation and design of infrastructure can exacerbate gender inequality (SDG 5)[31] and inequality more broadly (SDG 10)[32]. In Supplementary Table 2, we itemize how the implementation of infrastructure, without adequate consideration of sustainability, can have harmful impacts on each of the SDGs. However, each of these potential negative impacts is addressed elsewhere within the set of targets. Thus, there is a synergistic feedback mechanism between infrastructure systems and the SDGs, with infrastructure enabling delivery of the SDGs, while the targets provide a framework for guiding and constraining the provision of infrastructure so that it is sustainable.

Infrastructure is increasingly regarded as a 'system-of-systems' in which different infrastructure sectors act in concert to deliver sustainable services[33]. Of the 121 SDG targets that are influenced by infrastructure, 68% are influenced by multiple infrastructure sectors (Fig. 3a). For targets that can be influenced by only one sector, policy interventions can focus on that sector. In cases in which multiple influences exist for the same target, policy options from multiple infrastructure sectors can be considered. We characterize the nature of interdependence between multi-sector influences, based on whether the infrastructure systems each make a unique or shared contribution to the target (see Methods for details). In cases in which each infrastructure sector has a unique functional influence, the combined effect is simply additive, with different infrastructure sectors influencing the target in different ways (Fig. 3b). In several instances, different infrastructure sectors have the same functional influences (Fig. 3b). The target can therefore be influenced by different infrastructure systems in the same way. This overlap provides decision-makers with policy options and scope to add redundancy into the infrastructure system and build systemic resilience. This is the most pronounced for the interdependency between the transport and digital communications sectors, because these sectors provide substitutable access to information and services as a primary function. Decarbonization of the energy sector—which is essential to meet the commitments in the Paris Agreement—has implications for all other sectors, including the transport sector, which presents opportunities for the synergistic use of electric vehicles and renewable energy. This Analysis points to the importance of a programmatic approach to infrastructure planning that recognizes the synergies between infrastructure sectors and manages potentially harmful interdependencies.

Agenda for research

Although the analyses described in this Analysis have identified the existence of potential influences of infrastructure on the SDGs—similar to previous systematic sector-level analyses of the SDGs[34–36]—it has not sought to quantify the scale of influence. It is reasonable to argue that any such analyses would need to be context-specific[37]. The most studied influence has been the relationship between infrastructure and economic growth[38], although even literature on that topic shows quite widely ranging effects. At the same time, there is a growing number of detailed studies (including randomized controlled trials)[39] that document the effects of infrastructure interventions on the well-being of individuals and communities. The message that emerges from the growing evidence base is that how infrastructure is implemented is fundamental to the sustainability outcomes. In the most challenging situations, a single infrastructure intervention will seldom be sufficient to robustly achieve sustainable development outcomes, which need to be achieved through sets of complementary policies[40,41]. Therefore, for example, infrastructure has been cited as one of the means of encouraging the economic and social recovery of deprived post-industrial regions. However, it seems to only yield benefits if accompanied by complementary policies that also seek to address unemployment, education, housing and so on[42]. Overall this points to a major unresolved research question that investigates under what conditions infrastructure contributes to sustainable development, as well as how and for whom.

Researchers who seek to respond to this question face difficult methodological challenges of coping with causality that can work

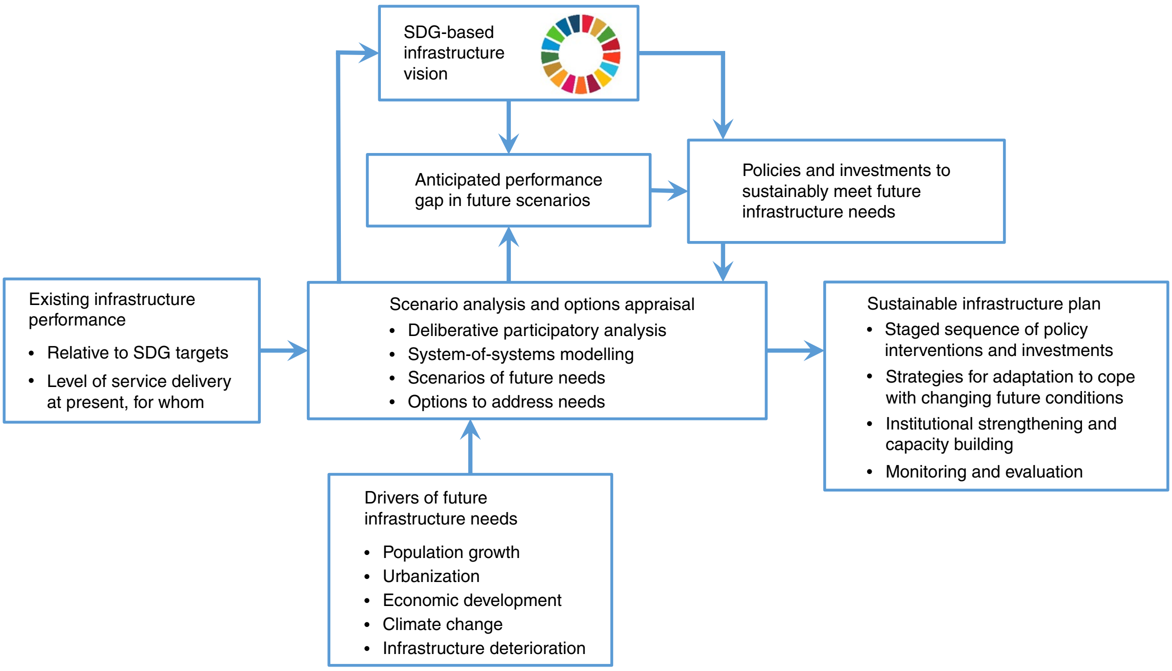

Fig. 4 | Process for infrastructure prioritization to meet the SDGs. Schematic of the components necessary for the strategic development of infrastructure to support achievement of the SDGs.

in both directions (development tends to result in more and better infrastructure being provided, at the same time as infrastructure contributing to sustainable development) and a lack of counterfactuals, as infrastructure projects tend to be large and unique[43]. Targeted studies and rigorous monitoring and evaluation of the role of infrastructure in sustainable development will help to bridge the gap between inputs, outputs and outcomes. Beyond individual influences and outcomes, theoretical and empirical work is required to conceptualize and understand interdependencies between the infrastructure networks addressed in this Analysis, the natural and built environments and society. Strengthening our understanding of the social dimensions of infrastructure will require in-depth analysis of the array of actors and institutions that are involved in the supply of, and demand for, infrastructure services. Incorporating the complex interdependencies between individual components of the systems will allow critical feedback effects and long-term dynamics to be assessed.

Researchers are also confronted with major challenges of obtaining data, although Earth observation, low-cost sensors and crowd sourcing are providing exciting new opportunities for data acquisition. Part of the challenge for researchers has been that data have existed in different silos: asset location and performance data have been the preserve of engineers; economists are more interested in the quantity, quality and affordability of infrastructure services; whereas the project management and finance communities are focused on the costs, delivery and revenues of projects. The standardization of data types and consolidation of datasets will help researchers to examine the sustainability of infrastructure in different contexts and establish whether there are general lessons that are transferrable across contexts. The different academic disciplines that are studying infrastructure also use a diverse array of methodologies and models, from qualitative methods in the social sciences, to econometrics and computer simulations. Better mutual understanding of these methodologies, including their strengths, weaknesses and complementarities, is essential for the development of a more integrative perspective on infrastructure systems and services.

Agenda for practice

The SDGs provide a mandate for integrated infrastructure planning to ensure long-term sustainable development. The SDGs encompass and integrate all of the existing efforts to enhance sustainability, including the Paris Agreement, the Sendai Framework for Disaster Risk Reduction and the New Urban Agenda[44]. Systematic sustainability analyses will enhance the scrutiny of nationally determined contributions and 'long-term low greenhouse gas emission development strategies' under the Paris Agreement, to ensure that the requisite infrastructure investments and policies are in the pipeline and they do not entail unintended impacts. In the context of the Sendai Framework, the SDGs provide an immediately accessible set of priorities and a checklist of impacts to avoid when 'building back better' following natural disasters or destructive conflicts.

Figure 4 provides an overview of a systematic process for the assessment and prioritizaton of the infrastructure systems-of-systems to support the achievement of sustainable development outcomes. At the heart of this is an iterative stakeholder-led process of envisioning the desired future performance of national infrastructure, which should be guided by the SDGs and national and/or subnational development plans. A separate strand at the start of the process begins with assessment of the state and performance of existing infrastructure relative to the SDG targets. The next step is to project infrastructure performance into the future, subject to drivers of future change, which include population growth, urbanization, economic development, climate change, infrastructure deterioration and obsolescence. The process of scenario analysis can be assisted through the use of tools for systems analysis and visualization[45]. Scenario analysis provides projections of the extent to which existing infrastructure networks can meet future aspirations for sustainable performance of infrastructure under a range of possible future conditions. Where gaps in the performance of infrastructure systems are identified, there needs to be a creative stakeholder-led process for identifying policy and investment options. At this point, analysis of interdependencies between infrastructure sectors (see Fig. 3) will help to develop coherent policies and investments that collectively contribute to achieving the SDG targets. This will include policies to stimulate behavioural change related to infrastructure use and operation, as well as investments and other interventions that can increase the capacity for sustainable supply. Action to manage demand—for example, for water and energy—is particularly important in areas in which usage is excessive and inefficient. System-of-systems modelling and simulation can be used to test the performance trade-offs between a range of possible policies and interventions, from sectors that have traditionally been analysed in isolation[45]. Testing 'in silico' allows for a wide range of possible future conditions to be simulated, which enables the identification of solutions that robustly and sustainably meet future needs, under uncertainty. A sustainable infrastructure plan should be presented as a staged sequence of policy interventions and investments, with strategies for adaptation to cope with changing future conditions[46]. Continuous implementation of the process, including updating the data, decisions and knowledge that it integrates, will promote infrastructure development that is adaptive and fit-for-purpose in changing circumstances[47].

One recent instance of this type of analysis was conducted for the Government of Curaçao, which revealed imminent challenges for the reliability of energy supplies, in part driven by a growing tourist industry and increasing use of water desalinization, and the potential contribution that better waste management could contribute to the sustainability of the island[48]. The analysis identified a series of 'quick wins', in particular in demand management, and has helped to coordinate action across government ministries. The study was delivered alongside a programme of training and capacity building, within the government, local university and private sector. Such developments of competency, across all aspects of the infrastructure system, are a necessary requirement to address the highly complex and urgent challenges that decision-makers now face[49].

There are many other successful examples that decision-makers can already draw on—for example, for sustainability accreditation of infrastructure projects[50]. Regulatory reform, with an emphasis on whole-life costs, can encourage practices that make the most of existing assets by maintaining and adapting them. The growing movement for financial reporting of climate risks (including exposure to fossil-fuel liabilities and to physical climate hazards) is providing added impetus to the reporting of infrastructure sustainability[51]. Initiatives such as the Construction Sector Transparency Initiative are helping to curb corruption in infrastructure construction, while citizen's juries such as the French Commission Nationale du Débat Public are enabling well-informed deliberation about contentious infrastructure projects. Enhanced capacity in the planning, procurement and project management of infrastructure systems is necessary to ensure that sustainability is fully embedded in decision-making. In countries from Nigeria to Australia, strategic approaches are being adopted to plan infrastructure for the long term[52]. Datasets and methodologies are emerging to help to navigate trade-offs and enable the participation of the public in complex decisions[53].

The fact that mainstream discourse about infrastructure does not dwell on sustainability is an opportunity as well as a threat. The threat is clear: failure to make the right choices in the coming years about the large amounts of infrastructure development that will take place will lock-in unsustainable patterns of development. Failure to commit to sustainable infrastructure for the poorest will deny billions of people the basic services and human dignity that are targeted by the SDGs. However, by focusing on the sustainability of infrastructure, we have the opportunity to achieve impact across the SDGs at a scale that would otherwise be impossible. The political will that the SDGs are helping to mobilize can be backed up with datasets, tools and methodologies to help to guide infrastructure choices towards sustainability.

Methods

We mapped the influence of five infrastructure systems (energy, transport, digital communications, water and waste management) on the SDGs. This approach differs from previous studies that have mapped the interdependencies between the SDGs[34–37]. We build on this previous work by increasing the breath of infrastructure sectors included within the analysis (by additionally identifying the influences of digital communications and waste management on the targets of the SDGs); and by identifying interdependencies between infrastructure sectors, through their mutual influence on targets and their functional characteristics. Nonetheless, we have drawn on the expert elicitation methodology adopted in previous studies, by adopting an iterative approach to enable categorization of influences, which was subsequently reviewed.

Process for classification. Classification was carried out in two parts. First, the influences of the five infrastructure systems (sectors) were mapped on the 169 SDG targets. Second, the functional interdependency between sectors for the 169 SDG targets was analysed.

Classification of infrastructure influences on the 169 SDG targets.

- Assess for each SDG target the relation to each of the five sectors:
    - Can one or more infrastructure sectors directly influence progress toward the given target (as assessed by the definition of direct influence below)?
        - If 'Yes', classify accordingly for all relevant sectors and proceed to the next target.
        - If 'No', does any published literature provide evidence of indirect influence of any of the sectors on the target (as assessed by the definition of indirect influence below)?
            - If 'Yes', classify accordingly for all relevant sectors and proceed to the next target.
            - If 'No', infrastructure is considered to have no identified influence on the target (see below for the definition). Proceed to the next target.
- Repeat for all 169 targets.
- Proceed to the second part.

Classification of functional interdependency between sectors for the 169 SDG targets.

- Assess for each of the 169 targets:
    - How many sectors can influence progress toward the target?
        - If '0' or '1', there are no functional interdependencies acting within the infrastructure system to achieve the target. Proceed to the next target.
        - If '2' or more, does any pair of sectors perform a substitutable function in relation to achieving the target (see definitions of unique and shared functions below)?
            - If 'No', classify functional interdependency as 'unique'.
            - If 'Yes', classify functional interdependency as 'shared'.
- Repeat for all 169 targets.
- End of classification process.

Definitions of influence. We adopt three categories of influence that infrastructure services can have on SDG goal and target outcomes.

Direct influence on SDG targets. Direct influences on an SDG target include cases in which the SDG target is described directly in terms of the service that an infrastructure system provides. For example, target 7.1 (By 2030, ensure universal access to affordable, reliable and modern energy services) can be directly influenced by the provision of energy infrastructure. For the energy sector, these influences are noted when a direct reference to energy services is made, including related emissions and pollution. The transport sector is considered to directly influence targets related to roads, traffic or related externalities such as air quality. Direct influence of the water (the Integrated Water Resources Management) sector includes targets that address water resources or supply; wastewater-related targets that involve sanitation or hygiene; impacts on marine or coastal areas; or vulnerability to climate-related hazards or extreme events, particularly flooding. Solid-waste infrastructure is linked directly to targets that reference waste generation or management, including consumption and recycling trends, or the pollution of terrestrial or marine environments from debris and dumping. Digital communication involves provision of information and communications technology. Where reference is made to infrastructure systems as a whole, including in relation to buildings such as housing, all sectors are directly implicated.

Indirect influence on SDG targets. Indirect influences on an SDG target include cases in which the SDG target is not described specifically in terms of the service that an infrastructure system provides, but for which published evidence indicates that achievement of the target will be enhanced through the provision of improved infrastructure services. This includes the effect that infrastructure may have on economic development (that is, SDG 8), but excludes the many ways in which economic development may contribute to other targets. It includes areas in which services are primarily delivered by information and communications technologies (for example, hazard warning systems or financial services), but excludes the broader contribution that digital communications infrastructure makes to information sharing and monitoring, which is implicit in all of the SDGs. Additionally, this excludes influences that may arise due to improvements in aspects of the infrastructure sector that do not directly relate to service delivery (for example, influences that result from changes in how the sector is governed), therefore we consider improvements in service delivery only. For example, target 3.9 (By 2030, substantially reduce the number of deaths and illnesses from hazardous chemicals and air, water and soil pollution and contamination) can be indirectly influenced by improved energy, transportation, water and waste services.

No influence on SDG target identified. No influences on the target identified indicates that no direct or indirect influences were identified in the characterization process. For example, target 17.14: Enhance policy coherence for sustainable development, can neither be directly nor indirectly influenced by enhancing the provision of infrastructure services.

The classification reflects the current evidence that is available to support the identification of influences. As such, it is expected that the classification will be updated as more evidence becomes available from the research and practitioner communities.

For targets that relate to inputs (for example, development assistance) rather than outputs (infrastructure assets and systems) or outcomes (provision of infrastructure services), these are similarly classified as being directly, indirectly or not linked to infrastructure.

See Supplementary Table 3 for a justification of our classification of each SDG target.

Definitions of functional interdependency. We adopt two categories of functional interdependency between different infrastructure sectors.

Unique functions. Unique functions were identified where sectors provide individual and independent contributions toward achivement of the target. By influencing the target in different ways, the impacts of each sector toward target progress are additive and non-substitutable. For example, target 4.a (Build and upgrade education facilities that are child, disability and gender sensitive and provide safe, non-violent, inclusive and effective learning environments for all) can benefit from contributions from the energy, water, waste and digital communications sectors, which each provide a unique contribution to improving conditions in schools and other education facilities. However, no function can be substituted by another sector.

Shared functions. Shared functions were identified as cases in which a pair of sectors provided a function that could be substituted in the context of achieving the target. In such a case, both sectors provide a means to achieve progress towards the target through the same functional means. Such overlap provides decision-makers with a choice of how to influence certain targets, with the ability to also add redundancy and build systemic resilience. For example, for target 6.1 (By 2030, achieve universal and equitable access to safe and affordable drinking water for all) the secure provision of safe drinking water can be provided locally through investments in water infrastructure such as water pipes, wells or water-purification technology. However, in particularly arid or rural regions, the delivery of water by means of trucks may be the more feasible option; thus, a reliable road network to access these communities can substitute for physical water infrastructure. The transport and water sectors thus have a shared function in relation to this target.

A definition of infrastructure. Our definition of infrastructure includes physical assets in the five categories of infrastructure as well as the human and governance systems that are necessary to sustainably deliver services from those assets, including various versions of planning and organization. Where grey infrastructure can be substituted with green infrastructure (for example target 6.6: water-related ecosystems), then green infrastructure is also included within our classification. The water sector is defined according to the framework of Integrated Water Resources Management, and therefore including all aspects of the water cycle (that is fresh water, wastewater and flood risk management).

Data availability
The data that support the findings of this study are available within the paper and its Supplementary Information.

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References

1. Carse, A. in *Infrastructures and Social Complexity: A Companion* (eds Harvey, P. et al.) (Routledge, 2016).
2. Pederson, P., Dudenhoeffer, D., Hartley, S. & Permann, M. *Critical Infrastructure Interdependency Modeling: A Survey of US and International Research* (Idaho National Laboratory, 2006).
3. *A National Infrastructure for the 21st Century* (Council for Science and Technology, 2009).
4. Frischmann, B. M. *Infrastructure: The Social Value of Shared Resources* (Oxford Univ. Press, 2012).
5. Allen, S. *Points and Lines: Diagrams and Projects for the City* (Princeton Architectural Press, 1999).
6. Erickson, P., Kartha, S., Lazarus, M. & Tempest, K. Assessing carbon lock-in. *Environ. Res. Lett.* **10**, 084023 (2015).
7. Weinberger, R. & Goetzke, F. Unpacking preference: how previous experience affects auto ownership in the United States. *Urban Stud.* **47**, 2111–2128 (2010).
8. Clark, S. S., Seager, T. P. & Chester, M. V. A capabilities approach to the prioritization of critical infrastructure. *Environ. Syst. Decis.* **38**, 339–352 (2018).
9. Steinbuks, J. & Foster, V. When do firms generate? Evidence on in-house electricity supply in Africa. *Energy Econ.* **32**, 505–514 (2010).
10. Fischer, M. M. *Innovation, Networks, and Knowledge Spillovers, Selected Essays* (Springer, 2006).
11. Fujita, M., Krugman, P. R. & Venables A. J. *The Spatial Economy: Cities, Regions, and International Trade* (MIT press, 2001).
12. *The Sustainable Infrastructure Imperative: Financing for Better Growth and Development. The 2016 New Climate Economy Report* (The Global Commission on the Economy and Climate, 2016).
13. Scholz, M. & Lee, B. H. Constructed wetlands: a review. *Int. J. Environ. Stud.* **62**, 421–447 (2005).
14. van der Kamp, G. & Hayashi, M. The groundwater recharge function of small wetlands in the semi-arid Northern Prairies. *Great Plains Res.* **8**, 39–56 (1998).
15. Dadson, S. J. et al. A restatement of the natural science evidence concerning catchment-based 'natural' flood management in the UK. *Proc. R. Soc. A* **473**, 20160706 (2017).
16. Lewis, T. G. *Critical Infrastructure Protection in Homeland Security: Defending a Networked Nation* (Wiley, 2006).
17. Rinaldi, S. M., Peerenboom, J. P. & Kelly, T. K. Identifying, understanding, and analyzing critical infrastructure interdependencies. *IEEE Contr. Syst. Mag.* **21**, 11–25 (2001).
18. Bollinger, L. & Dijkema, G. Evaluating infrastructure resilience to extreme weather – the case of the Dutch electricity transmission network. *Eur. J. Transp. Infrastruct. Res.* **16**, 214–239 (2016).
19. *Global Infrastructure Outlook: 2017* (Global Infrastructure Hub, 2017).
20. Bhattacharya, A. et al. *Delivering on Sustainable Infrastructure for Better Development and Better Climate* (Brookings Institution, 2016).
21. Ascensão, F. et al. Environmental challenges for the Belt and Road Initiative. *Nat. Sustain.* **1**, 206–209 (2018).
22. *Private Participation in Infrastructure (PPI) Annual Report: 2017* (The World Bank, 2017).
23. *World Bank Press Release 2015/041/EAP* (The World Bank, 2014).
24. *Better Infrastructure, Better Economy* (European Investment Bank, 2017).
25. *African Economic Outlook: 2018* (African Development Bank, 2018).
26. Adam, M. C. & Bevan M. D. *Public Investment, Public Finance, and Growth: The Impact of Distortionary Taxation, Recurrent Costs, and Incomplete Appropriability* (International Monetary Fund, 2014).
27. *Inclusive Green Growth: The Pathway to Sustainable Development* (The World Bank, 2012).
28. *Connecting People, Creating Wealth: Infrastructure for Economic Development and Poverty Reduction* (Department for International Development, 2013).
29. Ruan, Z., Wang, C., Ming Hui, P. & Liu, Z. Integrated travel network model for studying epidemics: interplay between journeys and epidemic. *Sci. Rep.* **5**, 11401 (2015).
30. Pfeiffer, A., Hepburn, C., Vogt-Schilb, A. & Caldecott, B. Committed emissions from existing and planned power plants and asset stranding required to meet the Paris Agreement. *Environ. Res. Lett.* **13**, 054019 (2018).
31. Gaynor, C. & Jennings, M. *Gender, Poverty and Public Private Partnerships In Infrastructure, (PPPI).* Annex on Gender and Infrastructure (The World Bank, 2004).
32. Bajar, S. & Rajeev, M. The impact of infrastructure provisioning on inequality in India: does the level of development matter? *J. Comp. Asian Dev.* **15**, 122–155 (2016).
33. Hall, J. W., Nicholls, R. J., Tran, M. & Hickford, A. J. *The Future of National Infrastructure: A System Of Systems Approach* (Cambridge Univ. Press, 2016).
34. Fuso Nerini, F. et al. Mapping synergies and trade-offs between energy and the Sustainable Development Goals. *Nat. Energy* **3**, 10–15 (2018).

35. Bhaduri, A. et al. Achieving sustainable development goals from a water perspective. *Front. Environ. Sci.* **4**, 64 (2016).
36. *Transport and Sustainable Development Goals* Transport and Communications Bulletin for Asia and the Pacific No. 87 (United Nations Economic and Social Commission for Asia and the Pacific, 2017).
37. Weitz, N., Carlsen, H., Nilsson, M. & Skånberg, K. Towards systemic and contextual priority setting for implementing the 2030 agenda. *Sustain. Sci.* **13**, 531–548 (2018).
38. Straub, S. *Infrastructure and Development: A Critical Appraisal of the Macro Level Literature* (The World Bank, 2008).
39. Lee, K., Miguel, E. & Wolfram, C. Appliance ownership and aspirations among electric grid and home solar households in rural Kenya. *Am. Econ. Rev.* **106**, 89–94 (2016).
40. Banister, D. & Berechman, Y. Transport investment and the promotion of economic growth. *J. Transp. Geogr.* **9**, 209–218 (2001).
41. Duranton, G. & Venables, A. J. *Place-based Policies for Development* World Bank Policy Research Working Paper 8410 (The World Bank, 2018).
42. Mathur, V. K. Human capital-based strategy for regional economic development. *Econ. Dev. Q.* **13**, 203–216 (1999).
43. Venables, A. J., Laird, J. & Overman, H. *Transport Investment and Economic Performance: Implications for Project Appraisal* (Department for Transport, 2014).
44. *New Urban Agenda A/RES/71/256* (United Nations, 2017).
45. Hall, J. W. et al. Strategic analysis of the future of national infrastructure. *Proc. Inst. Civ. Eng. Civ. Eng.* **170**, 39–47 (2017).
46. Otto, A. et al. A quantified system-of-systems modeling framework for robust national infrastructure planning. *IEEE Syst. J.* **10**, 385–396 (2016).
47. Allenby, B. & Chester, M. V. Reconceptualizing infrastructure in the Anthropocene. *Issues Sci. Technol.* **34**, 3 (2018).
48. Adshead, D. et al. *Evidence-based Infrastructure: Curaçao National Infrastructure Systems Modelling to Support Sustainable and Resilient Infrastructure Development* (United Nations Office for Project Services, 2018).
49. Chester, M. V. & Allenby, B. Toward adaptive infrastructure: flexibility and agility in a non-stationarity age. *Sustain. Resilient Infrastruct.* https://doi.org/10.1080/23789689.2017.1416846 (2018).
50. Siew, Y. J. R., Balatbat, M. C. A. & Carmichael, D. G. A review of building/infrastructure sustainability reporting tools (SRTs). *Smart Sustain. Built Environ.* **2**, 106–139 (2013).
51. *Final Report: Recommendations of the Task Force on Climate-Related Financial Disclosures* (Task Force on Climate-Related Financial Disclosures, 2017).
52. *Strategic Infrastructure Planning: International Best Practice* (OECD, 2017).
53. *How to Design an Infrastructure Strategy for the UK* (Institute for Government, 2017).
54. *The Global Competitiveness Report 2017–2018* (World Economic Forum, 2017).

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Author contributions
S.T. designed the study. D.A., S.T. and J.W.H. performed most of the analyses. J.W.H., S.T. and D.A. wrote most of the manuscript. All authors contributed to the development of the manuscript through methodological advice, analysis, comments and edits to the text and figures.

Competing interests
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