1. Introduction

Over the next decade, around $90 trillion will need to be spent on sustainable infrastructure assets globally (Bhattacharya 2015). By 2050, urban areas, where much of the world's infrastructure is concentrated, are estimated to expand by two-and-a-half times (Ramaswami 2016). As demand for infrastructure services increases amid pressures from demographic trends, urbanisation, economic growth and climate change, infrastructure systems must evolve and adapt to meet these needs effectively, efficiently and sustainably. The concept of sustainability is generally considered and assessed in terms of trade-offs between a set of core dimensions, or pillars, including: *economic* (generating a net positive economic return); *social* (contributing to enhanced livelihoods and social well-being); and *environmental* (preserving, restoring and integrating the natural environment while ensuring resilience to climate risks) (IADB 2018). Drawing on the Brundtland (1987) definition of sustainable development, infrastructure systems should thus be designed to meet both present and future needs, ensuring sustainability across each of these domains over the entire life cycle of the projects.

Major infrastructure decisions have largely centred on the economic perspective, with a large focus on cost benefit analysis which monetises inputs and outputs (e.g. European Union 2015). However, this approach may not accurately represent the range of benefits valued or desired by infrastructure users. In the United Kingdom, infrastructure performance indicators have been criticised for not adequately incorporating the wider context of societal, environmental and economic needs (ICIF 2015). The UK Institute for Government suggests that multi-criteria analysis may prove more effective than traditional cost-benefit analysis in the valuation and appraisal of infrastructure, particularly where the monetisation of impacts – such as health, safety and environmental – lead to inconsistency in project assessment (Atkins et al. 2017). Recent assessments have aimed to broaden indicator selection to capture a wider range of attributes considered by infrastructure decision-makers (e.g. Covec & Beca 2013). While these multi-attribute infrastructure performance metrics have been applied cross-sectorally to a limited extent (Hall et al. 2016; Young & Hall 2015), the scope of such assessments has generally been confined to a single sector or infrastructure type (e.g. Zegras 2006; Jeon et al. 2013; Pakzad & Osmond 2016).

Within the energy sector, the challenge of multi-objective decision-making has been defined around trade-offs between energy security, universal access to affordable energy services, and environmentally sensitive production and use of energy – the so-called "trilemma" (World Energy Council 2017). This concept represents a restructuring of the traditional cost-benefit analysis, and suggests that delivering on each of these dimensions entails complex links between private and public actors, governments, regulators and other economic, social and environmental factors, with implications for policy coherence and integrated policy innovation. Although the three pillars of sustainability are reflected in the trilemma, the core ideas underlying these concepts are not interchangeable. For instance, security of supply in the context of infrastructure provision does not contribute exclusively to the development of social well-being – it also allows firms to benefit from reliable infrastructure services required to ensure economic growth. Beyond energy, similar sets of trade-offs between attributes of infrastructure performance extend across the wider infrastructure system: the trilemma concept has provided a suitable structure for the assessment of infrastructure challenges in the transport (Bryce et al. 2014) and water (Ives et al. 2018) sectors.

The 2030 Agenda for Sustainable Development, which represents a shared commitment by UN member states to address development challenges in the national context, provides another means of conceptualising sustainability objectives related to infrastructure that does not attempt to replicate the traditional cost-benefit analysis package. Across the Agenda's 17 Sustainable Development Goals (SDGs), the three pillars of sustainability and dimensions of the trilemma are echoed throughout 169 cross-cutting development targets. Such a framework exposes a new set of trade-offs with regard to infrastructure decision-making: between progress within larger thematic areas of global development, each requiring some degree of contribution from one or more infrastructure sectors.

The projected influx of investment in infrastructure has large potential to embrace these targets, with approximately half of SDG financing needs for lower- and lower-middle income countries estimated to originate from investments in sustainable infrastructure (Franks et al. 2018). The 'big five' networked infrastructure sectors of energy, transport, water (including wastewater and flood protection), solid waste and digital communications, are estimated to directly or indirectly influence on 72% of SDG targets (Thacker et al. 2019). This influence increases with the inclusion of non-networked infrastructure such as schools, hospitals and community centres (Thacker et al. 2018).

The SDGs are now widely recognised as a framework to shape sustainability initiatives within governments and NGOs (UNDP 2016; OECD 2017; Prakash et al. 2017). Similarly, sustainability reporting is increasingly integrated into projects or business strategies through initiatives targeting specific SDGs in line with a long-term vision (e.g. Busco et al. 2017). The universal recognition of the Agenda has brought about efforts to operationalise the SDGs at the global, regional, national and sub-national level through the development of scientifically robust, data-driven measurement and tracking tools (Schmidt-Traub et al. 2017) and the identification of gaps in indicator availability and coverage (Cassidy 2014; OECD 2017). In the infrastructure context, the 2030 Agenda provides a useful framework for informed decision-making, planning and implementation. In order to successfully implement large-scale investments and policy, infrastructure planners require a means of measuring the potential impact of these decisions on long-term objectives, with applicability to a range of international contexts and development challenges.

This proposed assessment of infrastructure performance in terms of SDG achievement builds on previous studies exploring the 'nexus' perspective on sustainable development pathways to facilitate integrated policymaking (Weitz et al. 2014; van Vuuren et al. 2015), including the inter-connectedness of targets within the 2030 Agenda. This literature has outlined extensive networks of links between targets (Le Blanc 2015; Zhou & Moinuddin 2017) which provide a comprehensive understanding of SDG interactions in terms of synergies and trade-offs in target achievement (Nilsson et al. 2016). At a more granular level, analysis of these interactions suggest inextricability between pairs of development targets (Weitz et al. 2018). This integrated thinking around the development agenda provides a means of operationalising the SDG framework as a decision-making tool to prioritise effective actions by capturing the diverse range of impacts of infrastructure policies or investments across development objectives. In particular, it allows decision-makers to navigate the breadth of solutions made possible by infrastructure and to aim for balanced sustainability outcomes in the context of an uncertain future.

Taking this further, a handful of studies have catalogued the extensive links between a single infrastructure sector – e.g. energy, water, or transport systems – and the range of SDG targets (Fuso Nerini et al. 2018; Bhaduri et al. 2016; UNESCAP 2017). These findings have particular relevance for actors or policymakers working toward achievement of a specific SDG – for example, the water (SDG 6) or energy (SDG 7) goals. Other studies demonstrate the potential broader SDG influence of interventions in a particular area, such as education (Vladimirova & Le Blanc 2016) and health and wellbeing (Nunes et al. 2016), or at the level of individual programmes or projects such as climate action (UNDP 2016) or large infrastructure initiatives such as China's Belt and Road programme (Hong 2016).

Yet, the contribution of these 'nexus'-based approaches to sustainable infrastructure in the context of the SDGs is limited to understanding the web of wider potential impacts – positive or negative – of a project, policy or investment beyond the primary objective of the intervention. Effective national infrastructure planning toward a development 'vision' requires that national development objectives be defined at the outset of the planning process and used to inform long-term and prioritised infrastructure implementation. To provide this capability, a means of quantifying and comparing the relative performance, in sustainability terms, of sets of possible investment and policy options across sectors is required, incorporating the interdependencies between them. In this context, a sustainability metric for cross-sectoral infrastructure aligned with the Sustainable Development Goals is proposed.

Attempts to identify infrastructure-related metrics to evaluate international development objectives precede the current 2030 Agenda (e.g. Cheng et al. 2012). However, performance assessment of integrated infrastructure systems in terms of wider implications for sustainable development has been limited. A recent study integrating existing UK indicators with the SDG framework aimed to identify infrastructure performance indicators that are relevant to measuring SDG progress in the United Kingdom (Masterton et al. 2017). While this provided insight into infrastructure's role in contributing to national wellbeing in the UK context, the study looked only at historical SDG progress linked to infrastructure and does not provide a basis for future strategic infrastructure planning. Additionally, a more generalizable indicator framework derived directly from SDG targets would address a wider range of international development challenges shown to be influenced by cross-sectoral infrastructure.

Systematic assessment of national infrastructure performance grounded in a vision for SDGs builds on a process developed by Hall et al. (2017) for the United Kingdom and subsequently applied to international contexts by Ives et al. (2019) and Adshead et al. (2018). Such a process outlines a strategic infrastructure planning capability designed to facilitate a systematic estimation of infrastructure needs and a means of meeting them over the long-term. This process includes an estimation of current infrastructure performance, projections of future needs, and the provision of infrastructure strategies allowing decision-makers to respond to these needs. Although the plausible combinations of infrastructure investments and policies are vast, past assessments have focused on a concise set of these strategies to illustrate diverse and distinct visions of national infrastructure provision (Hickford et al. 2014). As proposed by Hall et al. (2017), these strategies may be programmed as pre-determined lists of investments or policy interventions in infrastructure; sets of rules that determine these implementation decisions subject to given criteria; or as means of optimising given outcomes subject to constraints.

The following sections outline the proposed methodology and demonstrate its application to the context of Curaçao, a small island country with a particular set of development challenges. First, SDG targets linked to the provision of infrastructure services are identified. Next, a set of infrastructure-based indicators are developed and assigned to the selected targets to account for each of its components. Within each target, a quantified performance level is set for each relevant indicator, designating achievement of the target in the given country or context. Using infrastructure investment and policy options available to the country, a portfolio of interventions is designed which represents a strategy for meeting long-term SDG achievement for the selected targets. The SDG performance of this strategy is evaluated through national infrastructure systems modelling by calculating progress toward SDG target achievement for all infrastructure-linked targets, and can be represented individually or on aggregate. The implications for strategic infrastructure planning in the context of future uncertainty is discussed.

2. Methods

This paper incorporates three main contributions to national infrastructure assessment: (a) the methodological development of performance metrics for infrastructure which enable the tracking of SDG targets linked directly to the provision of infrastructure services; (b) the integration of these metrics into an infrastructure system modelling framework; and (c) an application of this assessment to assist infrastructure policy and planning in a nation state. Together, this provides a novel and useful tool for decision-makers to select and implement infrastructure investments and policies of appropriate scope to deliver on national development objectives.

Figure 1 conceptualises the interaction between interdependent infrastructure system function and wide-ranging progress across the SDGs. This interaction is influenced both by exogenous *scenarios* of future demand drivers (such as population, economic and climate drivers) used to explore uncertainty in a range of possible futures, and *strategies* of infrastructure investments, regulatory or policy interventions that decision-makers may implement to modify demand for, or provision of, infrastructure services (Hickford et al. 2014; Hall et al. 2017). The metrics that emerge from this modelling capability provide the basis for choosing between alternate strategies.

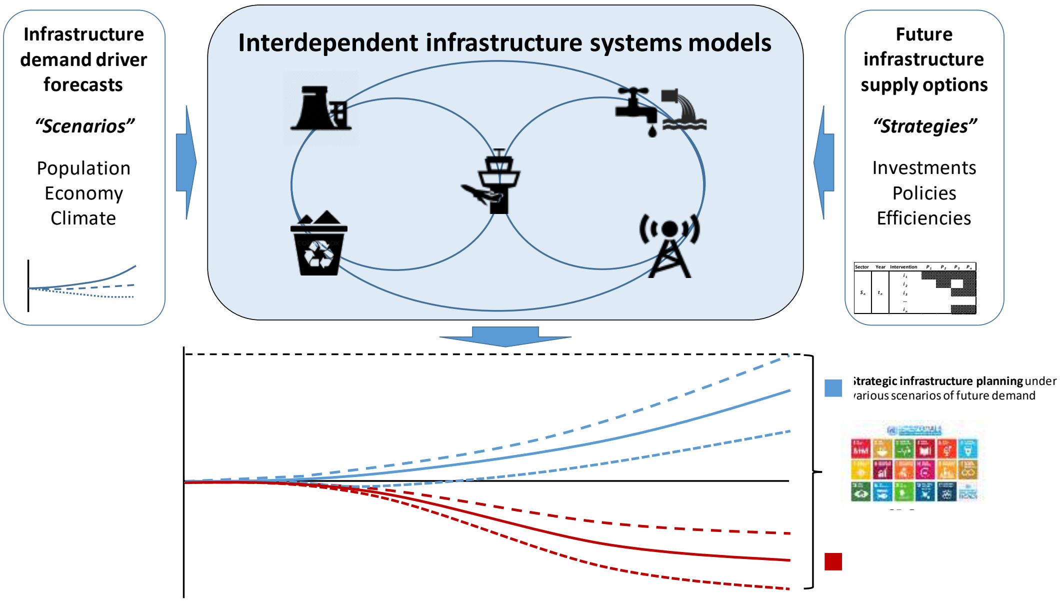


Figure 1: Infrastructure-driven SDG performance at the national level

2.1 Targeting SDGs with strong links to the provision of infrastructure services

Of the 169 SDG targets, approximately 72% can be directly or indirectly influenced by the provision of infrastructure (Figure 2); we focus this analysis on those with a direct influence. As defined by Thacker et al. (2019), a direct influence is one in which "the SDG target is described directly in terms of the service that an infrastructure provides"; this allows us to define target progress concretely in terms of how much infrastructure is being provided in relation to needs. Across 12 SDGs, 31 targets fit these criteria, of which 22 can be directly influenced by a single infrastructure sector: energy (4 targets), water (3 targets), wastewater (2 targets), solid waste (3 targets), digital communications (3 targets), transport (2 targets), and flood risk management (5 targets). A further 9 targets are influenced by a combination of two or more infrastructure sectors, either independently or as part of an interdependent system.

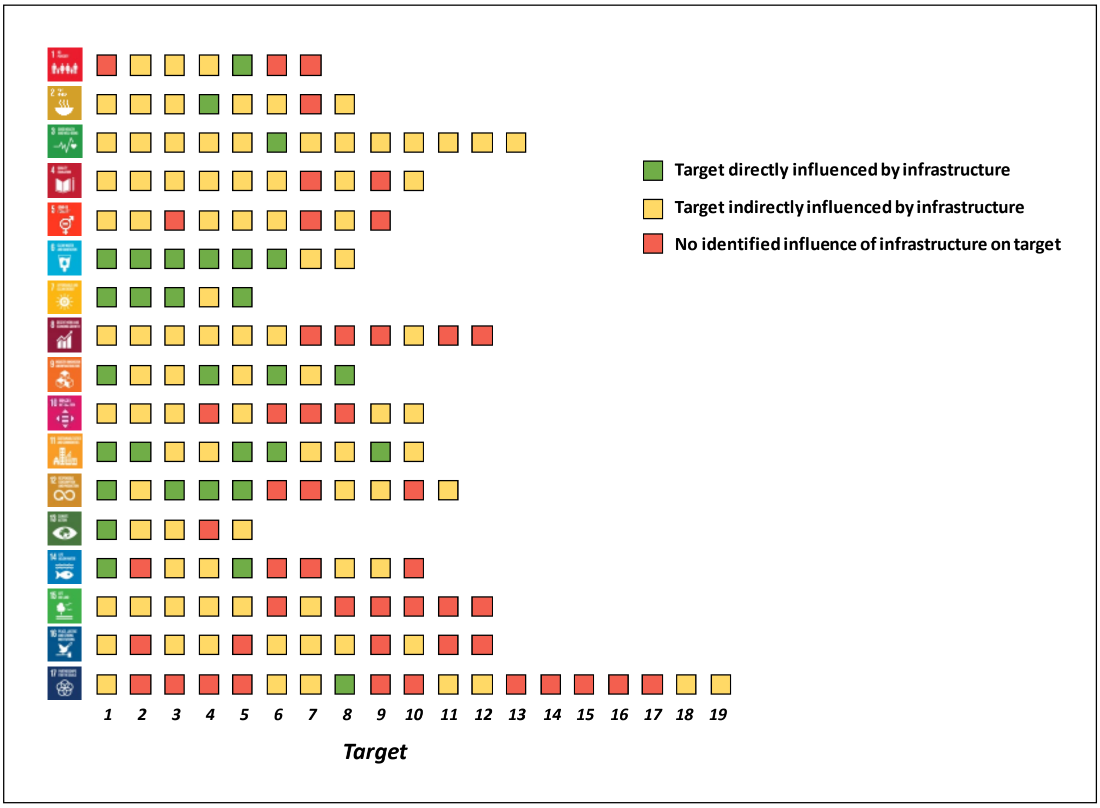


Figure 2: Direct and indirect influence of infrastructure on 169 SDG targets (adapted from Thacker et al. 2019)

2.2 Identifying attributes of infrastructure in the context of SDG targets

In the context of the pillars of sustainability, and given the decision-making challenges inherent in the related trilemma concept, assigning indicators to assess infrastructure’s contribution toward fulfilment of a given SDG target requires the consideration of multiple sustainability dimensions within each thematic area. The relative importance of each dimension, however, is not explicitly defined within the SDG framework and will ultimately depend on the national or regional context. Similarly, the contribution of a single infrastructure sector toward target progress is seldom precise, particularly in relation to SDGs with broad infrastructure system requirements. Nevertheless, by scrutinising the (often) qualitatively-delineated targets identified in the previous section, we can arrive at a flexible indicator framework that incorporates a comprehensive treatment of infrastructure performance aspects.

Within each thematic area of the SDGs, certain targets maintain a focus on a single dimension of sustainability and can thus be measured or proxied by a single metric for each relevant sector. These one-dimensional metrics assess target achievement in terms of one of the following a) provision of a required quantity of the infrastructure service; b) environmentally sustainable delivery of the infrastructure service, with no stipulation as to whether all needs are met; or c) the affordability and accessibility of the infrastructure service to those who depend on it. For example, target 7.2 *("By 2030, increase substantially the share of renewable energy in the global energy mix")* addresses solely the environmental dimension of sustainability within the energy sector. Conversely, target 6.1 *("By 2030, achieve universal and equitable access to safe and affordable drinking water for all")* specifies a need for at least two metrics within the water sector, covering both adequate provision of the service and its affordability. Target 11.2 *("By 2030, provide access to safe, affordable, accessible and sustainable transport systems for all, improving road safety, notably by expanding public transport, with special attention to the needs of those in vulnerable situations, women, children, persons with disabilities and older persons")* incorporates all three sustainability dimensions; the target outcome cannot be evaluated without assessing the affordability, environmental impact and level of service provision within the transport sector. The distribution of these dimensions across each of the 31 targets identified as being directly linked to infrastructure is shown in Figure 3.

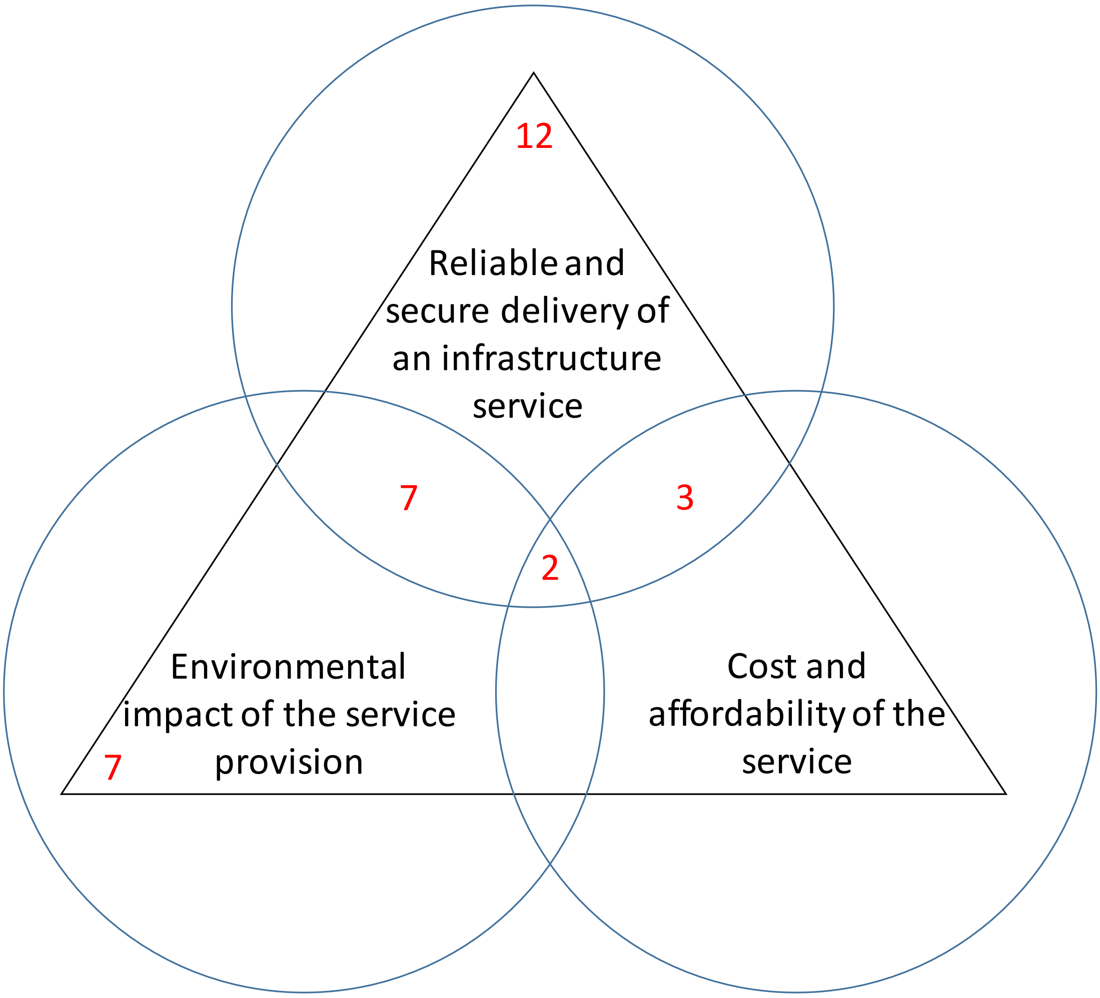


Figure 3: Distribution of SDG sustainability dimensions for 31 infrastructure-linked targets, highlighting trade-offs of infrastructure provision in the context of the trilemma concept.

Constructing indicators for infrastructure performance in sustainable development terms similarly requires consideration of the number of infrastructure sectors that may contribute toward SDG target progress. Some targets focus exclusively on a single sector, for example 5.b (*"Enhance the use of enabling technology, in particular* *information and communications technology, to promote the empowerment of women"*), in which case the performance of the digital communications sector alone is assessed. Targets may also incorporate individual or interdependent contributions from multiple sectors, as in 6.2 (*"By 2030, achieve access to adequate and equitable sanitation and hygiene for all and end open defecation, paying special attention to the needs of women and girls and those in vulnerable situations"*) in which both water and wastewater systems must perform at an adequate level for target achievement. Finally, SDG targets may refer to system-wide infrastructure without specifying the contribution of particular sectors, e.g. 9.1 *("Develop quality, reliable, sustainable and resilient infrastructure, including regional and transborder infrastructure, to support economic development and human well-being, with a focus on affordable and equitable access for all")*, resulting in some vagueness as to which sectors should be included in an appropriate indicator. Given this complex relationship between interventions in a particular infrastructure sector and potential development outcomes within a given SDG target, decision-makers require a systematic approach to indicator design in order to provide a suitable assessment of infrastructure performance.

A multi-attribute approach to the valuation of infrastructure (see French et al. 2009) in relation to its SDG target contributions provides a means of systematically addressing the multiple objectives embedded in the SDGs and targets. The SDG targets provide an extensive list of sustainability attributes valued by policy-makers around the world, with a subset of these able to be directly addressed through the provision of infrastructure. These attributes can be clustered by infrastructure sectors, which define similar types of actions required to achieve them, namely, investment and policy and regulatory decisions made by governments, utilities and regulators. Given the value assigned to each attribute, this allows decision-makers to assess the scope of interventions required in a particular sector to achieve the desired objectives – the affordability of a service, reliability of service provision, the environmental sustainability of a system, and so on.

However, in each context, the unique value of these sustainability attributes, and their relative importance to national development objectives, must be ascertained. Indicators that provide a direct or proxied measure of the consequences of infrastructure allow us to assess the degree to which sustainability objectives are, or need to be, satisfied. Decision-makers within the national context are ultimately best-placed to determine priorities for development, and to apply appropriate weighting to the clusters of attributes or required actions by sector. The following notation provides a framework to structure this approach.

2.3 Deriving a sustainability metric for infrastructure

From the full range of 169 SDG targets, a subset are directly influenced by infrastructure, given by:

$$Z = \{z_1, z_2, \ldots, z_m\}$$

The set of all potential indicators considered by the decision maker across sectors is given as:

$$I = \{i_1, i_2, \ldots, i_n\}$$

Each of these indicators can be correspondingly given a value or measurement, denoted by:

$$C = \{c_1, c_2, \ldots, c_n\}$$

Each infrastructure-linked SDG target, z_j, is assessed using a subset of one or more indictors across sustainability dimensions and sectors. Based on the description of each SDG target, a set of indicators is selected to assess progress toward the target:

$$I_j = \{i_1, i_2, \ldots, i_y\}, \qquad where\ I_j \subseteq I$$

The indicator subset I_j is assigned a set of weights according to perceived importance of each indicator *k* to target achievement in the national context:

$$W_j = \{w_{j1}, w_{j2}, \ldots, w_{jy}\}, \qquad where \sum_{k=1}^{y} w_{jk} = 1$$

In a given application, the assignment and weighting of indicators are achieved through a set of steps roughly conforming to the stakeholder elicitation process for multi-criteria analysis established in previous studies (e.g. Gamper & Turcanu 2007; Grafakos et al. 2010). First, stakeholders are presented with the decision context and alternatives to be assessed, i.e. the set of SDG targets that can be influenced by national infrastructure investments or policies. Second, the evaluation criteria is elaborated in terms of the set of available indicators to measure progress toward these targets. Third, stakeholders are asked to consider the potential impact of all evaluation criteria toward the SDG targets, resulting in the assignment of indictors to each target. Fourth, stakeholder preferences are elicited to determine the relative importance of each to measuring progress on a given target. This may be achieved in the first case through the ranking of assigned indicators, and subsequently, through subjective agreement on a weight value for each. Finally, these indicator preferences are aggregated for each SDG target according to an additive rule as outlined above.

For targets assessed using multiple indicators, this linear weighting approach relies on additive aggregation of decision criteria. It allows for the elicitation of preferences among decision-makers with regard to the importance of various factors in tracking the requirements for achieving SDG targets in different national contexts. A limitation of this approach is the compensatory nature of linear weighting such that poorly-performing indicators can be outweighed by strongly-performing ones. A provisional solution to this problem is introduced later in the notation by applying a limit to indicator contributions for any given target. Another potential weakness involves the subjectivity inherent in decision-makers' judgment with regard to assigning weight values. However, given the qualitative nature of most SDG targets, these expert judgments are often the only means of establishing and assessing the balance of indicators necessary to quantify nationally-defined SDG performance.

2.4 Quantifying levels of target achievement

Infrastructure system performance is interpreted nationally in that levels required to achieve SDG targets vary according to the development priorities of a country or region. Highly urbanised regions may require a larger proportion of the population to be served by public transport infrastructure in order to achieve sustainable cities. Similarly, a country with particularly sensitive marine or terrestrial habitats may require a higher level of efficiency in the water and wastewater sectors to fulfil related SDG targets.

The ability of existing global SDG assessments to provide clear and consistent measurement of a country's sustainability performance using indicators as policy support instruments has been met with scepticism. Due to the lack of consistency between countries' national indicator frameworks, such assessments are at risk of providing ambiguous and confusing assessments (Janoušková et al. 2018). In focusing specifically on infrastructure-related indicators, we provide a flexible and transferrable assessment framework by drawing on established indicator sets and metrics that provide a direct measure of progress for a subset of SDG targets.

To operationalise infrastructure assessment in the SDG context, our indicator set requires a baseline against which to measure current and future infrastructure performance. This takes the form of desired "performance levels", denoting requirements for target achievement, which are a function of the specific SDG target (z_j) and its set of relevant indicators (I_j). In assigning these desired performance levels, stakeholders tasked with national interpretation of SDG performance should be asked to consider the indicator values at which the components of the SDG target being assessed are considered completely achieved, reflecting national interpretation of the SDG targets in terms of a country's circumstances or capabilities. The performance of indicator i_k is represented as a fraction f_{jk} of its measured value over the desired performance level, where, for $f_{jk} < 1$, f represents the degree of non-performance relative to the desired performance.

$$f_{jk} = \frac{c_k}{p_{jk}}$$

As each SDG target can only be considered *achieved* once each indicator assigned to it reaches its respective desired value, f_{jk} is bounded at 1 to avoid over-performance of one indicator compensating for under-performance of another.

2.5 Using SDG indicator assessment to inform long-term infrastructure planning

The definition and assignment of performance levels related to infrastructure form a user-defined vision for SDG progress that can be encoded at the beginning of a long-term strategic infrastructure planning process and inform recommendations for the implementation of infrastructure investments and policies (Thacker et al. 2019; Fuldauer et al. 2019).

In the context of responding to international development challenges, we build a set of cross-sectoral strategies that prioritise infrastructure interventions such that a predefined SDG vision will be achieved under a range of future conditions:

$$S = \{s_1, \dots, s_r\}$$

For each strategy, we select investments and policies of diverse magnitude and composition, which demonstrate alternative ways of achieving infrastructure-linked SDGs under a range of future demands that represent uncertainty in drivers such as population and tourism growth. The performance measures c_k therefore vary with the implementation of different strategies.

2.6 Calculating SDG target achievement across infrastructure strategies

Using national infrastructure systems models that use previously-developed methodology for national infrastructure planning in the United Kingdom (Hickford et al. 2014; Hall et al. 2017), we derive values for each indicator in the case of *inaction* as well as each SDG-assessed strategy for different levels of future infrastructure need, calculated using specified demand drivers, at time *t*.

The performance in a given year can be measured by inputting future values of c_k that occur given the implementation of a certain infrastructure strategy. For each strategy *s*, we calculate the time *t* indicator performance relative to each performance level:

$$f_{jk}(t,s) = \frac{c_k(t,s)}{p_{jk}(t)}$$

Incorporating the weighting terms above, the overall performance (or 'achievement level') of an SDG target z_j can be derived for a given year under a selected infrastructure strategy:

$$\hat{f}_j(t,s) = \sum_{k=1}^{y} w_{jk} f_{jk}(t,s)$$

3. Application

To demonstrate these methods in a practical case study, we apply them to a recent infrastructure assessment in the small-island Caribbean country of Curaçao, which focused on long-term planning of the energy, water, wastewater and solid waste sectors (Adshead et al. 2018). National development priorities were ascertained through a series of interactions with 150 stakeholders and practitioners from government, industry and local NGOs and used to inform optimal future performance levels and the combination of indicators used to measure these. Engagement with these stakeholders included extensive data collection on current infrastructure assets and networks as well as investment and policy options available to decision-makers in the country, including actions confirmed or proposed for implementation by the Government of Curaçao or adapted from regional or international best practice. A range of scenarios for long-term infrastructure needs were developed using the main drivers of infrastructure demand as identified by local stakeholders: residential population and tourism growth. Residential population growth scenarios were defined by 'high immigration', 'standard immigration' and 'emigration wave' forecasts published by the Curaçao Central Bureau of Statistics (2015). Scenarios for stay-over tourism (spending at least one night) and cruise ship tourism (for day visits only) were developed to encapsulate the range of potential tourism growth driven by major planned and ongoing port and airport capacity extensions that increase visitor numbers to the island (Curaçao Tourism Board 2016; 2016b; Airport tech 2017; Curaçao Ports Authority 2017; Business Curaçao 2015). The three scenarios underlying infrastructure needs in the four sectors addressed are represented as a combined total of these three components for 2030 in Figure 4.

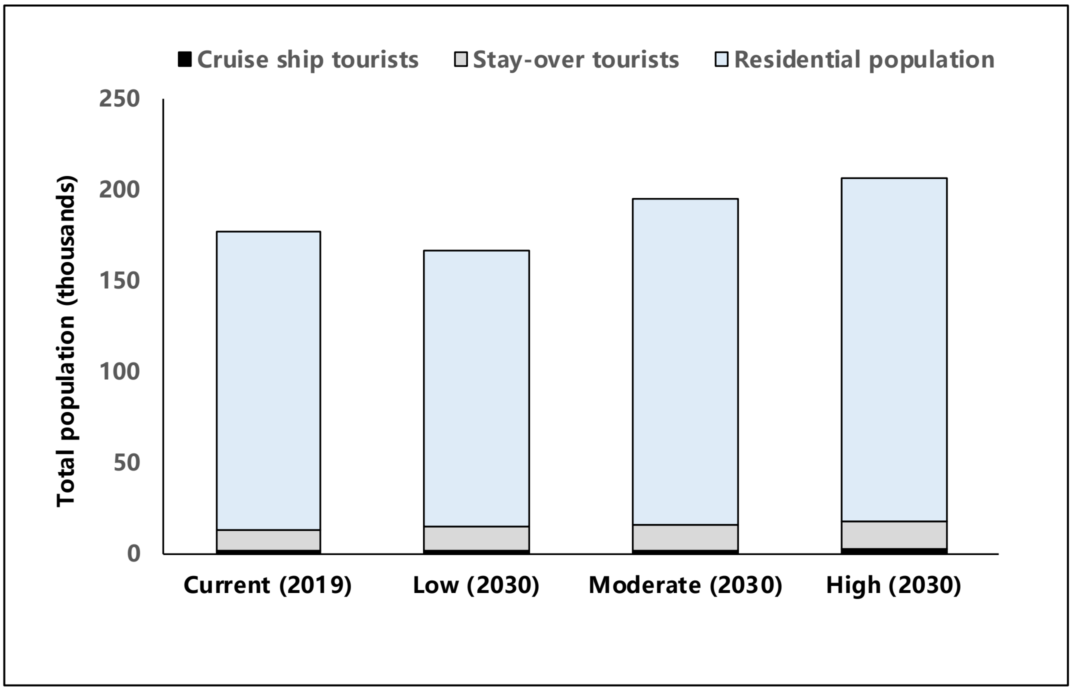


Figure 4: Aggregated population scenarios for Curaçao, composed of residential population, stay-over tourism and cruise ship tourism. Current total compared to 2030 projections for low, moderate and high demand drivers.

To assess key objectives raised by the stakeholders, we extract a set of indicators from an infrastructure systems model designed to provide insights into the cross-sectoral performance of Curaçao's infrastructure system (Fuldauer et al. 2018), which is based on a generalised approach to system-of-systems infrastructure modelling for sustainable development (Thacker et al. 2017). These indicators, shown in Table 1, focus on service delivery and environmental sustainability within the four sectors due to constraints imposed by data availability on the island, and can be applied to 6 SDGs and 19 SDG targets linked to infrastructure provision in the four assessed sectors.

Indicator	Sector	Description	Performance level value	Target value justification	SDG targets assigned	Indicator weight in target
Capacity margin (%)	Energy	Electricity generation capacity in relation to total annual demand.	35	Consistent with global IEA recommendation	7.1, 7.3, 9.1, 9.a, 11.1	w_{j1}
Renewables (%)	Energy	Percent of total electricity generation portfolio supplied by renewables.	50	Objective of the Government of Curaçao's National Energy Policy	7.2, 7.b, 9.1, 9.4, 9.a, 11.6, 12.4	w_{j2}
Capacity margin (%)	Water	Water supply capacity in relation to total annual demand.	34	In line with current performance	6.1, 6.2, 6.5, 9.1, 9.a, 11.1	w_{j3}
Energy use (GWh)	Water	Amount of energy used to generate annual water supply.	N/A		6.4, 9.1, 9.4, 9.a, 11.6, 12.4	N/A
Treatment rate (%)	Wastewater	Treatment capacity of wastewater treatment plants in relation to total wastewater generated.	58	Halved untreated from current level in line with SDG target requirement	6.3	w_{j4}
			48	Interpolated from capacity growth reaching government objective of 100% in 2050	6.2, 6.6, 9.1, 9.a, 11.1, 11.6, 12.4, 14.1, 14.5	w_{j5}
Reuse rate (%)	Wastewater	Percent of total wastewater reused (e.g. residential, irrigation uses).	N/A		9.1, 9.4, 9.a, 11.6, 12.5	N/A

Recycling rate (%)	Solid waste	Total recycling capacity in relation to total waste generated.	25	Ambitious target set at half the current EU Article 11 target	6.3, 9.1, 9.4, 9.a, 11.6, 12.1, 12.3, 12.5, 14.1	w_{j6}
Waste managed (%)	Solid waste	Total waste management capacity (including landfill) in relation to total waste generated.	100	Set as urgent priority due to limited space on the island, avoiding need for dumping or waste export	6.2, 6.3, 6.6, 9.1, 9.a, 11.1, 11.6, 12.4, 14.1	w_{j7}
CO2 emissions (Mt)	All sectors	Carbon emissions associated with the portfolio of infrastructure assets in use, based on a per-unit emissions factor for each technology.	N/A		7.2, 7.b, 9.1, 9.4, 9.a, 11.6, 12.4	N/A

Table 1: Key indicators extracted from national infrastructure systems model for the energy, water, wastewater and solid waste sectors, with application to 19 infrastructure-linked SDG targets. Includes indicator performance level assignment and justification for application to Curaçao. Performance levels set to "N/A" are not included in the case study

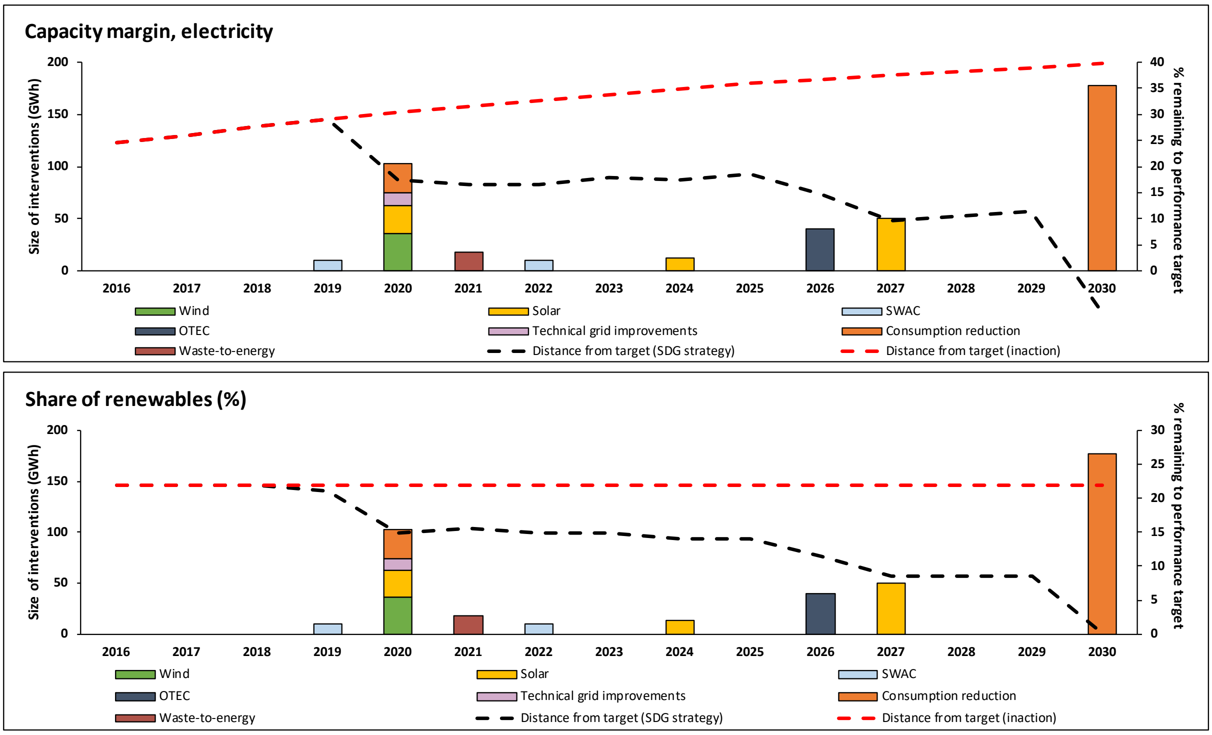
Through stakeholder interaction we identified key sector-specific challenges in the country:

- Curaçao's energy sector is currently fossil fuel-dependent. In order to decrease economic vulnerability to changes in international fuel prices, the sector aims to decarbonise with the achievement of 50% renewable production by 2030.
- Water supply is currently at safe levels of provision though produced entirely through reverse-osmosis desalination. Stakeholders aim to maintain this capacity margin around the current level (34%) through increased demand reductions, decreasing costs and energy reliance associated with desalination.
- Only 16% of Curaçao's wastewater is treated before it is discharged, threatening the health of the natural environment on which the island's tourism sector depends. By 2050, the government aims to increase wastewater treatment capacity to 100%.
- Capacity of the island's only landfill is nearing depletion. Effective solutions are required to address this urgent challenge, including recycling and waste prevention initiatives.

4. Results and discussion

Using these priorities and other benchmarks we quantify optimal 2030 target performance for Curaçao across these indicators, corresponding to the desired achievement date for the SDG agenda. We focus our analysis on six indicators across the four sectors. With the exception of the wastewater treatment indicator, for which a separate objective is set for SDG target 6.3, each performance level is assigned consistently across relevant SDG targets. Given this assignment of indicators and performance levels, we assemble a cross-sectoral portfolio of infrastructure interventions derived from options considered feasible in relation to the national context of Curaçao. This portfolio is structured around investments and policies that, once implemented, provide the type and amount of infrastructure services required to achieve relevant SDG targets given our moderate demand growth scenario for residential population and tourist numbers.

Figure 5 demonstrates how the performance of each of the six indicators considered for this analysis can be aligned with the performance levels set in Table 1, and how this can be practically implemented through infrastructure investments and policies across each of the four sectors to 2030. Interventions, including both demand- and supply-side options, are clustered by date of implementation and colour-coded by type, with the magnitude associated with each indicated on the left-hand axis. A dashed red line, indicating a case of *inaction*, shows the trajectory of the indicator should no infrastructure be built or policies implemented, while a dashed black line denotes that of the *SDG strategy*, linked to the timing of selected interventions, which narrows the achievement gap until the performance level is achieved by 2030.


Capacity margin, electricity
Size of interventions (GWh)
% remaining to performance target
2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030
Wind
Solar
SWAC
OTEC
Technical grid improvements
Consumption reduction
Waste-to-energy
Distance from target (SDG strategy)
Distance from target (inaction)
Share of renewables (%)
Size of interventions (GWh)
% remaining to performance target
2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030
Wind
Solar
SWAC
OTEC
Technical grid improvements
Consumption reduction
Waste-to-energy
Distance from target (SDG strategy)
Distance from target (inaction)

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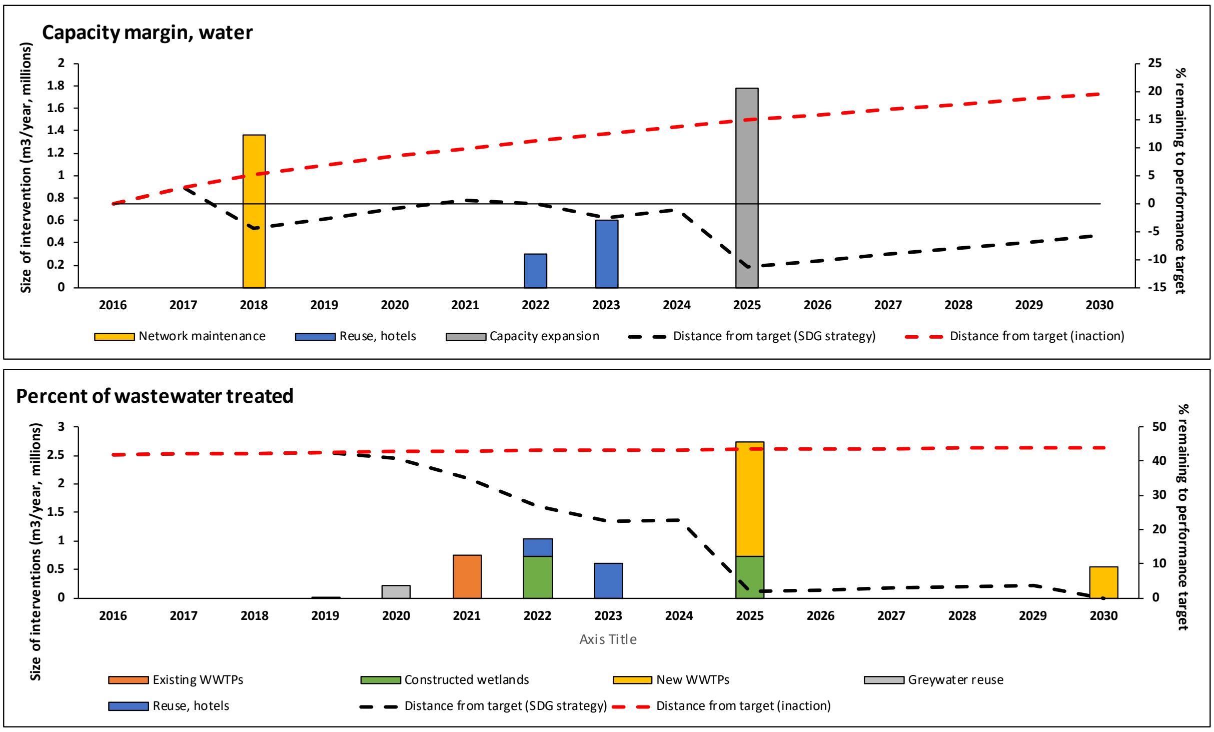

Capacity margin, water
Size of intervention (m3/year, millions)
% remaining to performance target
2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030
Network maintenance
Reuse, hotels
Capacity expansion
Distance from target (SDG strategy)
Distance from target (inaction)
Percent of wastewater treated
Size of interventions (m3/year, millions)
% remaining to performance target
2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030
Axis Title
Existing WWTPs
Constructed wetlands
New WWTPs
Greywater reuse
Reuse, hotels
Distance from target (SDG strategy)
Distance from target (inaction)

2

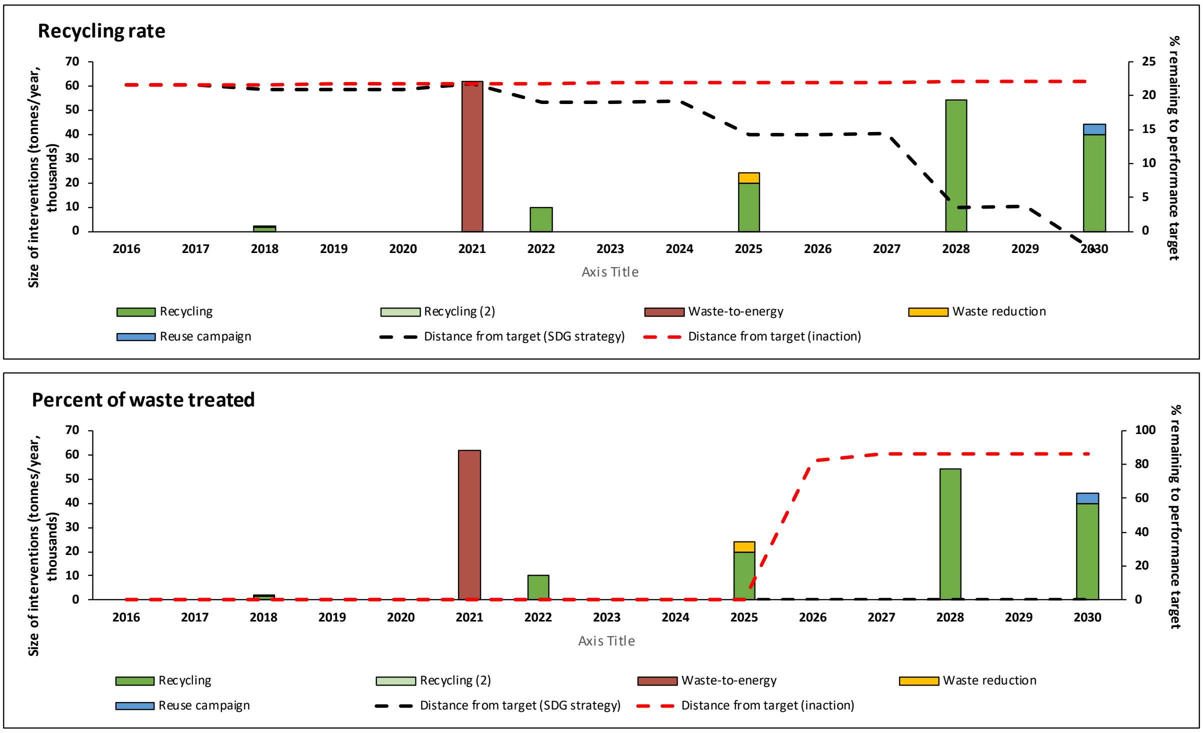
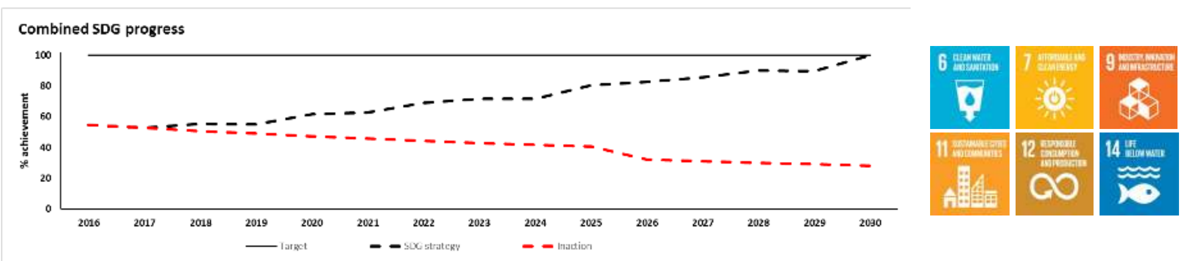


Figure 5: Strategy portfolio required to meet relevant SDG targets by 2030. Selected based on a moderate demand scenario for Curaçao's energy, water, wastewater and solid waste sectors.

Next, we examine how the attainment of these indicator performance levels may translate into overall achievement across SDG targets linked to infrastructure. Overall, we can see that *inaction* with regard to infrastructure planning will lead to a deterioration, at a minimum, of those SDG targets directly linked to the provision of infrastructure services. Specifically, average SDG attainment across these targets is projected to decrease from approximately 56% to 28% by 2030, representing insufficient provision of essential infrastructure services in relation to Curaçao's needs at a national scale.

From the aggregate graph in Figure 6, we can note the impact of major investment or policy implementations, or conversely, failure to provide adequate levels of infrastructure, on average SDG progress. The latter is most evident in terms of managed waste, where the depletion of landfill capacity around 2026 serves as a tipping point in sustainable management of the solid waste sector in Curaçao. Due to the many SDG targets it influences, this causes a pronounced slump in aggregate achievement in the *inaction* trajectory. A modified weighting of the relative importance of indicators in target achievement by a decision-maker will alter the scale and distribution of these impacts.

At the level of individual indicators, Figure 6 allows us to disaggregate impacted SDGs linked to each type of infrastructure. Notably, we can assess the estimated timeline for achievement of certain SDG targets based on infrastructure service provision challenges in Curaçao that affect the speed of potential progress in each sector. The need for the island to rapidly catch up to sustainable levels of wastewater and solid waste management will necessitate larger investments and policy shifts, often at greater financial cost. Thus, while SDG targets linked to improvements in energy or water supply infrastructure may face rapid improvement with the implementation of the specified strategy portfolio, Goals and targets that rely on success in the wastewater and solid waste sectors will see more gradual progress as sustainable wastewater and solid waste solutions kick in over time. An exception is the total capacity to manage waste (shown in the last panel), which achieves its target of 100% of total waste generated until 2026, when landfill capacity is depleted and additional treatment solutions require implementation.



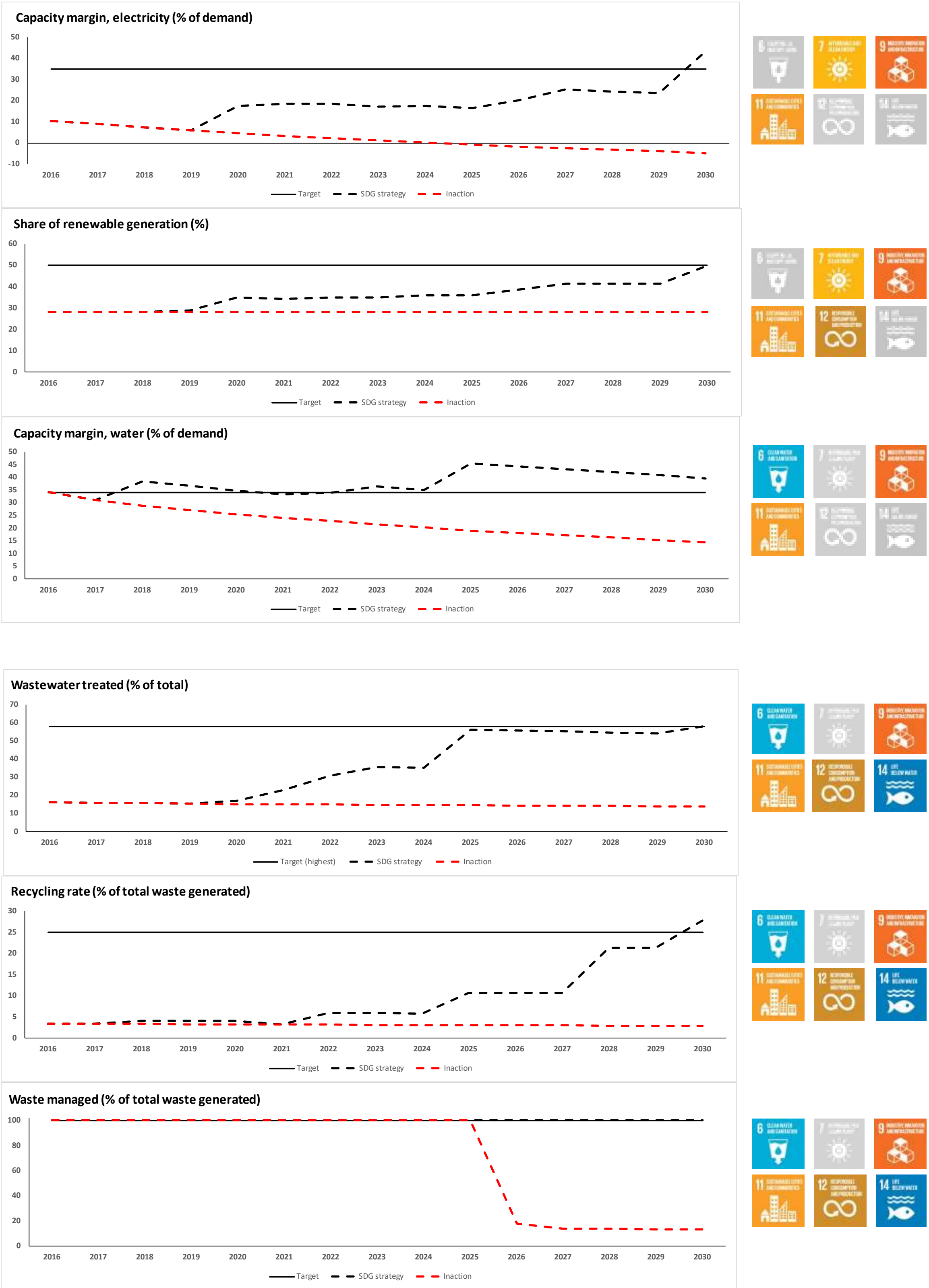


Figure 6: Indicator contributions to full achievement of relevant SDG targets by 2030, using indicator targets defined with stakeholder input

Under a moderate demand scenario, we have selected a strategy of interventions that achieves the 19 relevant SDG targets by 2030. So far, we have shown how investments and policies add capacity in order to affect key indicators of infrastructure sustainability, and how these indicators can be combined to provide an aggregate SDG metric for infrastructure performance. In Figure 7, we break down each of the 6 SDGs addressed in this application to Curaçao into their constituent SDG targets, thus showing the timeline for achievement of each target. This figure also shows where targets within an SDG are influenced by a similar set of interventions, and thus will progress along a similar trajectory with the implementation of the given strategy.

The importance of infrastructure interdependencies is highlighted in this figure as many SDG targets require a contribution from more than one infrastructure sector in order to achieve full achievement. Infrastructure sector requirements are separated out for each target and indicated to the right of each trajectory, illustrating the extent of cross-sectoral infrastructure planning required to achieve any given SDG. The figure shows that achievement of nearly 50% of the targets assessed within the four sectors require interventions from two or more sectors; this further emphasises the value of considering infrastructure decisions within the context of an interdependent system. While some Goals demonstrate an intuitive relationship to certain sectors (e.g. water and energy to SDGs 6 and 7, respectively), others require several sectors to work in concert to fully achieve targets. Goals 9 and 11 are prime examples of SDGs that rely on an extensive range of infrastructure services: industry and innovation are improved through sustainable inputs and outputs provided by multiple types of infrastructure, while expanding cities and urban environments are dependent on, among other things, secure energy generation, reliable water provision and sustainable management of large quantities of waste and wastewater. Only through improvement of infrastructure system sustainability as a whole can these Goals succeed.

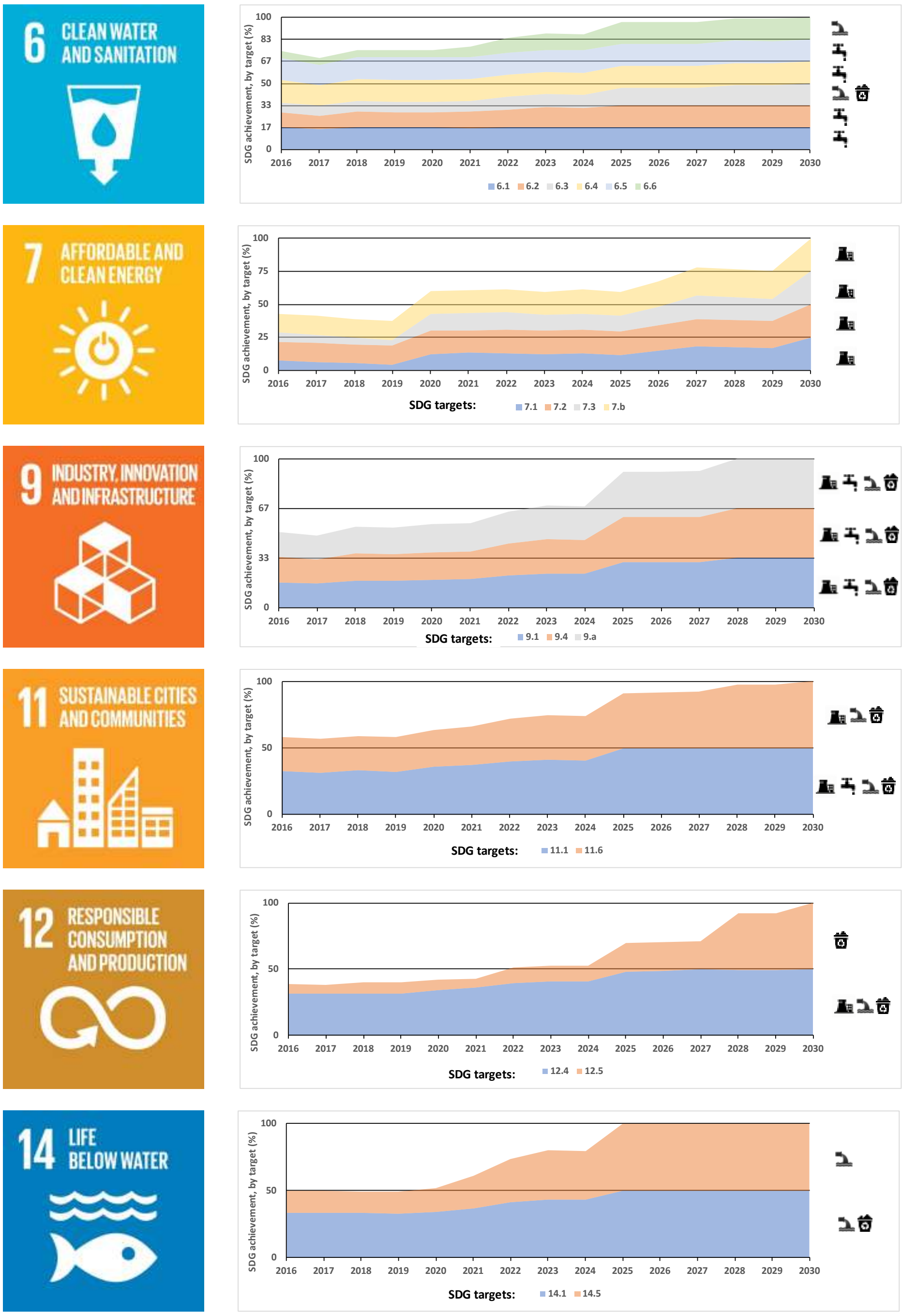


Figure 7: Target contribution to SDGs by 2030, showing trajectory to achievement of infrastructure-linked targets. Required sector inputs are displayed for each target along the right-hand side.

Infrastructure decision-makers must confront uncertainty around future demand drivers in deciding how much infrastructure capacity to implement to increase the likelihood of meeting performance targets and achieving SDG progress. Given budgetary constraints on infrastructure planning, analysts require information on the potential range of infrastructure demand in order to produce evidence-based policy recommendations. By exceeding performance targets under expected growth scenarios in one or more sectors, decision-makers may add resilience to the system or provide flexibility should critical infrastructure be affected by unexpected or extreme events (Birkmann et al. 2016). At the same time, it may account for a misallocation of spending on unneeded projects that ultimately raise costs of national infrastructure provision and impact negatively on user affordability and access.

Figure 8 plots the indicator performance of the *SDG strategy* on the six indicators incorporated in this analysis of Curaçao, which was developed based on the expectation of moderate residential population and tourism growth on the island as defined by census data and tourism projections. Notably, such a strategy would vastly outperform in the energy and water supply sectors in the case of low demand, providing nearly double the capacity required to meet resilience targets. While some target over-achievement is evident in terms of wastewater treatment and recycling, the current under-capacity in these sectors suggests that the extra investment would be more effectively utilised.

This analysis also highlights the trade-offs between indicators and targets and the need to consider balanced investment and policy interventions in strategy formulation. Interventions contributing to positive growth of one indicator might have the opposite impact on others: in the case of Curaçao, the implementation of a waste-to-energy plant greatly increases generation and treatment capacity in the energy and waste sectors, respectively. However, this also impacts the renewable energy generation portfolio and diverts resources away from more environmentally-friendly waste solutions such as recycling facilities.

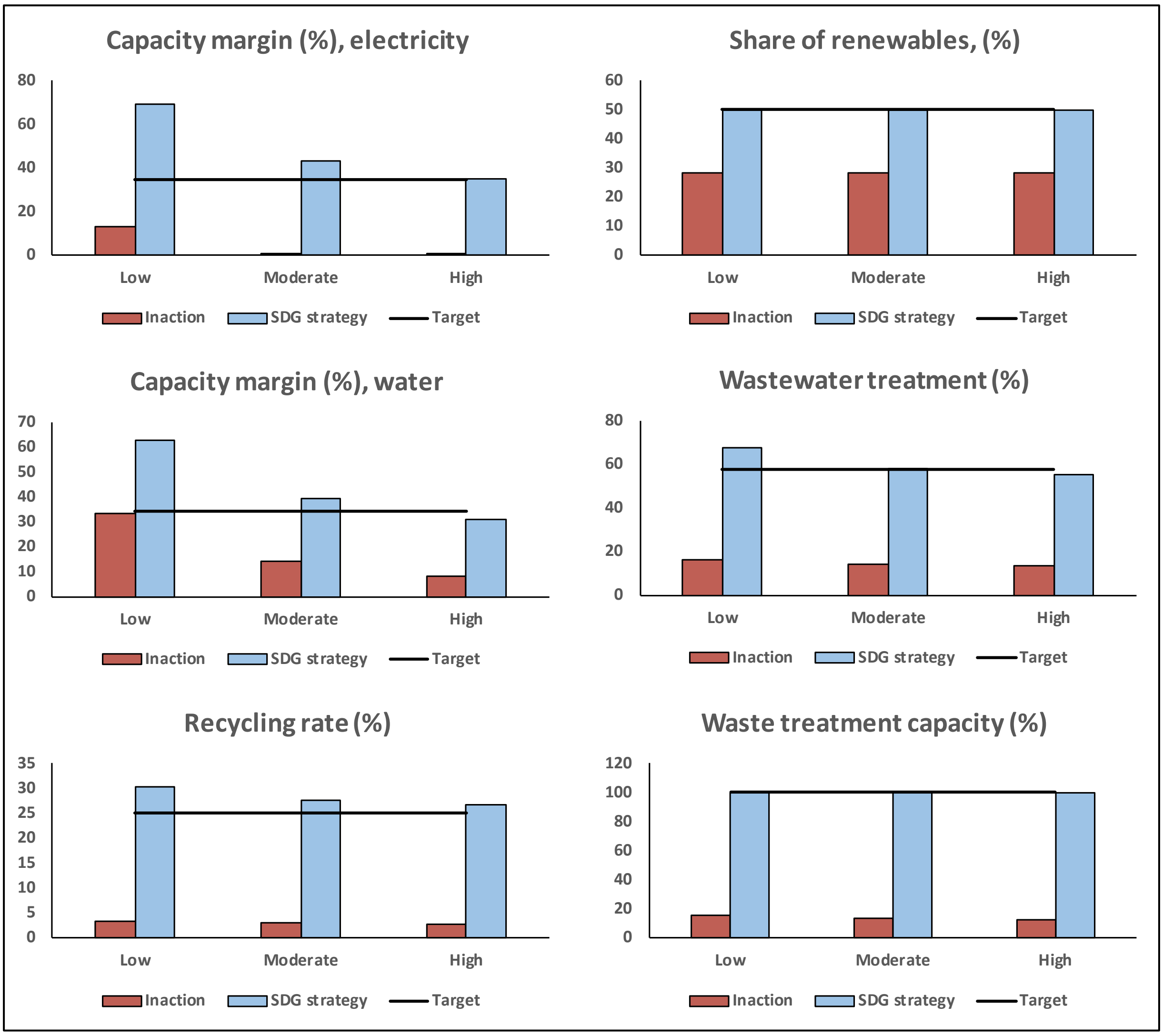


Figure 8: Indicator performance of SDG strategy in relation to stakeholder-defined targets under three scenarios of infrastructure demand for 2030: low, medium, high

These findings suggest that successful strategies should incorporate flexibility and uncertainty into infrastructure system design and implementation. For large investments such as wastewater treatment plants or solar farms, planning for modular capacity growth can promote solutions that are adaptive to uncertain future scenarios, a concept already widely developed in the fossil fuel industry (de Neufville 2009). Iterative infrastructure assessments, updated and informed in real-time by the most recent data, can guide decision-makers to plan infrastructure interventions appropriately in the context of technological, demographic, economic or environmental uncertainty. These actions have commenced (National Infrastructure Commission 2018) or been initiated (New Zealand Treasury 2019) by independent bodies or commissions tasked with integrated infrastructure planning in certain countries.

5. Conclusion

This paper has outlined the role infrastructure can play in delivering on a wide range of Sustainable Development Goals and targets within the 2030 Agenda. Further, it highlights the importance of developing an informed process for infrastructure decision-makers to capitalise on opportunities to achieve these goals through investments and policy. In creating a new framework to assess infrastructure performance based on a set of indicators linked to specific SDG targets, this analysis provides a means of assessing infrastructure service capacity against performance levels defined at the national scale. An application of this framework to Curaçao allows us to develop cross-sectoral infrastructure portfolios designed to optimise the achievement of 19 relevant SDG targets under a range of demand driver uncertainties.

This application of the framework faced a few main limitations. First, the analysis focused on four sectors – energy, water, wastewater and solid waste – for which data on future national infrastructure needs as well as demand- and supply-side interventions could be integrated from infrastructure systems models, providing the ability to assess long-term performance. The analysis notably did not include the transport and digital communications sectors, which provide key functions required for the achievement of many SDG targets – both independently and as part of the broader infrastructure system. While this concept of infrastructure-linked SDG assessment can nonetheless be demonstrated using four sectors, extending the sector coverage would increase the number of SDG targets that can be included in the analysis and provide greater insight for policy makers. Second, the indicator selection across the four sectors was limited to those that could be extracted from the use of a specific infrastructure systems model; of these, we used a reduced set to demonstrate the performance assessment of selected strategies. A wider range of available indicators may allow decision-makers to undertake a more nuanced quantification of infrastructure-linked SDG targets, which are often stated in broad terms. Third, while many of the SDG targets in the analysis could be assessed from the standpoint of infrastructure service provision or environmental impact, there was insufficient data to account for the affordability aspect – the third component of the 'trilemma' concept framing infrastructure decisions. Although this dimension of sustainability is referenced less frequently throughout the SDG targets, it provides crucial information on the economic and financial sustainability of an infrastructure system and can otherwise constrain the type or quantity of infrastructure available to users. A further analysis could benefit from including or proxying for the cost of infrastructure (either through utility tariffs, fares or taxes) for present and future generations. Fourth, while the inter-dependent systems model developed for this study maintains important insights about the role of sequenced investments and policies in achieving development outcomes, it does not fully capture the dynamic complexity of infrastructure systems and the roles physical, natural, and social capital play in contributing to sustainable infrastructure development. A focus on modelling assets in the built environment assumes that financial, human (knowledge), and environmental mechanisms are in place to support these interventions.

This framework lays the groundwork for future analysis related to infrastructure and the SDGs. The current study largely relies on expert judgments to determine plausible performance targets in a given national context, a realistic approach in line with how the SDGs were designed for implementation. A more exhaustive study, incorporating a broader range of potential target values, could highlight the range of required actions for stakeholders based on sustainability principles such as a fully renewable energy sector or circular economy. A broader inclusion of the types of capital within the infrastructure systems modelling may aim to capture the elements of a complex and dynamic infrastructure system. Further practical extensions of this research include the transfer of this analytical capability to other national or sub-national contexts for large developing or emerging countries or rapidly developing city states – or to provide 'build back better' decision-making capability for post-disaster, post conflict countries. Further methodological development is required to increase the robustness of strategy portfolios by analysing the scale and timing of strategic alternatives and trade-offs between multiple objectives faced by decision-makers. In defining strategies that allow greater flexibility to adapt to demand driver uncertainty, adaptive pathways methodology can incorporate additional robustness in strategic infrastructure planning, particularly in the case of countries with a greater range of development options such as post-conflict countries. Although this analysis has focused on the long-term planning aspect of infrastructure, there is also a need to account for the development implications of short-term shocks, particularly those linked to climate change drivers, which are incorporated in many SDG targets. As such, our understanding of infrastructure's potential contribution to minimising socio-economic risks and vulnerabilities can be enhanced through the inclusion of spatial and geographical data analysis at the national and sub-national scales.

Infrastructure has a major role to play in the achievement of the Sustainable Development Goals. Given the large investments and policy decisions that will be made in the coming decades, there is a need to understand the potential implications of these in terms of development outcomes: we have provided the first step towards being able to do so using a consistent and systematic framework that acknowledges the national context of priority-setting within the 2030 Agenda for Sustainable Development. By establishing clear and informed development trajectories linked to national-scale interventions at the level of individual policies or investments, we provide a practical means of operationalising the SDGs, using indicators to provide the basis for sound and effective decision-making. Such focused assessment, in infrastructure and other fields, is required if significant progress is to be made toward the Sustainable Development Goals within the agenda’s timespan.

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